



# NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

## SYSTEMS ENGINEERING CAPSTONE PROJECT REPORT

**EFFICACY EVALUATION OF CURRENT AND FUTURE  
NAVAL MINE WARFARE NEUTRALIZATION METHOD**

by

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December 2016

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WARFARE NEUTRALIZATION METHOD**

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Submitted in partial fulfillment of the  
requirements for the degrees of

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## **ABSTRACT**

This capstone report analyzes the expected mine countermeasures (MCM) performance of legacy and emerging mine neutralization systems on multiple platforms. The systems evaluated are the SLQ-48 “Mine Neutralizing System,” the SLQ-60 “SeaFox,” the AN/AQS-235 “Airborne Mine Neutralization System/Archerfish,” and the “Improved Mine Neutralization System–Barracuda” currently being developed by Raytheon. The platforms in which these systems are to be supported on are the Avenger MCM ship, the MH60S “Knighthawk” helicopter, and the littoral combat ship (LCS). The study focused on three measures of effectiveness (MOEs): mission time, weapon expenditures, and mission effectiveness. Using an operational simulation and design of experiments (DOE), our team determined which configuration variations of these systems on supported platforms appeared to be the most effective. The study found that the performance of the “Improved Mine Neutralization System–Barracuda” presented an increase in capability over legacy systems. In addition, the simulation analysis results depicted a significant performance increase from aerial-deployed neutralizers and neutralizers deployed simultaneously in parallel configurations. This report suggests that, when possible, mine neutralization should be conducted in a parallel configuration from multiple platforms with the most capable neutralizer available.

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## LIST OF ACRONYMS AND ABBREVIATIONS

ALMDS	airborne laser mine detection system
AMCM	airborne mine countermeasures
AMNS	airborne mine neutralization system
AOR	area of responsibility
ASW	antisubmarine warfare
ASuW	anti-surface warfare
CAS	combat air support
CCTV	closed-circuit television
COBRA	coastal battlefield reconnaissance and analysis
CG	cruiser ship designator
CONOPS	concept of operations
CPA	closest point of approach
CSW	crew-served weapon
CUSV	common unmanned surface vehicle
CVN	nuclear aircraft carrier ship designator
DDG	destroyer ship designator
DOD	department of defense
EDP	environment definition program
EOD	explosive ordinance disposal
EPF	environment python file
FFG	frigate ship designator
FRS	fleet replacement squadron
FOC	final operational capability
HA/DR	humanitarian aid/disaster relief
LCS	littoral combat ship designator
LHD	amphibious assault ship designator
LHS	launch and handling system
L-I-N	localization, identification, neutralization
LPD	amphibious transport dock ship designator
M&S	modeling and simulation

MCM	mine countermeasures
MCMC	mine countermeasures mission commander
MCMMP	mine countermeasures mission package
MIW	mine warfare
MNS	mine neutralization systems
MOE	measures of effectiveness
MTS	multi-spectral targeting system
MSC	military sealift command
MSES	Masters of Science in engineering systems
MSSE	Masters of Science in systems engineering
NMMP	Navy marine mammal program
NPS	naval postgraduate school
OASIS	organic airborne surface influence sweep
PC	patrol craft
pM	probability of malfunction
pMID	probability of misidentification
PR/CSAR	personnel recovery/combat search and rescue
RAMICS	rapid airborne mine neutralization system
RHIB	rigid hull inflatable boat
RMS	remote mine hunting system
RMMV	remote multi-mission vehicle
SAR	search and rescue
SE	systems engineering
SLOC	sea line of communication
SME	subject matter expert
SOF	special operations force
SUW	surface warfare
tD/R	time to deploy/recover
TTP	tactics, techniques, and procedures
UAV	unmanned aerial vehicle
UISS	unmanned influence sweep system
USS	United States ship

UUV	unmanned underwater vehicle
USV	undersea vehicle
VOD	vertical onboard delivery

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## EXECUTIVE SUMMARY

As a continuation of previous Naval Postgraduate School (NPS) Mine Warfare (MIW) reports (Cohort 311-132M in 2014 and Cohort 311-132O in 2015), the purpose of this study is to analyze the efficacy of current United States Naval Mine Neutralization Systems (MNS) within the broader operational context of Naval Mine Countermeasures (MCM). The performance of legacy MNS and a future MNS was modeled and analyzed under various environmental and employment scenarios, in order to determine the most relevant performance parameters to be considered in future developments and/or upgrades. The study focused on three measures of effectiveness (MOEs): mission time, weapon expenditures, and mission effectiveness.<sup>1</sup>

Through stakeholder solicitation and other research methods, the analysis team identified three currently fielded, and one proposed platform, to support the Naval MNS mission, along with four currently fielded, and one proposed Naval MNS for evaluation as indicated in Table 1. Demonstrated performance characteristics, or planned performance characteristics for Naval MNS in development, were determined for these systems.

Table 1. Platforms and MNS under Study

Platform	Mine Neutralization System (MNS)
MCM-1 Avenger Class Ship	AN/SLQ-48 Mine Neutralization System
MH-53E “Sea Dragon” Helicopter	AN/SLQ-60 SeaFox
Littoral Combat Ship (LCS)	AN/ASQ-235 AMNS Archerfish
MH-60S “Knight Hawk” Helicopter	AMNS Barracuda ( <i>Future System</i> )

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<sup>1</sup>A product of weapon expenditures compared to mines neutralized.

Utilizing the performance characteristics of these systems, individual operational configurations were developed based upon current Fleet MCM tactics, techniques, and procedures (TTP) and a set of proposed new TTPs. Even though the mine hunting and neutralization continuum is broadly composed of Detection, Classification, Localization, Identification, and Neutralization, the purpose of this study is to focus on the Localization, Identification, and Neutralization (L-I-N) segment of the mine neutralization continuum for current and proposed platform/system configurations and combinations, under a range of field configuration and environmental conditions to investigate the following study questions:

What configurations, using current neutralization systems and platforms, are most effective (fastest) in clearing a minefield?

What configurations, using current and / or proposed neutralization systems and platforms, are most effective (fastest) in clearing a minefield?

What individual platform or neutralization system performance parameters (i.e., range, speed, probability of kill) have the greatest impact on the efficacy of current or proposed operational scenarios?

Mine neutralization can be performed in a number of different ways. The methods of performing a MNS mission depend on several factors depending on what systems are being utilized. To have sufficient data to assess the relative efficacies of each mission variant, simulation runs were made utilizing each variant, at every possible performance variable value (determined by a full factorial Design of Experiments (DOE)), for each employment configuration, against a single mine field model generated from Environment Definition Program (EDP) output as illustrated in Figure 1.

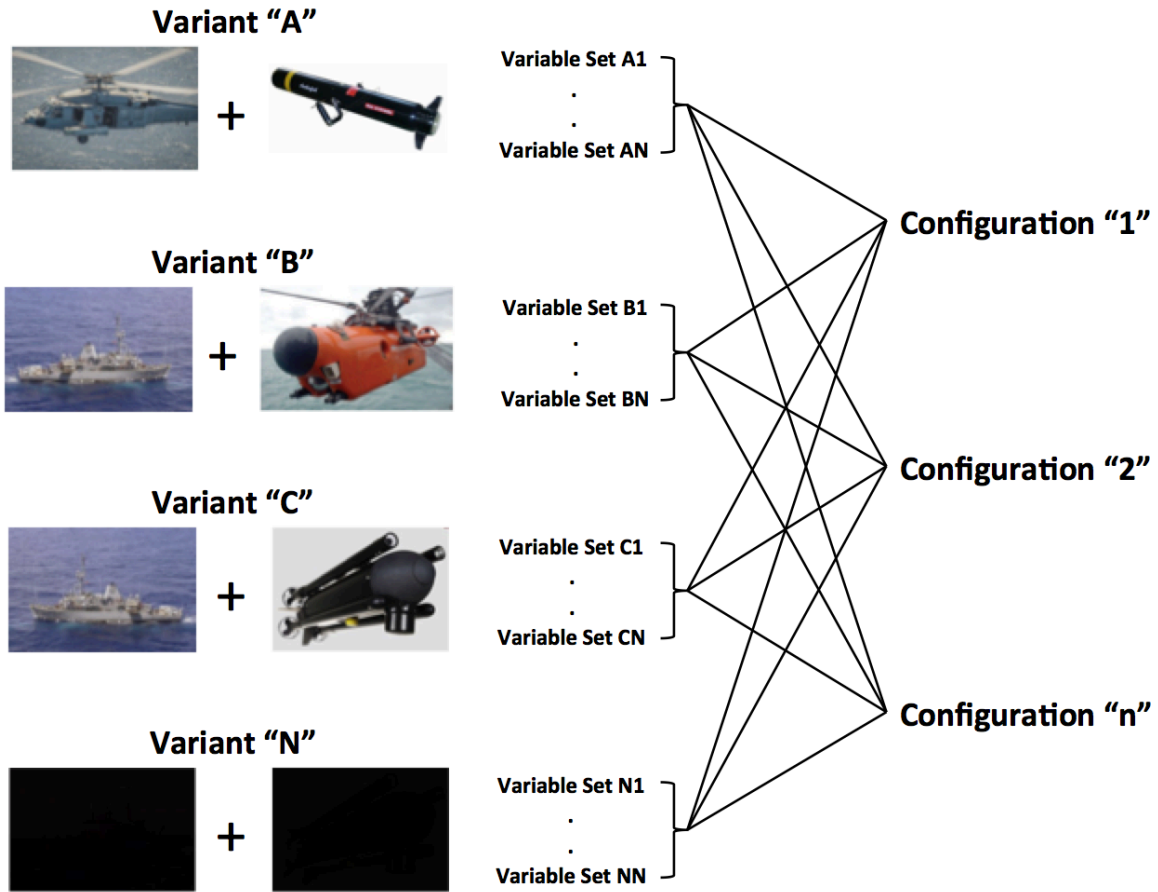


Figure 1. Simulation Framework. Sources: BAE Archerfish Mine Neutralization System (2016), Furey (2014), Hammond (2004), MarineLink (2012), and Program Executive Office Littoral and Mine Warfare (2009).

Using a simulation built with the Python programming language, available at Python Software Foundation <https://www.python.org>, models representing mine fields of varying target density, depth, type, and environmental conditions were created to test each operational combinational variant of the platform and MNS. This analysis allowed for determination of the efficacy of each type of operational scenario as illustrated in Table 2 and Figure 2.

Table 2. Neutralizer Performance

System	Configuration 1 1 Neutralizer		Configuration 2 2 Neutralizers		Configuration 3 4 Neutralizers	
	Mission Time	Mission Effectiveness	Mission Time	Mission Effectiveness	Mission Time	Mission Effectiveness
SLQ-48	98.27	0.671	52.68	0.673	31.41	0.672
SLQ-60(1)	78.58	0.775	42.24	0.772	25.21	0.776
SLQ-60(2)	88.53	0.773	47.52	0.778	28.48	0.776
AMNS	65.77	0.915	34.92	0.914	20.71	0.912
Barracuda	52.97	0.958	28.02	0.959	16.49	0.957

This table shows Mission Time in hours and Mission Effectiveness as a ratio (mines / weapon expenditure).

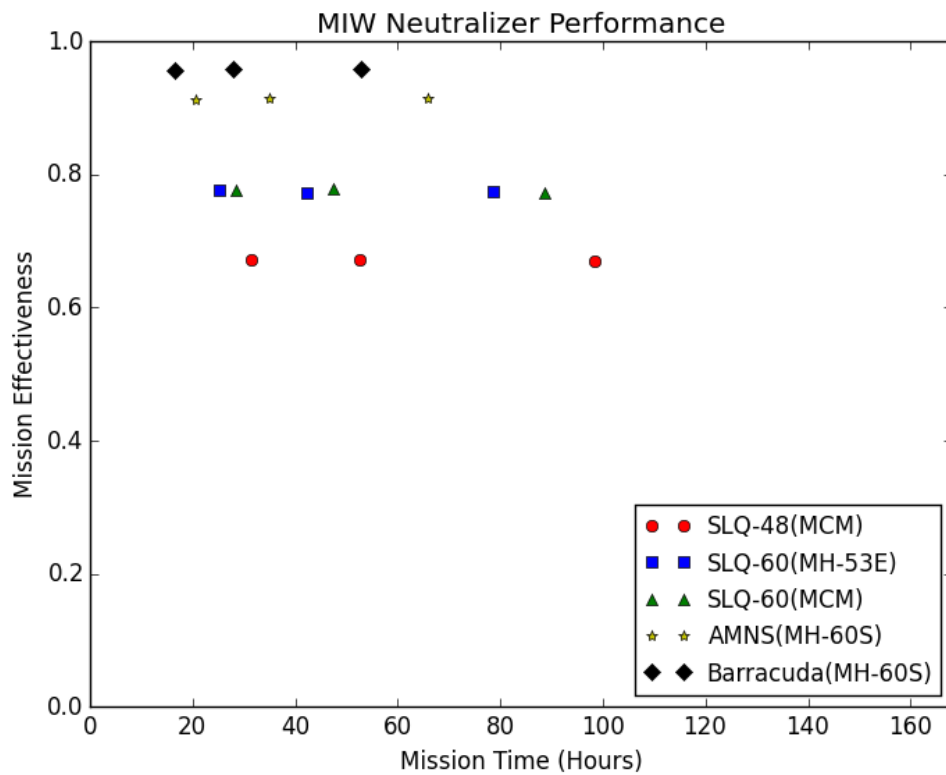


Figure 2. MIW Neutralizer Performance



Additionally, through the use of regression analysis, the relative importance of each individual platform and MNS performance characteristic's impact on overall scenario efficacy was determined. An overall relationship between the primary independent variables, Probability of Malfunction (pM) and Probability of Misidentification (pMID), and the combined dependent variables, Mission Effectiveness / Time, showed a higher effect from pM – as pM decreases, Mission Effectiveness / Time increases substantially. The equivalent type of effect from pMID is significantly less substantial, as seen by the slopes indicated in Figure 3.

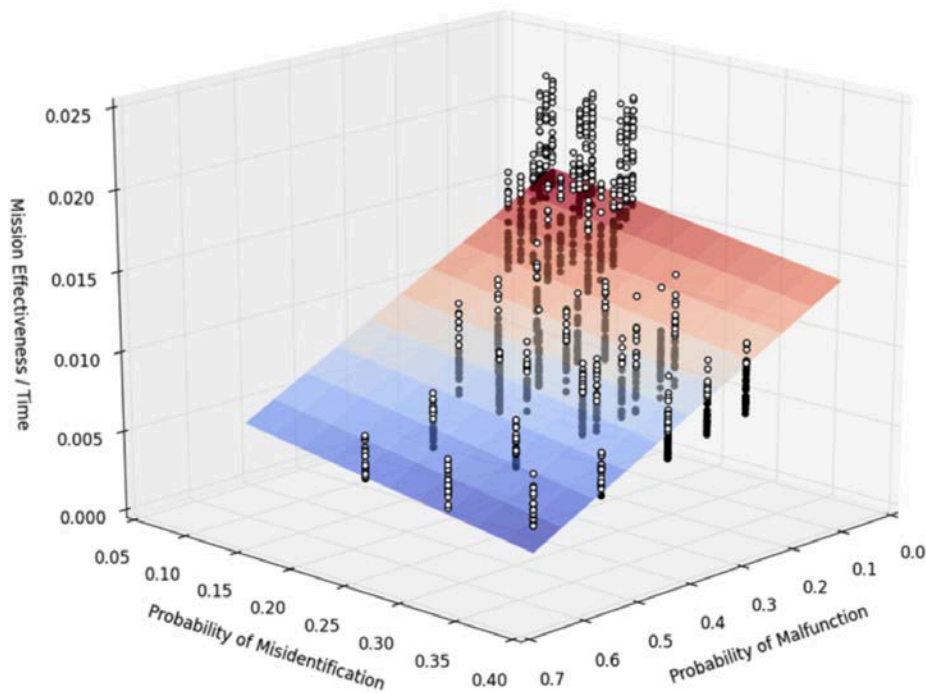


Figure 3. Overall Performance Effects

Overall, the performance of the AMNS Barracuda (future system currently in development) presents an increase in capability over legacy systems. In addition, model analysis shows a significant performance increase from aerial-deployed neutralizers and neutralizers deployed simultaneously in parallel configurations due to the decreased mission time required to clear a given minefield.

This report suggests that, when possible, mine neutralization should be conducted in a parallel configuration from multiple platforms with the most capable neutralizer available. It is accepted, however, that operational limits may present an obstacle to the use of multiple MIW platforms simultaneously, and the increased presence of platforms may provide diminishing results as the number is increased.

Recommendations for further study and improvement include the expansion of this model and its associated input variables to account for more MOEs that can be specified by future MNS acquisitions teams. To accurately account for the MOEs used in this model, it is recommended that the input variables used to represent neutralizer and platform capabilities be set as constants representing the actual capabilities of the neutralization systems reviewed in this report. This information and the associated result would, however, require a classified environment.

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# **I. INTRODUCTION AND BACKGROUND**

## **A. PURPOSE**

The purpose of this study is to analyze the efficacy of current United States Naval Mine Neutralization Systems (MNS) within the broader operational context of Naval Mine Countermeasures (MCM). In this analysis, the performance of legacy MNS was modeled and analyzed under various environmental and employment scenarios in order to determine the most relevant performance parameters to be considered in future developments and/or upgrades. The results of this study will ultimately yield an effective and lower cost acquisition for future MNS systems. This study was conducted to partially fulfill the requirements of the Naval Postgraduate School (NPS) Master of Science in Systems Engineering (MSSE) and Master of Science in Engineering Systems (MSES) programs.

## **B. OUTLINE OF STUDY**

Through stakeholder solicitation and other research methods, the analysis team identified four currently fielded, and one proposed Naval MNS mission for evaluation. Demonstrated performance characteristics, or planned performance characteristics for Naval MNS in development, were determined for these systems. Utilizing the performance characteristics of these systems, individual operational configurations were developed based upon current Fleet MCM tactics, techniques, and procedures (TTP) and a set of proposed new TTPs. Even though the mine hunting and neutralization continuum is broadly composed of Detection, Classification, Localization, Identification, and Neutralization, the scenarios developed for the modeling and analysis for this study, were limited to the Localization, Identification, and Neutralization (L-I-N) continuum segment. Using a simulation built with the Python programming language, available at Python Software Foundation <https://www.python.org>, models representing mine fields of varying target density, depth, type, and environmental conditions were created to test each operational combinational variant of the MNS and platform. This analysis allowed for determination of the efficacy of each type of operational scenario. Additionally, through

the use of regression analysis, the relative importance of each individual MNS and platform performance characteristic's impact on overall scenario efficacy was determined.

## **C. BACKGROUND**

### **1. Freedom of the Seas**

There is probably no greater expression of national sovereignty than the ability to freely traverse the world's seas. In a world where water covers 70 percent of the Earth's surface, 80 percent of the world's population lives near the ocean, and 90 percent of all international trade travels by sea (Feller 2011), unimpeded maritime freedom is essential to both the economic prosperity and the defense of any nation state. Early in its history, the United States realized the importance of freedom of the seas to national prosperity and identity. Post-revolutionary conflicts along the coast of the United States threatened tribute-free passage in the Mediterranean Sea (Thomas Jefferson Foundation, Inc. n.d.). To protect harbors and the coastline, the inventor Robert Fulton advocated the use of naval mines by the United States, which President Jefferson saw potential in. After a decade of development and demonstrations, mines were ultimately employed by the U.S. Navy and were an effective component of the national defense by the War of 1812.

### **2. Effectiveness of Mining**

The very benefits that drove a resource limited United States in the early nineteenth century to employ mines remain today as incentive for countries all over the globe to employ them as part of their offensive and defensive naval strategies. For nation states that lack the economic resources or technology, an industrial base to deploy blue water navy mines can provide these states with some level of stature (and leverage) on the world stage. Sea mines are a low-cost force multiplier that has the potential to restrict severely the commercial and military freedom of the seas. Furthermore, the low cost to acquire and deploy naval mines is significantly disproportionate to the cost of locating and neutralization. Even the threat of a minefield can bring military and commercial shipping to a crawl as dedicated systems must be brought in-theater to locate and neutralize the threat. The relative costs of mine hunting and neutralization versus

placement and maintenance of the field is enormous. For example, since the 1980s the Navy has utilized the MCM-1 Avenger Class platform for the MCM mission. The annual, per ship cost is approximately \$5M in constant 1996 dollars. (Pike 1999) This does not include the cost to get those ships to theater. Conversely, some mines can be purchased for less than \$2,000 and can be deployed from small craft. Once a field is laid it remains a persistent and costly threat until it is mitigated.

The cost of producing and laying a mine is usually anywhere from 0.5% to 10% of the cost of removing it, and it can take up to 200 times as long to clear a minefield as to lay it. Parts of some World War II naval minefields still exist because they are too extensive and expensive to clear. It is possible for some of these 1940s-era mines to remain dangerous for many years to come. (North Atlantic Treaty Organization 2014)

### **3. Countering the Threat**

As of 2009 there are “(m)ore than a quarter-million sea mines of more than 300 types are in the inventories of more than 50 navies worldwide” (Program Executive Office Littoral and Mine Warfare 2009). It is clear from the sheer number of mines in existence and with the ease of their employment, that if the U.S. Navy is to maintain its dominance of the seas, it must continue to develop ever better systems and tactics to find, exploit, and destroy mines. Since the late 1980s, the U.S. Navy has maintained a dedicated force to conduct the MCM mission that is comprised of a triad of MCM delivery platforms and systems to conduct Mine Sweeping and Mine Hunting. Mine Sweeping is the broad area, indiscriminate method to expose and destroy mines using mechanical or influence (i.e., acoustics, magnetic, pressure) methods. Mine sweeping, while useful absent the ability to conduct mine hunting operations, does not provide the same level of field clearance confidence as mine hunting and neutralization. As a result, and due to the differences in operational implementation of mine hunting/neutralization systems and mine sweeping systems, mine sweeping scenarios were not analyzed as part of this study.

### **4. The Neutralization Continuum**

The overall mission of hunting and neutralizing mines is comprised of five distinct tasks: detection, classification, localization, identification, and neutralization.

Each task is presently accomplished by using components of the Navy MCM Triad of the current, dedicated MCM force centered on the Avenger Class and MH-53 platforms. “During the next decade, the Service will transition the mine countermeasures capability from today’s dedicated assets to an aircraft carrier and expeditionary strike group-focused organic force” centered around the Littoral Combat Ship (LCS) with MCM Mission Packages (MCMMP). The LCS MCMMPs will be comprised of both air and surface assets, some of which are being employed today. For this study, only the Location, Identification, Neutralization (L-I-N) portion of the Mine Neutralization Continuum was considered.

## **5. The Triad**

The Navy’s “triad” of “dedicated” mine countermeasures forces (shown in Figure 1) comprises surface mine countermeasure ships, airborne mine countermeasures helicopters, and Explosive Ordnance Disposal (EOD) divers and their systems which are used to execute the five components of the neutralization continuum. Once a threat region has been identified and bounded, a sonar or laser detection sweep for candidate mines is conducted from an Avenger class ship (MCM-1), a LCS, or MCM helicopters (including the MH-60S or MH-53E).



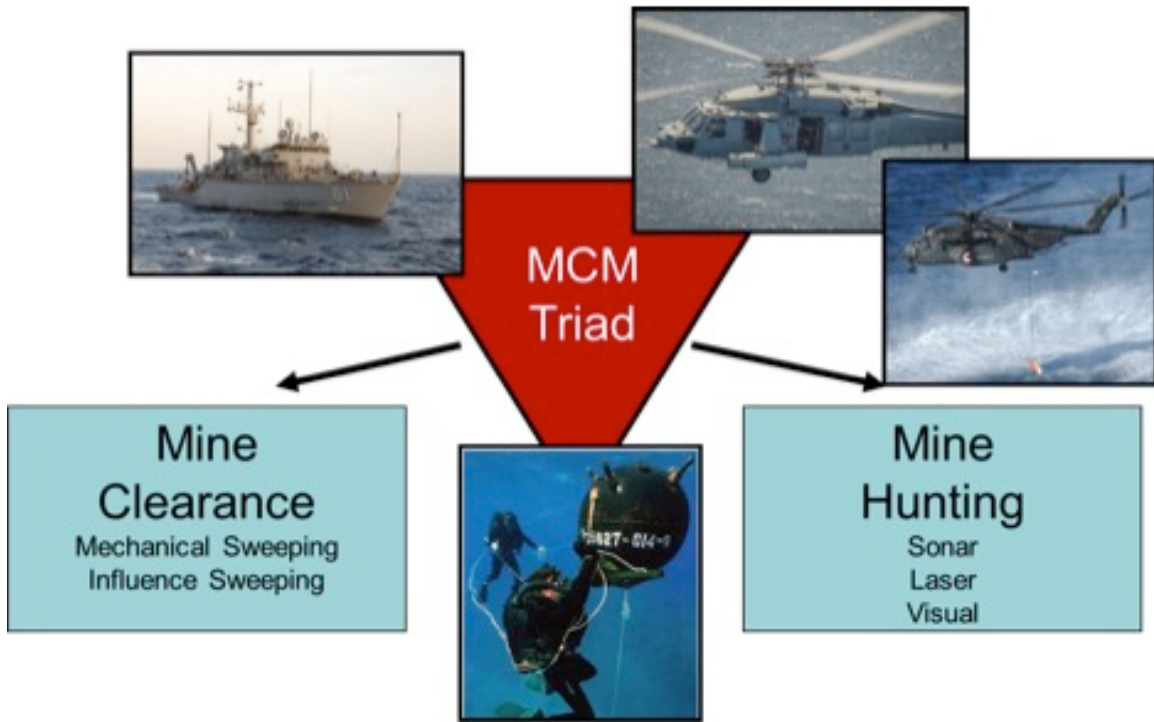


Figure 1. MCM Triad

The systems currently employed for detection and classifications are:

- SQQ-32 variable-depth mine detection and classification sonar (MCM-1)
- AQS-24 multi-beam side-looking mine-hunting sonar (MH-53)
- Remote Multi-Mission Vehicle (LCS)
- AQS-20A Mine Hunting Sonar (MH-60S and with Remote Multi-Mission Vehicle from LCS)
- AES-1 Airborne Laser Mine Detection System (MH-60S)

Another platform under consideration for detection and classification is the common unmanned surface vehicle (CUSV).

Once a field has been mapped and objects classified, the target data is used by neutralization assets to reacquire (locate), verify (identify), and if required, neutralize the target. The systems currently employed (or planned for future use) for reacquisition and neutralization are:

- SLQ-48(V) Mine Neutralization System (MCM-1)
- SLQ-60 SeaFox (LCS)
- AN/AQS-235 Airborne Mine Neutralization System (MH-60S or CUSV)
- Barracuda Mine Neutralization System (MH-60S or CUSV)
- EOD Divers with Navy Marine Mammals

#### D. SYSTEMS ENGINEERING APPROACH

Numerous systems engineering process models were considered for this study including the Waterfall, Spiral, and “Vee” models. Given the tight schedule of the capstone process a sequential SE model that also allowed for iteration and feedback between phases was required. The classic “Vee” model (Figure 2) was selected as the best approach to meet the study’s requirements.

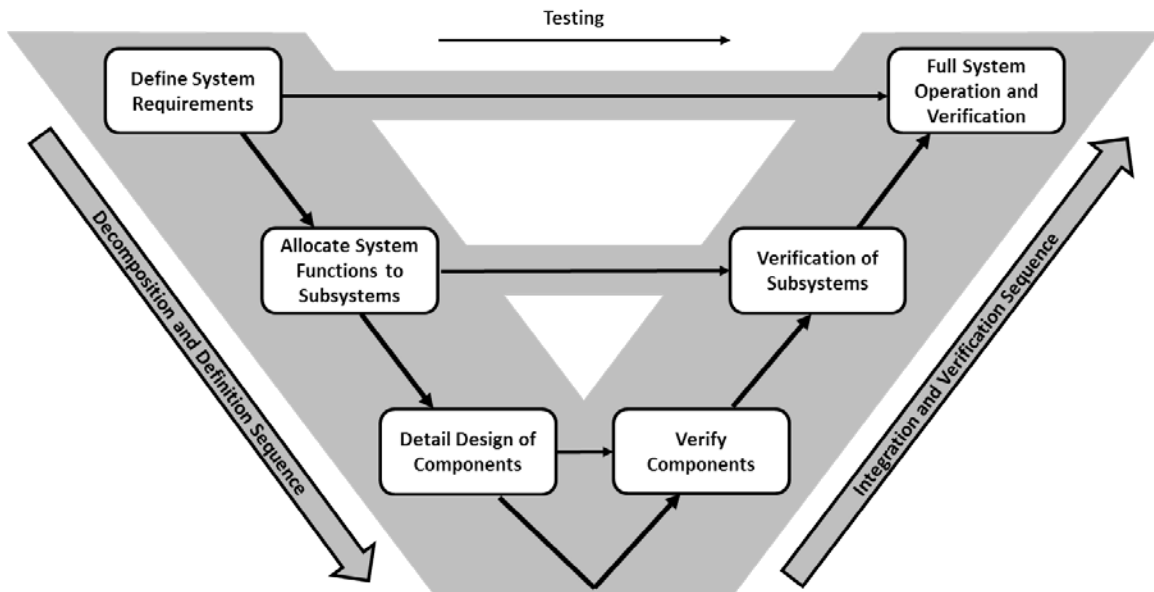


Figure 2. Classic “Vee.” Source: Blanchard and Fabrycky (2011).

However, in order to comprehensively model neutralization scenarios of interest, the classic “Vee” needed to be tailored to allow parallel system definition efforts as shown in Figure 3. Early research involving MCM stakeholders, subject matter experts

(SMEs), and prior similar capstone efforts, led the team to decide that a three-pronged, simultaneous, system definition effort was best to meet the need to quickly build a flexible mine neutralization model and simulation. Sourcing for input for each of the three high-level requirement domains is discussed in detail in Chapter II, “Definition of High Level System Requirements.” Each high level requirement of the ultimate simulation system was allocated to one of three groups within the project team. One group focused on researching and defining the environmental and minefield (threat) composition. Simultaneously, a second group focused on defining the various platforms and mine neutralization systems performances. As the research on environmental and neutralizer approaches matured, a third group was able to model scenarios that would be built into the simulation. Definition of the environment, sub-systems, and scenarios was an iterative process that was conducted through weekly team and advisor meetings. This report is organized per the tailored “Vee” Model presented in Figure 3. Chapter II develops the High Level System Requirements and Defines the System Environment, Chapters III - VI present the detailed requirements synthesis, Chapter VII presents the modeling architecture, Chapter VIII presents simulation analysis, and Chapter IX presents conclusions and recommendations.

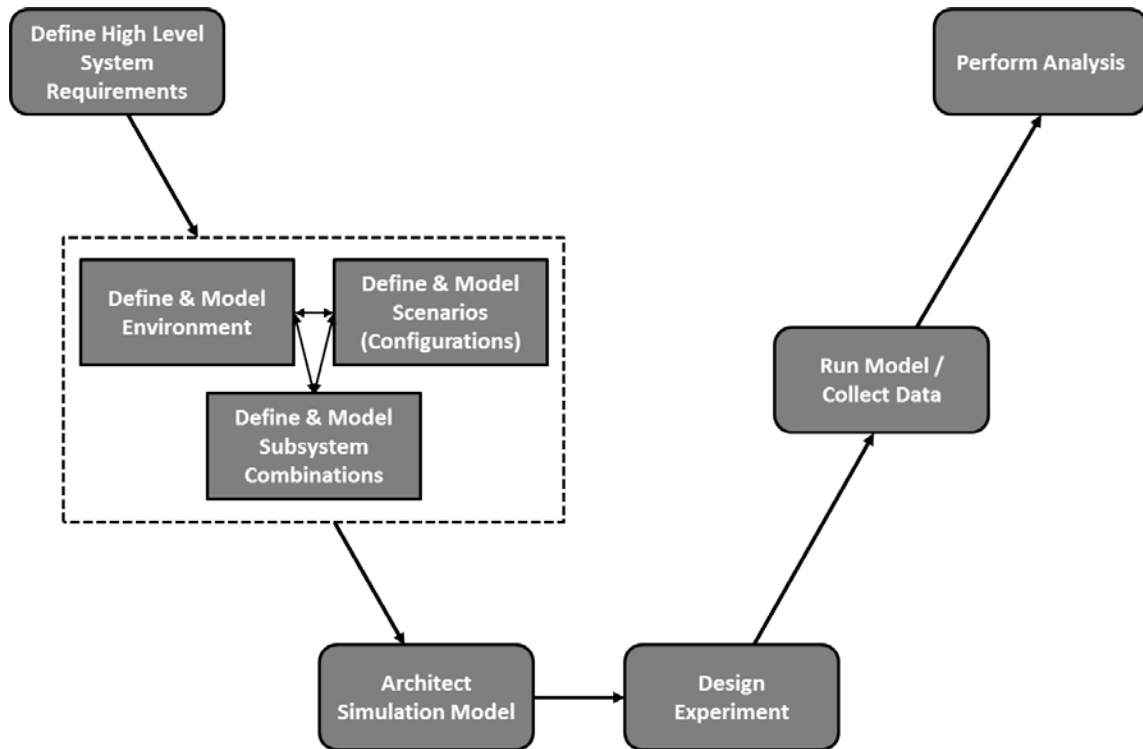


Figure 3. Tailored Systems Engineering Process

## E. RESEARCH QUESTIONS

The purpose of this study was to focus on the localization, identification, and neutralization (L-I-N) segment of the mine neutralization continuum for current platform/system configurations, and also for proposed combinations, under a range of field configuration and environmental conditions to investigate the following study questions:

What configurations, using current neutralization systems and platforms, are most effective (fastest) in clearing a minefield?

What configurations, using current and / or proposed neutralization systems and platforms, are most effective (fastest) in clearing a minefield?

What individual platform or neutralization system performance parameters (i.e., range, speed, probability of kill) have the greatest impact on the efficacy of current or proposed operational scenarios?

## **II. TAILORED SYSTEMS ENGINEERING (SE) APPROACH**

### **A. DEVELOPMENT OF THE TAILORED SE APPROACH**

This chapter covers the development of the study's tailored SE approach which involves three distinct domains: high-level definition of the operational physical environment (including the threat distribution), high-level examination of the MNS delivery platform and specific MNS relevant performance characteristics, and the operational scenario definition. The specific study domains detailed in following chapters are fully traced to the high level requirements discussed here.

### **B. ENVIRONMENTAL AND MINE FIELD DEFINITION**

Subject Matter Expert input early during the development of the tailored SE approach (RADM ret. Richard Williams, personal comm.) stressed the importance of investigating neutralizer efficacy that would build upon the work of previous MIW detection and clearance studies done at NPS. Consistent with these previous capstones (Cohort 311-132M in 2014 and Cohort 311-132O in 2015), the mission space for this component of the overall simulation is defined as a blue water grid of dimension 10 x 10 nautical miles (nm) and up to 800 feet in depth indicative of an open water, sea line of communication (SLOC). This space was randomly populated with a combination of three mine types: bottom mines (proud), bottom mines (buried), and moored volume mines that are typically effective in this region (U.S. Navy Expeditionary Warfare Directorate 2009 and CAPT Scott Burleson, personal comm.). These mine types are discussed in detail in Chapter III. Initially, the target types, numbers, and locations (x, y, and z coordinates) were set randomly by the Environment Python File (EPF) (see the appendix), but the values for these field attributes were determined during by the EPF through a time-step adjustment during the simulation runs taking into account the effect of field environmental characteristics (i.e., current direction, current speed).

There are numerous environmental and field variables that were considered as input variables into the EPF for use in determining target locations, or to be simply passed through for use by the full system simulation. These were drawn not only from

those considered in prior studies but also from literature searches of environmental conditions that may have impact on the neutralizer component of this study. Environmental conditions that were considered as simulation inputs included (Council 2001):

- depth
- bottom type and composition
- current
- sea state
- water clarity
- water temperature
- wind speed and direction
- air temperature

Since environmental factors can significantly affect the performance of the MNS platforms, systems, and true target locations they were randomly defined (within realistic possible ranges) for each field simulation definition. Details regarding the full list of environmental factors with ranges as well as the methods used to vary the values for each run can be found in Chapter III and Chapter VII of this capstone report.

### **C. PLATFORM AND MINE NEUTRALIZATION SYSTEM PERFORMANCE**

As discussed in Chapter I, and illustrated in Figure 4, the overall mission of finding and neutralizing mines is comprised of five distinct, serial tasks: detection, classification, localization, identification, and neutralization:

Sonars are the primary means to detect and classify mine-like contacts. Identifying each contact as a mine or a “NOMBO” (Non-Mine/Mine-Like Bottom Object) can also be carried out by EOD divers and the Navy’s marine mammal systems, video cameras on mine neutralization vehicles, and laser systems. In this regard, advanced sonars on unmanned underwater vehicles offer good promise to enhance mine-hunting capabilities.

A contact that is classified as mine-like must be identified as a mine or NOMBO and, if a mine, rendered safe before the Navy mine countermeasures commander, or the Coast Guard in a domestic mine crisis, can declare a route or area cleared. (As the Lead Federal Agency for maritime homeland security, the Coast Guard's Captains of the Port are the only officials who can close and open U.S. ports in response to an emergency.) Depending on the accuracy of the location of the contact, the characteristics of the bottom (e.g., smooth or rough), sediment type, amount of clutter, and the depth of the water, among other factors, the process of reacquisition and identification of each mine-like contact can take several hours. EOD divers, marine mammals, and mine-neutralization systems are the Navy's primary means for neutralizing sea mines and underwater IEDs" (U.S. Navy Expeditionary Warfare Directorate 2009).

The study focus of the effort is to identify and analyze the delivery platform and MNS performance factors that impact neutralization efficacy in the localization, identification, and neutralization (L-I-N) portion of the continuum. Therefore, for the purposes of this analysis, it is assumed that the minefield has been searched (detection) and targets of interest have been identified (classification).

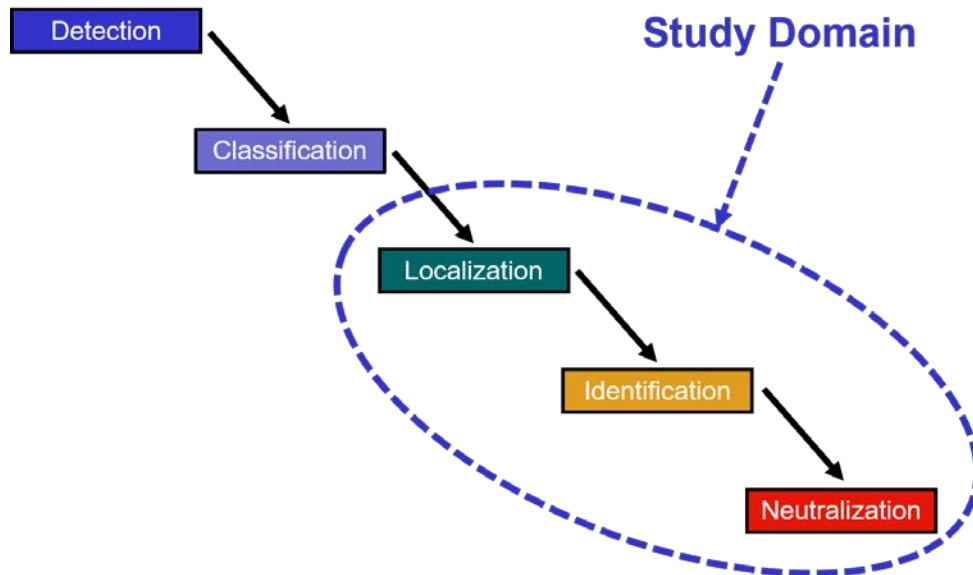


Figure 4. The Neutralization Continuum

An example of a representative L-I-N segment scenario is illustrated in Figure 5. In this example of the Archer Fish MNS, target locations have already been defined and the MNS is being deployed from the MH-60S hovering over the minefield. In this configuration the MH-60S is operating from a LCS staged on the edge of the field.

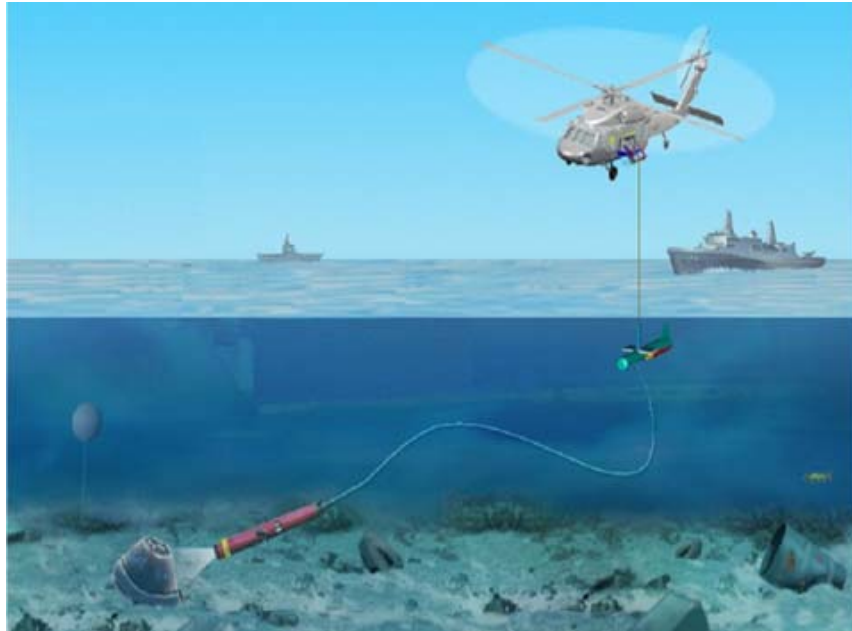


Figure 5. Archerfish MNS Mission. Source: Hibbert (2006)

For each of three platforms (MCM-1, MH-60S, and MH-53E) ranges for relevant performance parameters were determined. The relevant performance parameters considered included those factors that could impact the ability of the platform to deliver and operate the MNS on station during the L-I-N portion of the neutralization continuum such as:

- Speed and range of the platform to move from outside the minefield to and between targets is required.
- Weapon load of the platform before replenishment of the MNS is required from outside of the minefield.
- Reset time of the MNS packages when replenishment is required.

Specific performance values used during simulation runs were set to discrete values that were uniformly distributed across the performance ranges for each parameter.



This was to allow for an individual factor sensitivity assessment on overall minefield clearance performance. Additionally, each discrete performance factor was further adjusted for each scenario simulation run to account for the effect of environmental factors as derived from the EPF.

In a similar fashion, and also derived from discussions with MNS stakeholders (CAPT Scott Burleson, personal comm.), for each of the four mine neutralization platforms (SLQ-48, SLQ-60, AN/AQS-235, and Barracuda), ranges for relevant performance parameters were determined. Relevant performance parameters considered included:

Target Depth – The target max depth includes the low, med and high value ranges of the maximum depth that the system can safely accomplish. This value effects the time it takes for the MNS to travel and reacquire the targets of interest.

Launch range from base – This is the range from the staging platform outside of the minefield that the MNS delivery platform can be deployed. This is usually based on range of helicopter.

Range (from launch) – This is the range of the MNS from the delivery platform.

Detect Range - This is the range in which the MNS can accurately detect a mine.

Probability of Misidentification – This is the detection accuracy.

Speed – The is the speed in which the MNS can maneuver.

Endurance – This is the operating time before the system must be recharged.

Probability of Malfunction – This is the operational availability of the MNS.

Deployment Time – This is the time it takes to deploy the MNS from the delivery platform.

Specific performance values used during scenario simulation runs were set to discrete values that were uniformly distributed across the performance ranges for each parameter and adjusted to reflect the environmental conditions regulated time-step wise from the EPF. Details regarding these ranges and discrete value determinations can be found in Chapter IV and V of this capstone report.

#### **D. MINE NEUTRALIZATION SCENARIO DEFINITION**

In discussions with SMEs, it was determined that there was interest in simulating neutralizer efficacy in a minefield where priority was given to clearance of a center lane (i.e., “Q” route) during the clearance operation (CAPT Scott Burleson, personal comm.). This differed from the prior clearance and detection studies where a uniform “Mowing the Lawn” approach was taken. For this study where only the location, identification, neutralization (L-I-N) portion of the mine neutralization continuum was considered, the target locations were predetermined making a more directed operation possible. Each current or proposed mine neutralization search pattern configuration considered was varied in its number and composition of platforms and MNS employed. Each run consisted of one or more surface platforms, one or more air platforms, and multiple underwater neutralization components. For example, with a scenario consisting of a single deployment of the SLQ-48 Mine Neutralizing System, a single platform (MCM-1) and a single MNS (SLQ-48) was built into the scenario simulation model or for an air mission simulation of the AN/AQS-235 Airborne Mine Neutralization System, a single air platform (MH-60S), and a single MNS with multi-shot capability. For each scenario modeled, key performance parameters for the platforms and MNSs were set to a limited number of uniformly distributed values with a specific performance range (i.e., highest value, median value, and lowest value for speed). All combinations of these discrete performance values were built into separate routines yielding multiple variants for each simulated scenario (configuration). Details regarding the configuration and variant compositions can be found in Chapter VI and VII of this capstone report.

### **III. ENVIRONMENTAL AND MINE FIELD CHARACTERISTICS**

#### **A. OVERVIEW**

This overview of Chapter III provides an insight into the environmental and mine field characteristics of this MIW effort. This effort utilized several environmental and mine field characteristic variables that were determined using real world values. These variables were updated and modified to account for variations based upon different regions. This section also presents several variables that may be of interest to other studies that were beyond the scope of this analysis.

#### **B. SCOPE**

The scope of this effort is defined by the variables that were taken into account when the program was developed. There are both environmental and minefield variables that are required to be taken into account. There are also variables that were not taken into account as they would either have little to no impact on the results or they were not feasible to calculate. Those variables are discussed as limitations of scope.

#### **C. LIMITATIONS OF SCOPE**

There were some limitations of the scope of this effort that will need to be identified. These limitations include field variables that may not impact the results of this study but must be identified for consideration by potential follow on efforts. The first limitation was the water salinity. With the exception of the Dead Sea, all other areas with known hostile mines have water salinity that is virtually the same. It was determined that even though the salinity of the water will affect the depth of some mines, the salinity variations of known hostile waters was negligible and could be ignored for this effort. The next limitation was that of marine life. There are circumstances where active marine life in the area could impact the current effort, it was determined that the research required to identify all types of marine life in the area and their ability to interfere in this effort was too costly and time consuming and would not provide usable values or information. Therefore, all marine life impacts were negated from this effort. The last

limitation that was identified was other vessel traffic. There are going to be occasions where there may be other vessels in the area during this effort, however it was determined that if this was in fact an active mine field, then most vessel traffic would avoid the area and would maintain at least a 15nm closest point of approach (CPA) which would be outside the 10nm dimension of the blue water box.

#### **D. MINE TYPES**

The three types of mines utilized for this effort include: Bottom Mine (Proud), Bottom Mine (Buried), and Moored Volume Mine. The characteristics of each are identified as follows:

(1) Bottom Mine (Proud)

The Bottom Mine (Proud) is a mine that sits on the bottom of a sound or channel. This mine carries more explosives than that of a moored mine. The Proud designation of this mine means that it sits on the ocean floor and is not buried. These mines are most notably utilized in water depths of less than 660 feet.

(2) Bottom Mine (Buried)

The Bottom Mine (Buried) has the same characteristics as the Bottom Mine (Proud) with the exception that it is more difficult to detect. These mines remain buried until a submarine comes close enough for detonation of the mine.

(3) Moored Volume Mine

The Moored Mine is a mine that is tethered to the bottom by an anchor. The depth of these mines can be varied but usually will not be deeper than 40 feet for surface ship attack. There are Moored mines in deeper water that are in place for submarine attack.

#### **E. ENVIRONMENTAL CHARACTERISTICS**

The mission space for this effort is a blue water grid with the overall dimensions of 10 nm X 10 nm with a depth range of 0–800 feet. This defined space was identified in order to accommodate the minimum and maximum depths of both the bottom and

moored mines. The space is randomly populated with a combination of three different types of mines. The mine types includes Bottom Mine (Proud), Bottom Mine (Buried), and Moored Volume Mine. A depiction of the environment is shown in Figure 6.

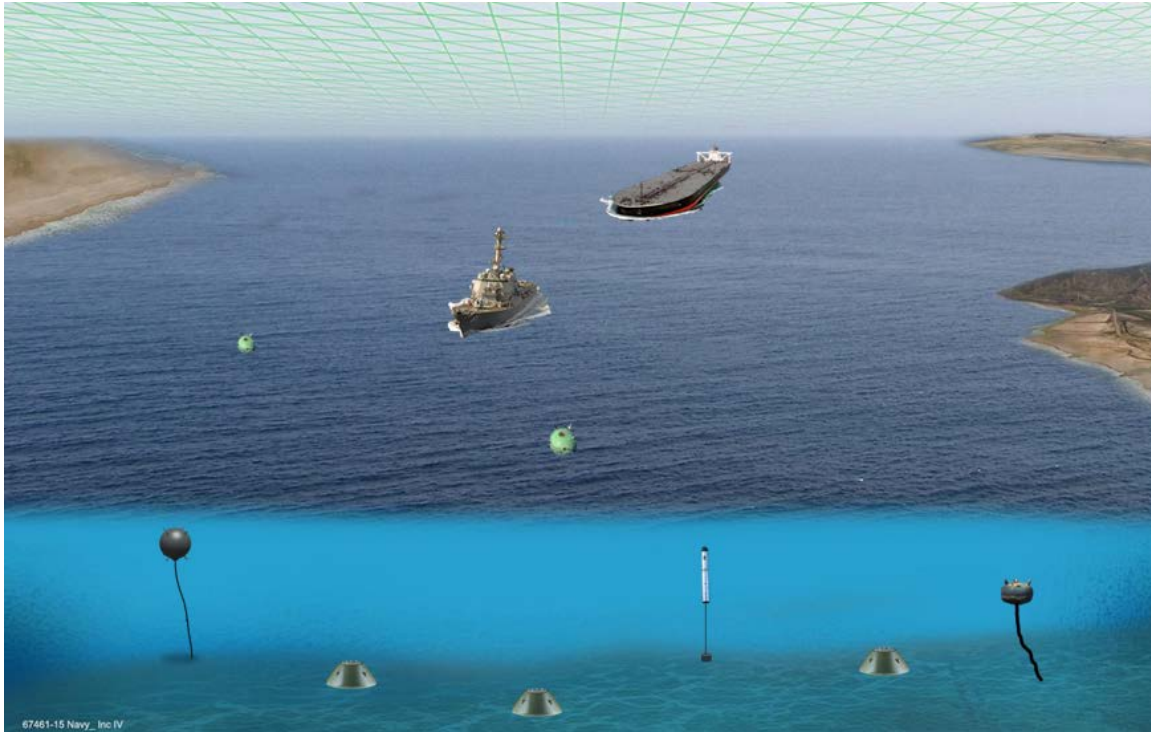


Figure 6. Underwater Minefield Environment.

The minefield variables utilized for this effort include the mine types, distribution numbers and mine locations (x, y, and z coordinate). These values were initially randomly set by the Environment Definition Program (EDP) in the EPF, but the final values for the field attributes were determined by the EDP taking into account the effect of field environmental characteristics (i.e., current direction, current speed). The environmental field variables that were utilized by the EDP included the following:

Depth – The depth variable value varied from 0–800 feet and was determined based on the type of mine.

Bottom Type and Composition – This field variables identifies the type of mine (Bottom Mine (Proud), Bottom Mine (Buried), or Moored Volume Mine) as well as the composition of the floor (sand, mix of rock, or sand and rock).

Current – The sea current for this effort was limited by recorded values in regions with similar dimensions. The current values range from no current to four knots of current. Current of greater than four knots is rarely seen in most hostile waters.

Sea State – The sea state for this effort utilized a range of values from regions with known hostile mine activity. The sea state will range from flat seas to sixfeet at eight seconds (6 ft. @ 8 sec.). MCM efforts are not advised in more extreme sea states.

Water Clarity – The water clarity for this effort included the full range of values from known hostile waters. The water clarity will range from zero visibility to 20 feet of visibility.

Water Temperature – The water temperature range of values was identified to cover all known hostile mine fields. The water temperatures range from 65 degrees to 85 degrees.

Wind Speed and Direction – The wind speed and direction range of values for this model varied was based on normal conditions. High storm conditions were not tested in this effort.

Air Temperature – The air temperature ranges were based on actual ranges from territories with known hostile mine activity. The air temperature variables range from 60 to 100 degrees.

**F. ENVIRONMENTAL VARIABLES**

Table 1 identifies the environmental variables that were utilized during the testing phase of this effort. The table includes the low, medium and high values.

Table 1. Environmental Variables Used for Testing

Environmental Variables	Low	Med	High
Depth	0	400	800
Bottom Type and Composition	Sandy	Mix Sand and Rock	Rock
Current	0kts	2kts	4kts
Sea State	Flat	3ft @ 10 sec	6ft @ 8 sec
Water Clarity	1ft	10ft	20ft
Water Temperature	65	75	85
Wind Direction and Speed	10kts	15kts	20kts
Air Temperature	60	80	100

## **IV. PLATFORM PERFORMANCE CHARACTERISTICS**

### **A. OVERVIEW**

Chapter IV contains general descriptions of the platforms that are currently in use within the MIW Triad. In this context, a “platform” is defined as a system that is required by the MIW subcomponents in order to transport, power, control, or otherwise employ sensors or weapons in order to affect mine hunting or mine sweeping missions. Specifically, this chapter will provide contextual history for the MCM-1 Avenger Class MCM ship, MH-53E “Sea Dragon” Helicopter, LCS, MH-60S “Knight Hawk” helicopter, MQ-8B “Fire Scout” unmanned aerial vehicle (UAV), and a brief overview for the U.S. Navy’s EOD divers and Navy Marine Mammal Program (NMMP). While not all of these platforms directly perform the mine neutralization functionality, it is essential to view all of these platforms and their subsystems as a wider family of systems that perform the MIW mission.

### **B. MCM-1 AVENGER CLASS MINE COUNTERMEASURES (MCM) SHIP**

The MCM-1 Avenger Class ship was produced by Peterson Shipbuilders and Marinette Marine for use by the U.S. Navy and is currently used to execute the missions of mine hunting and (if necessary) mine clearance and neutralization (Pike 1999). A profile view illustration of the ship is presented in Figure 7. MCM ships began production in the early 1980s and have been in operation since early 1987. As of the date of this study, there are 10 remaining Avenger-class vessels in operation and an additional four in the inactive reserve fleet. These ships and their overarching squadron command structure are currently slated for sundown and disestablishment within the next decade.

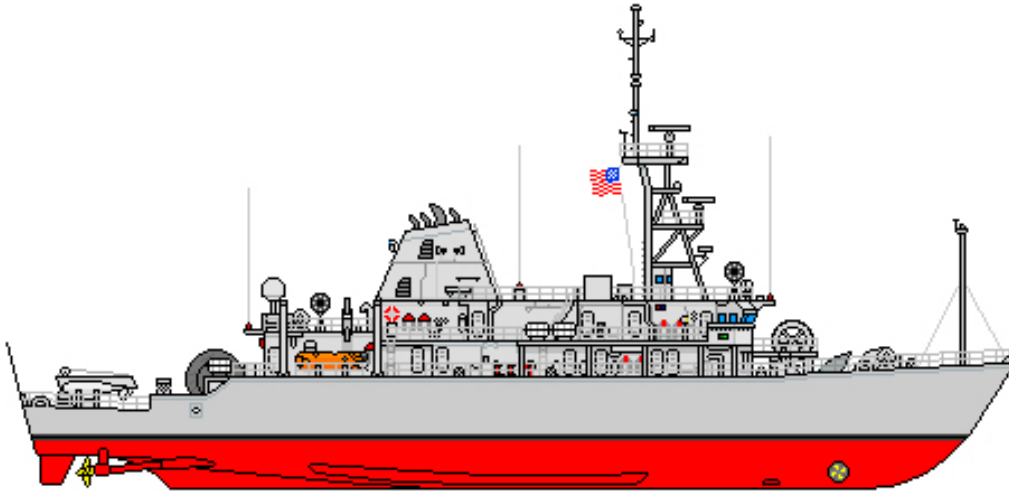


Figure 7. Profile View of an MCM-1 Avenger Class Ship. Source: “MCM Ships Avenger Class” n.d.)

The ship is approximately 224 feet long, 39 feet across at the beam, displaces 1312 tons (at maximum load), has a draft of 13 feet, and can traverse at approximately 14 knots. The vessel consists of a hull made from wood and fiberglass with a shallow draft to reduce any magnetic signature that may trigger a mine. This makes the ships ideally suited to transit in areas of possible mining activity without accidentally causing detonation. These vessels are crewed by a relatively small number of personnel consisting of eight officers and 76 enlisted personnel.

They are equipped with two remotely operated underwater search and neutralization vehicles (designated the AN/SLQ-48 Mine Neutralization System and AN/SLQ-60 SeaFox) that are both being considered in this study. In addition, the Avenger-class ships are equipped with the following systems: the AN/SLQ-47 magnetic and acoustic minesweeping system, the AN/SQQ-32 and AN/SQQ-30 MIW sonar systems, the AN/SSN-2 command and control system, and two 50-caliber machine gun crew-served weapon (CSW) systems utilized for self-defense. These other systems are either primarily utilized towards the mine localization mission or are utilized in a supporting role to the mine neutralization mission and therefore were not included as part of the



modeling and simulation analysis in this report (Commander Naval Surface Forces, U.S. Pacific Fleet 2016).

### **C. MH-53E “SEA DRAGON” HELICOPTER**

The MH-53E “Sea Dragon” is a heavy-lift helicopter produced by Sikorsky (as a subsidiary of the United Technologies Corporation which has recently been acquired by Lockheed Martin) (Lockheed Martin Corporation 2015). It first flew in December 1981 and entered operational use in June 1986. This aircraft performs two primary missions for the U.S. Navy: airborne mine countermeasures (AMCM) and vertical onboard delivery (VOD). An MH-53 is pictured alongside an MCM ship in Figure 8.



Figure 8. MH-53E Helicopter Pictured with an MCM Ship. Source: United States Navy (2007).

At the time of publication, one of the co-authors for this study is employed on a staff that assists in managing the future for this aircraft program. There are several issues with this aircraft’s future that are expounded here based on personal observations. Approximately 28 aircraft remain in the U.S. Navy inventory as of the date of this report

and no more aircraft are in production; however, there is currently no agreed upon sundown date for the aging platform, and it is suffering from a relative lack of funding, high cost and low availability of replacement parts and other generic safety concerns stemming from recent mishaps that have cost the lives of aircrew. An estimated target date for disestablishment is approximated to be fiscal year 2025, though there are differing opinions that intend to tie the sundown of the aircraft to the eventual approval and certification of final operational capability (FOC) for the LCS MCMMP in order to prevent a gap in operational capabilities.

The aircraft is crewed by two pilots and anywhere from one to six enlisted air crewmen depending upon the mission being executed. It normally can achieve a speed of up to 150 knots with a range of up to 770 nautical miles. This aircraft is capable of mid-air refueling as means of extending its range (which is a unique capability when compared to other U.S. Navy helicopters). The Sea Dragon is the only U.S. aircraft that is currently capable of towing MIW systems through the water due to the high airframe stresses that occur and the power required to accomplish that mission. As an illustration of this capability, the aircraft is capable of carrying up to 32,000 pounds of cargo (as compared to the MH-60S that can carry approximately 5000 pounds internally) and can tow 25,000 pounds laterally through the water (Monster Worldwide 2010). Some AMCM sub-systems have been in use for decades; some that remain in use today date back to 1967 or earlier (Tempest 2008). Those currently being utilized on the Sea Dragon include: the Mk-103 mechanical cutter array, the Mk-104 acoustic mine sweeping system, the AN/SPU-1W magnetic mine sweeping system, Mk-105 magnetic mine sweeping towed sled, and the AN/AQS-24 side-scan sonar. Of particular interest to this study is the Mk-105 (first introduced circa 1972), which is a mine clearance system that is towed behind the helicopter and trails from the sled two magnetic “tails” that are utilized to detonate influence mines (Panama City Living 2014). There have been several iterative improvements to the system over the years to increase its capabilities, but these efforts have been stymied by the uncertain future of the Sea Dragon. Finally, the Sea Dragon is also capable of launching the AN/ASQ-232 SeaFox, which is an airborne variant of the AN/SLQ-60 which will be discussed in detail later. The Sea Dragon can be

armed with a GAU-21 50-caliber machine gun and M-240 7.62-caliber machine guns along with standard aerial countermeasures (chaff and flare) for self-defense, but it cannot necessarily carry these systems while performing the AMCM mission due to its mounting locations on the aircraft.

The Sea Dragon is capable of operating from sea or shore. At sea, the large size of the aircraft makes it ideal to park it aboard the larger Naval vessels such as aircraft carriers (CVNs), amphibious assault ships (LHDs), or amphibious transport dock ships (LPDs). While they are capable of landing on smaller Navy ships (destroyers (DDGs) and cruisers (CGs) for transient operations (such as cargo transport and refueling), those ships are not capable of housing them for permanent deployment. Furthermore, the weight-bearing characteristics of the new LCSs do not allow the Sea Dragon to land on them for even transient evolutions (such as refueling or rearming). This means that in the overarching MIW concept of operations (CONOPs), it is likely that the MH-53E will be confined to being shore-based for the purposes of executing the mission or will be forced to be deployed aboard one of the larger vessels. However, those larger vessels previously mentioned are at high risk when placed in a minefield. Given the likelihood of standoff requirement for these ships, it can be assumed that the Sea Dragon will have a decreased operating range due to increased transit time to and from the operating area (“The Future of Airborne Mine Countermeasures” 2015).

#### **D. LITTORAL COMBAT SHIP (LCS)**

The LCS is a vessel that is in the process of being manufactured and delivered to the U.S. Navy in the form of two variants (INDEPENDENCE and FREEDOM). The intent is to create a ship that is smaller than the legacy, retired Frigate (FFG) class but larger and more capable than MCM or Patrol Craft (PC) vessels. The operational concept is to deploy these ships independently and utilize interchangeable “mission modules” (also termed “mission packages”) that allow for specialized capabilities that can be swapped either as part of a rotational schedule or as part of a quick reaction to an operational necessity in theater. It is built to be small, fast, maneuverable, and capable of performing three primary missions: anti-surface warfare (ASuW), MIW, and

antisubmarine warfare (ASW) missions. It will also be capable of performing freedom of navigation assurance operations, theater security, maritime law enforcement, counter-piracy, disaster relief, search and rescue, and other missions as required. The USS Independence (LCS-2) is pictured in Figure 9.



Figure 9. USS Independence (LCS-2) Operating with an MH-60S during RIMPAC Exercise in 2014. Source: Eckstein (2016).

Littoral combat ship crews will perform these missions with the assistance of embarked helicopter detachments that will employ the MH-60S “Knight Hawk,” the MH-60R “Sea Hawk,” or the MQ-8B “Fire Scout” UAV. The MH-60R is currently planned to be employed strictly in the ASW mission and will not deploy with a Fire Scout embarked and is therefore not discussed further in this study with regards to MIW.

The ships are armed with a 57-mm. gun, RAM or SeaRAM surface-to-surface missiles (depending on variant), .50-caliber machine guns, and decoys. There are different systems that are installed depending on which mission module variant is installed; discussed here are the pertinent systems for the MCMMP. These systems include: the MH-60S “Knight Hawk” helicopter, equipped with the Airborne Laser Mine Detection System (ALMDS) and Airborne Mine Neutralization System (AMNS), the MQ-8B “Fire Scout” UAV, equipped with the Coastal Battlefield Reconnaissance and Analysis (COBRA) system, the Remote Mine Hunting System (RMS), the Unmanned

Influence Sweep System (UISS), and the Knifefish Unmanned Underwater Vehicle (UUV). One of the primary goals of the MCMMP is to “remove the man from the minefield” as much as possible to improve safety and survivability by better utilizing technological solutions, automation, and remote controlled vehicles in their place.

The FREEDOM variant is being built by Lockheed Martin and is approximately 388 feet long, 58 feet across at the beam, displaces 3450 metric tons at full load with a 14.1-foot draft. The publically advertised speed of the vessel is in excess of 40 knots, but is much lower for sustained operations due to fuel efficiency. The INDEPENDENCE variant is built by General Dynamics and is slightly longer at 422 feet, wider at 104 feet, displaces slightly less at 3200 metric tons with a slightly deeper 15.1-foot draft.

This section describes the subsystems for LCS that is currently in production for inclusion in the MCMMP; this is illustrated in Figure 10. The subsystems installed on the MH-60S and the MQ-8B are addressed in their respective sections below. As of today, the Remote Multi-Mission Vehicle (RMMV), which is equipped with AN/AQS-20 sonar) is not achieving intended reliability and operational availability performance parameters. Significant programmatic changes are taking place to ensure that those discrepancies are addressed prior to fielding the subsystems in theater. While this affects the ability of LCS to perform the mine-hunting mission (detecting, classifying, and identifying mines), it does not negatively affect mine neutralization. The UISS is scheduled for delivery in fiscal year 2018 and will add the capability for sustained influence sweeping, which attempts to trigger magnetic or acoustic mines at a safe distance from the parent vessels by using decoy transmitters. The Knifefish UUV is scheduled for delivery in fiscal year 2019 and will include increased capabilities for buried and bottom mine hunting. It should be noted that the original plan for the AN/AQS-20 was to employ it as a subsystem to be towed behind the Knight Hawk helicopter but due to engineering reasons that will be discussed later, it was reengineered to allow it to be towed by the LCS or (potentially) by a future remotely operated surface vehicle. In summary, the LCS is a complicated vessel that will act as a hub for both current and future families of systems that will perform the full MIW mission while leveraging rotating crews to maintain a

perpetually forward-deployed presence in theater to the maximum extent possible (Defense Media Activity 2014).

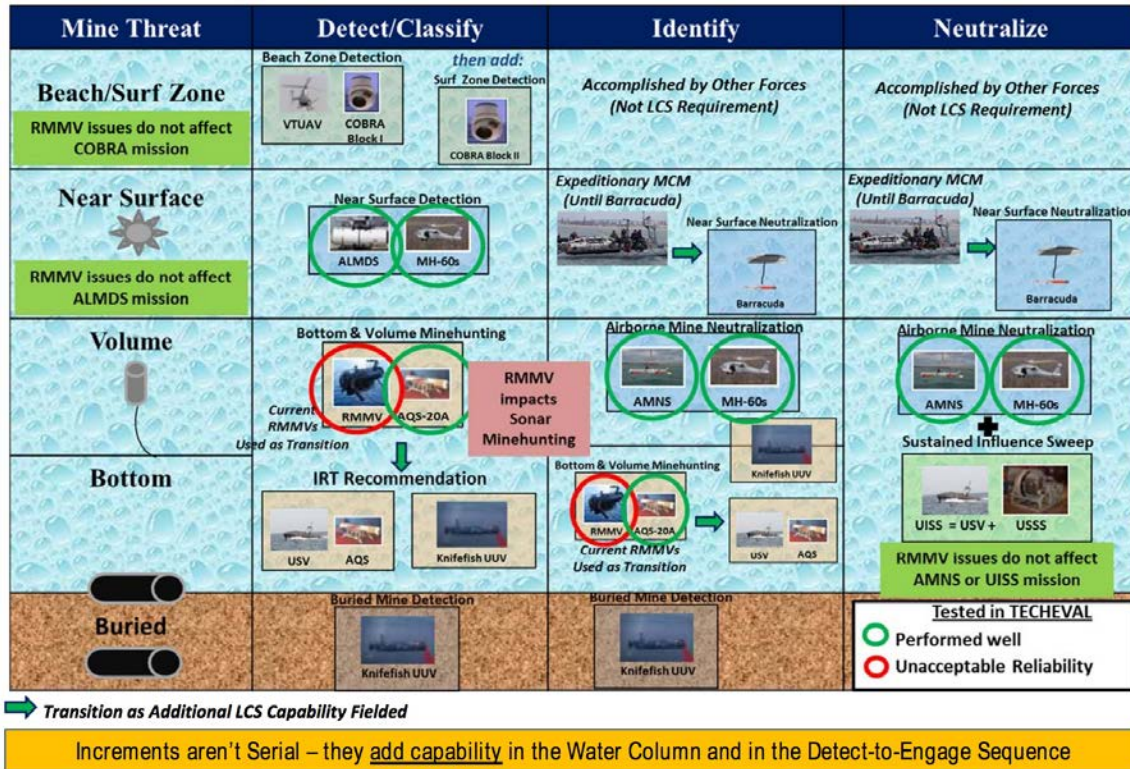


Figure 10. Summary of Current and Future LCS MIW Mission Module Subsystems. Source: Moton (2016).

**E. MH-60S “KNIGHT HAWK” HELICOPTER**

Sikorsky produced the MH-60S “Knight Hawk” as a multi-mission helicopter that is operated by the U.S. Navy and several other allied countries. The MH-60S is capable of a variety of missions to include: Search and Rescue (SAR), logistics, ASuW, special operations forces (SOF) support, combat air support (CAS), personnel recovery/combat search and rescue (PR/CSAR), humanitarian aid and disaster relief (HA/DR), and is beginning to transition to employing subsystems for MIW. An MH-60S with the AN/AQS-235 AMNS installed is presented above in Figure 11. The Knight Hawk entered service in February 2002 with over 237 aircraft having been acquired for use by the Fleet

and was designed based on proven design concepts from the U.S. Army's UH-60L Black Hawk combined with the Navy's legacy SH-60B Sea Hawk.



Figure 11. MH-60S Helicopter Equipped with AN/AQS-235 AMNS. Source: Mine Warfare Assn. (2013)

Current deployment platforms for the Knight Hawk include CVN ships, LHD ships, civilian-run Military Sealift Command (MSC) logistics ships, aboard hospital ships (USS Mercy and USS Comfort), and several shore-based operations. Furthermore, during fiscal year 2016 the community began deploying aboard the newly introduced LCS, albeit currently using the (tested and proven) ASuW configuration without any MIW capabilities. The aircraft is crewed by two pilots and between one and three enlisted air crewmen, most of which are also trained to operate as a SAR swimmer. The aircraft is capable of being armed with standard self-defense countermeasures (chaff and flares) and crew-served weaponry (including up to two M-240 7.62-mm. and two GAU-21 50-caliber machine guns). It has two external weapons pylons that are capable of mounting any of the following subsystems and are employed by the pilots: up to eight AGM-114 HELLFIRE missiles (four per pylon), up to 38 guided or unguided rockets, or a single 20-mm. machine gun (mountable to one side of the aircraft only). Of particular note is that none of these systems are (as of yet) approved for use while executing the MIW mission, especially since the external weapons pylons must be removed to accommodate mounting MIW equipment. The console utilized by the air crewmen to run the MIW systems replaces cabin space where the crew-served weapons could otherwise be mounted. The MH-60S can fly at a maximum speed of 180 knots (with a normal cruise

speed of about 130 knots) and has an operational range between approximately 250 and 520 nautical miles (depending on whether part of the cabin space is sacrificed to install either one or two removable extended range fuel tanks) (Naval Air Systems Command, 2014).

The first flight by Sikorsky of potential MIW equipment aboard the Knight Hawk was accomplished in 2003. Originally, five subsystems were being developed for the MH-60S (with Lockheed Martin contracted as the overall systems integrator): the AN/AES-1 ALMDS (produced by Northrop Grumman), the AN/AQS-235 AMNS (produced by Raytheon) equipped with four Archerfish mine neutralizers (produced by BAE Systems), the Rapid Airborne Mine Clearance Systems (RAMICS) employing a 30-mm gun (produced by Northrop Grumman), and the AN/AQS-20A towed sonar array (produced by Raytheon), and the organic airborne surface influence sweep (OASIS) system (produced by EDO Corporation). It should be noted that since contracting and development of these systems began, only two remain as active programs of record due to several reasons. The most significant reason for program cancellations is the fact that the MH-60S aircraft was experiencing structural cracks in fuselage components during towing evolutions. Furthermore, the engines and transmission are severely underpowered for towing through the water without incurring significant risk of complete loss of aircraft and crew in the event of any engine failure. Compound this with the questionable performance of RAMICS, and the Knight Hawk is left with only ALMDS for mine search and localization and AMNS for mine neutralization. These remaining systems are currently in the Fleet introduction phase with one fleet replacement squadron (FRS) having recently completed training (in late fiscal year 2016) of a small cadre of instructors who will begin to produce operators to the Fleet in the coming years. It should be noted that as of today, MIW is a skill set that has barely begun its incorporation into this helicopter community; there will be a steep learning curve as the LCS program progresses into full Fleet integration (Kable Intelligence Limited 2012).



**F. MQ-8B “FIRE SCOUT” UNMANNED AERIAL VEHICLE (UAV) HELICOPTER**

The MQ-8B “Fire Scout” UAV is shown above in Figure 3 and is currently operated by the U.S. Navy to accomplish a range of missions to include: reconnaissance, battle space situational awareness, and precision remote targeting for weapons launched by other platforms. As of today, the sole method of employing an MQ-8B outside of testing is by embarking an aircraft and detachment of personnel aboard a LCS where the command and control consoles are located. This logistical difficulty to execute training has caused options to be researched towards developing a mobile mission control system in order to gain operational flexibility and greater system availability for training or contingency operations. The MQ-8B is capable of up to eight hours of flight at a range of up to 110 nautical miles from the launch site while attaining a speed of approximately eighty knots. The Fire Scout is slated for inclusion in the LCS MCMMP by use of a subsystem called the AN/DVS-1 COBRA that builds upon the already-installed Multispectral Targeting System (MTS) and adds the capability to conduct reconnaissance in the littoral areas in order to detect minefields and other obstacles along shore that may impact amphibious assaults (United States Navy 2010). The MQ-8B was not modeled in this analysis due to the fact that it is not currently planned to have any mine neutralization capabilities. However, it is described here since it will be essential in the future MIW CONOPS aboard LCS. Planned delivery of COBRA to be installed on the Fire Scout is currently planned to begin in fiscal year 2017 (Moton 2016).



Figure 12. MQ-8B “Fire Scout” Unmanned Helicopter. Source: Stephens (2012)

### **G. EXPLOSIVE ORDNANCE DISPOSAL (EOD) DIVER PROGRAM**

EOD-trained sailors are considered a part of U.S. Navy SOF. They function both on land and at sea to dispose of potential threats and help maintain theater security among other missions. EOD technicians function in the MIW realm to provide final classification and identification of mine-like contacts and, if necessary, are capable of mine neutralization by attaching some form of explosive and remote detonator in order to dispose of the threat (as shown in Figure 13). They can be transported for maritime missions by either small boats [such as rigid hull inflatable boats (RHIBs)] or by deploying from helicopters. EOD divers may operate unassisted in the case of near surface or bottom mines or they may operate in conjunction with a UUV or Marine Mammals that have the capability to unmoor a mine to allow the divers access.



Figure 13. Navy EOD Divers Placing Charges to Detonate a Moored Mine. Source: Wikipedia Contributors (2016)

The majority of techniques, tactics, and procedures for executing this mission are generally classified, but significant risk exists to the diver when performing this mission due to the unpredictability of mine trigger mechanisms and the requirement to operate with explosives while afloat at sea. Though this has been a reliable method of mine disposal for many decades, the risk to human life and the improvement of technology have caused a cultural shift within the larger MIW community towards using unmanned systems. Navy EOD divers are not considered in the modeling and simulation process. This is partially due to the intent for the community to reduce the risk to human lives as well as the fact that neutralization-capable UUVs are generally faster at performing this mission regardless of scenario (Navy Recruiting Command 2014).

#### **H. NAVY MARINE MAMMAL PROGRAM (NMMP)**

The Navy Marine Mammal Program utilizes dolphins (as shown in Figure 14) or other similar animals in MIW efforts. Their keen sense of echolocation combined with competent training allows them to locate sea-borne mines for later disposal or avoidance. Furthermore, unlike divers, they are not at risk of health effects of repeated diving (such

decompression sickness or “the bends”). These animal and trainer teams fall under the same command cognizance as EOD divers. MIW is one of several missions that the NMMP can perform, but those details are generally classified. Similarly to the EOD divers, there is a desire to remove both man and animal from the minefield as much as possible to avoid casualties. The NMMP assets are generally not utilized for mine neutralization and were not modeled in the simulation to follow (Space and Naval Warfare Systems Command 2011).



Figure 14. NMMP Dolphin and Trainer. Source: Business Insider Inc. (2015)

## V. MINE NEUTRALIZATION SYSTEM PERFORMANCE CHARACTERISTICS

### A. OVERVIEW

This overview presents the Mine Neutralization Systems and their performance characteristics in support of this effort. These performance characteristics are provided in a range of values based upon known unclassified values. The value ranges provided for this effort are identified as low, medium, and high to remain unclassified. This section covers four Mine Neutralization systems as well as their performance characteristics. The platforms are AN/SLQ-48 Mine Neutralization System, AN/SLQ-60 SeaFox, AN/AQS-235 AMNS Archerfish, and AMNS Barracuda. These systems can be deployed from multiple platforms. Those platforms are covered in Chapter VI. The research for these systems was done mostly using military and contractor websites due to the relative lack of system documentation in publicly available literature. Most of the documents were in the form of briefs, power points, and online descriptions. The variables that that were utilized were discussed in Chapter II and were derived from discussions with MNS stakeholders (CAPT Scott Burluson, personal comm.), for each of the four Mine Neutralization Platforms (SLQ-48, SLQ-60, AN/AQS-235, and Barracuda), ranges for relevant performance parameters were determined.

The variables that are taken into account for this effort include the following:

Target Max Depth – The target max depth includes the low, med and high value ranges of the maximum depth that the system can safely accomplish.

Launch VIC range from base – This is the range from shore that this system can be deployed. This is usually based on range of helicopter.

Range (from Launch) – This is the range of the system from the launch platform.

Detect Range - This is the range in which the system can accurately detect a mine.

Probability of Misidentification (P\_Detection) – This is the detection accuracy

Speed – The is the speed in which the system can maneuver

tEndurance – This is the relative operating time before the system must be recharged.

Probability of Malfunction ( $p_{\text{Malfunction}}$ ) – This is the relative operational availability of the system

$t_{\text{Deployment}}$  – This is the time it takes to deploy the system.

## **B. MINE NEUTRALIZATION SYSTEMS DESCRIPTIONS**

### **1. AN/SLQ-48 Mine Neutralization System**

The AN/SLQ-48 Mine Neutralization System (Figure 15) is a self-propelled, remotely operated submarine developed by the Alliant Techsystems for utilization on the Avenger Class MCM vessels. The AN/SLQ-48 is mostly used for deep-water operations and can identify underwater objects with its remotely controlled submersible vehicle. If it is determined that the object is a mine, it will incapacitate the object. The objects can be incapacitated in two ways: for bottom mines, the vehicle will place an explosive charge and detonate while attached to the mine (causing a sympathetic detonation of the mine itself); and with moored mines, it will cut the cable and let the mine surface. Once the moored mine cable is cut, it will require the attention of the EOD team to neutralize. Table 2 provides performance characteristics of this system.



Figure 15. The AN/SLQ-48 Mine Neutralization System. Source: Kelly (2013)

Table 2. The AN/SLQ-48 Mine Neutralization System Performance Characteristics

<b>System of Interest:</b>		<b>AN/SLQ-48 Mine Neutralization System</b>		
<b>Launched Via:</b>		<b>Avenger Class MCM Ship</b>		
<b>Primary Functions:</b>		<b>Places charge on bottom mines, Cuts cable for moored mines (then requires EOD to neutralize)</b>		
<b>Parameters *</b>	<b>Units</b>	<b>Low</b>	<b>Med</b>	<b>High</b>
Launch VIC Range from base (one-way)	NM	N/A, ship-borne		
Range (from Launch)	ft	2625	3500	4375
DetectRange	NM	0.75	1	1.25
P_detection	[0,1] scale	0.5	0.4	0.3
Speed	kts	6	8	10
tEndurance	min	Infinite; ship umbilical		
pMalfunction	[0,1] scale	0.375	0.5	0.625
tDeployment	min	7.5	10	12.5

## 2. AN/SLQ-60 SeaFox

The AN/SLQ-60 SeaFox System (Figure 16) is a tethered, self-propelled, remotely operated submarine developed by ATLAS ELEKTRONIK as a multi-nation mine neutralization system. The AN/SLQ-60 was developed to operate with the MH-53 Helicopter, Avenger class MCM as well as mobile EOD units. The AN/SLQ-60 was developed to neutralize ground mines, short tethered mines, long tethered mines, and drifting mines. The system has both an automatic and manual guidance system for waypoint navigation. It includes a high frequency scanning active sonar with adjustable resolution, as well as a real time closed-circuit television (CCTV) imaging system. Table 3 provides performance characteristics of this system.



Figure 16. AN/SLQ-60 SeaFox System. Source: Marine Link (2012)

Table 3. AN/SLQ-60 SeaFox Performance Characteristics

<b>System of Interest:</b>		<b>AN/SLQ-60 SeaFox</b>		
<b>Launched Via:</b>		<b>MH-53E Helicopter, shore-based / Avenger Class MCM Ship / EOD Divers</b>		
<b>Primary Functions:</b>		<b>Sacrificial explosive delivery ROV</b>		
<b>Parameters *</b>	<b>Units</b>	<b>Low</b>	<b>Med</b>	<b>High</b>
Launch VIC Range from base (one-way)	NM	250 NM from SHORE (normally)		
Range (from Launch)	ft	3000	4000	5000
DetectRange	NM	0.75	1	1.25
P_detection	[0,1] scale	0.625	0.5	0.375
Speed	kts	4.5	6	7.5
tEndurance	min	75	100	125
pMalfunction	[0,1] scale	0.225	0.3	0.375
tDeployment	min	7.5	10	12.5

### 3. AN/AQS-235 AMNS Archerfish

The AN/ASQ-235 AMNS Archerfish (Figure 17) is a semi-autonomous system designed to be deployed from a helicopter. The system includes a Launch and Handling System (LHS) and four (4) destructor inserts. The system is designed for the LHS to be



lowered down from the side of a MH-60R helicopter. Once the LHS is deployed, it will travel in a preprogrammed route to the target. Once at the target, the operator will take over to determine if the target is a mine. Once identification is determined, the destructor will be deployed to detonate the mine. The Destructor system includes video and narrow scanned sonar in order to assist the operator in threat detection and confirmation. Table 4 provides performance characteristics of this system.

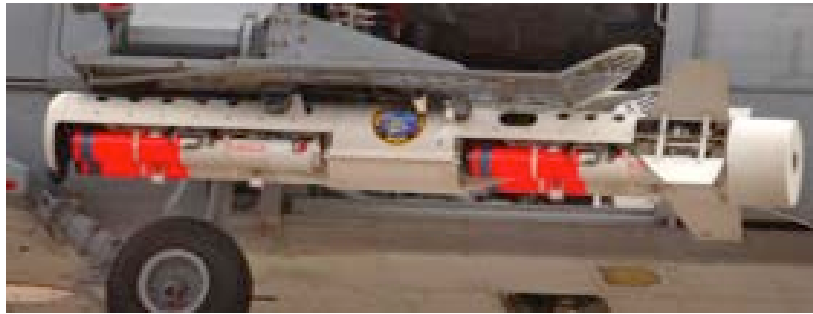


Figure 17. AN/ASQ-235 AMNS Archerfish. Source: Mine Warfare Assn. (2013)

Table 4. AN/ASQ-235 AMNS Archerfish Performance Characteristics

<b>System of Interest:</b>		<b>AN/AQS-235 AMNS</b>		
<b>Launched Via:</b>		<b>MH-60S Helicopter Embarked aboard LCS Ship</b>		
<b>Primary Functions:</b>		<b>Sacrificial explosive delivery ROV</b>		
<b>Parameters *</b>	<b>Units</b>	<b>Low</b>	<b>Med</b>	<b>High</b>
Launch VIC Range from base (one-way)	NM	180 NM from SHIP (can be from SHORE)		
Range (from Launch)	ft	4500	6000	7500
DetectRange	NM	0.75	1	1.25
P_detection	[0,1] scale	0.75	0.6	0.45
Speed	kts	4.5	6	7.5
tEndurance	min	45	60	75
pMalfunction	[0,1] scale	0.075	0.1	0.125
tDeployment	min	7.5	10	12.5

#### 4. AMNS Barracuda

The AMNS Barracuda (Figure 18) is under development to replace the AN/AQS-235 AMNS Archerfish. The Barracuda is designed to neutralize near surface, drifting, and in volume mines. The Barracuda AMNS is being advertised as being capable of being launched from a MH-60R sonobuoy launcher, but it will also be possible to launch it from the LCS or a shore location. This system has similar attributes to the AN/AQS-235 with regards to the functionality and performance. One thing to note is that as of 10 Jun 2016, PMA-299 has reallocated the funding for this project with no further funding sources identified. Table 5 provides performance characteristics of this system.



Figure 18. Depiction of an AMNS Barracuda Launched from Helicopter. Source: PennWell Corporation (2014)

Table 5. AMNS Barracuda Performance Characteristics

<b>System of Interest:</b>		<b>Barracuda (Future System)</b>		
<b>Launched Via:</b>		<b>TBD (Helo-borne Sonobuoy Launcher)</b>		
<b>Primary Functions:</b>		<b>Sacrificial explosive delivery ROV</b>		
<b>Parameters *</b>	<b>Units</b>	<b>Low</b>	<b>Med</b>	<b>High</b>
Launch VIC Range from base (one-way)	NM	180 NM from SHIP (can be from SHORE)		
Range (from Launch)	ft	5625	7500	9375
DetectRange	NM	0.9375	1.25	1.5625
P_detection	[0,1] scale	0.9375	0.75	0.5625
Speed	kts	7.5	10	12.5
tEndurance	min	93.75	125	156.25
pMalfunction	[0,1] scale	0.0375	0.05	0.0625
tDeployment	min	5.625	7.5	9.375

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## **VI. MINE NEUTRALIZATION SCENARIOS**

### **A. OVERVIEW**

Mine neutralization can be performed in a number of different ways. The methods of performing this mission depend on several factors depending on what systems are being utilized. As newer technologies begin to be added to the Fleet, there have been shifts as legacy families of systems are supplanted or reorganized and new functional relationships have developed. In this section we will address three overarching categories of MIW and (within those categories) specifically focus on those subsystems that are involved in mine neutralization. Those three categories are classified as the following: “legacy” or “dedicated” capabilities refer to families of systems that are still in use but are reaching the end of their life cycle; “current” capabilities refer to those families of systems that exist today and are in the final stages of Fleet integration for use in the foreseeable future; lastly, “future” capabilities refer to those families of systems that include upgraded components that are planned for but do not yet exist or have not been delivered to the Fleet. Finally, the scenarios presented represent generally accepted CONOPS that were used to inform the methodology for modeling, simulation and subsequent analysis.

### **B. LEGACY OR DEDICATED MIW OPERATIONAL SCENARIOS**

#### **1. Operational Level CONOPS**

In general, the specific tactics, techniques and procedures for MIW are classified. However, it is possible to infer many of the sequences of events that must occur in order to perform a MIW operation. CONOPS that pertain to the MCM ships in combination with the MH-53E are often referred to as “dedicated” assets within the community, inferring that they are generally specialized, older systems. The term “legacy” is sometimes used, but carries a connotation that these systems are no longer in operation or supported (which is false). The “operational” level of warfare is generally managed at a higher level of leadership and informs the larger view of the battle space. A “kill chain” in Department of Defense vernacular can be defined as a series of actions (or, in systems

engineering language, “functions”) that are required to take action against a target. This begins with detection and ends assessing the results. In traditional kinetic warfare (e.g., bombs, bullets), this is referred to by the acronym “F2T2EA” which represents the following generic tasks: Find, Fix, Track, Target, Engage, and Assess. As first mentioned in section IIC, in a MIW scenario, the generic tasks that must be performed include (in order) the following: mine-like object detection, classification, localization, identification, and finally (if necessary) neutralization. The focus of this analysis is on the ability to launch a neutralization system, reacquire a target (if necessary) with a known location and execute an offensive action against the target; as such, the CONOPS discussed below will elaborate this process with a specific focus on the latter part of the “kill chain” (Military Technology 2013).

## **2. Tactical Level CONOPS: MCM Avenger Ships**

It is possible for an MCM vessel to operate of its own accord to affect every section of the kill chain. Specifically, the MCM ship is uniquely equipped as a wood- and fiberglass-hulled vessel to enter an area where risk of influence mine exposure exists. It can utilize its on-board sonar subsystems, towed arrays, and remotely operated UUVs. Once the mine-like contact is localized, the MCM ship has an option to utilize the UUVs to confirm identification of the mine, launch EOD forces (if available), or launch the mine sweeping towed array (to cause influence-based detonations). Alternatively, it is possible for the MCM ship to pass the location of the mines to the MH-53E helicopters for further target prosecution. This choice is dependent on several factors, including theater threat considerations, known types of mines in the area, locations of territorial waters and shipping lanes, “white” (civilian) traffic in the area, and other considerations. In any case, if the decision by the Mine Counter Measures Mission Commander (MCMC) is to neutralize the mine, then any of the systems mentioned above may be used to affect the desired result.

### **3. Tactical Level CONOPS: MH-53E Aircraft CONOPS**

As discussed earlier, an MH-53E may be located ashore [as is common in the Fifth Fleet area of responsibility (AOR)] or aboard an amphibious type of vessel (LHD or LPD). This means that, similarly to the MCM vessel, the MH-53E must be capable of performing the entire MCM kill chain with minimal support from other MIW-capable assets. Furthermore, the long range and aerial refueling capability of the Sea Dragon make it possible for a ship to launch the helicopter from a relatively safe distance from a mine danger area, limiting the risk of collateral damage in accomplishing the mission.

The Sea Dragon will launch at the direction of the MCMC in order to clear a specific area of water space of mines. To do so, it utilizes a combination of its towed systems (such as the AN/AQS-24 side scan sonar) to detect mine-like contacts in the water column. Once an area of water space has been searched, the decision may be made to employ a mine sweeping system such as the Mk-105 (which aims to trigger magnetic or acoustically triggered mines by utilizing a sacrificial decoy) or to employ the AN/ASQ-232 SeaFox in a similar fashion to the MCM vessel's UUV. Any of these methods are a possible means of neutralizing a mine-like contact (Personal Interview, CDR Carman, 2016).

### **4. Tactical Level CONOPS: EOD Diver CONOPS**

In some cases, it is possible to utilize EOD divers to manually attach explosives to a mine and utilize a remote trigger to affect neutralization. This can be performed by deploying EOD forces from the air (via helicopter), by deploying them directly from surface ships, or by deploying a RHIB to allow the forces to travel a short distance to the mine. This presumes that the mine has already been located, identified, and classified. Likely candidates for EOD neutralization include floating mines, shallow moored mines, and deep-water moored mines that had their anchor cut by other means (such as the previously mentioned UUVs) that essentially turn them into floating mines. As previously mentioned, this operation is performed at high risk to those forces involved.

NMMP trained animals may augment EOD forces or independently perform some of the same tasks towards mission accomplishment.

## **C. CURRENT AND NEAR-TERM MIW OPERATIONAL SCENARIOS**

### **1. Operational Level CONOPS**

As previously discussed, there has been a shift in the MIW force structure and CONOPS that incorporates the newly introduced LCS vessels in place of the MCM ships and replaces the MH-53E with a composite air detachment consisting of one MH-60S and one MQ-8B. At present, this shift is in process and has not yet been completed; as such, the world of today consists of an amalgam of the “dedicated” forces above and some (but not all) of the end-state subsystems that will replace them. This is partly due to the phased nature of subsystem introduction that is programed to take place over several years in addition to the substandard performance of some of the subsystems that are under testing.

This section presents a hypothetical MIW scenario in the near future where the LCS MCMMP has been implemented but existing MCM ships and the MH-53E have not been retired from use in MCM operations.

### **2. Tactical Level CONOPS: LCS MCMMP**

From the point of view of the MCM mission planning staff, there is an opportunity for blending of available dedicated assets (MCM ships and MH-53E helicopters) and the new LCS concepts. The choice of which asset to utilize will depend greatly on location, which will drive which assets are stationed and available in theater. In the case of FIFTH FLEET (Middle East) operations, the dedicated assets above will likely remain until their disestablishment. Elsewhere, the LCS and composite air detachment will provide a mobile response team capable of executing missions elsewhere in the near future. The CONOPS for dedicated assets will likely remain the same as was explained above except for that they might operate in parallel with the LCS capabilities.



LCS, like the MCM ships, is equipped with its own integral method of scanning using sonar sensors. This provides a general localization of mine-like contacts within the water column. However, the precise localization capabilities are housed within the MH-60S's ALMDS system. Once an operating area has been designated that is likely to contain mines (either by intelligence provided from other communities or by utilizing the LCS's onboard sensors), it is expected that the helicopter will launch to perform a more thorough sweep of the operating area. This information will be returned to the ship; while the helicopter removes the ALMDS and installs the AMNS, the ship's company will perform the post-mission analysis that will identify mines using the obtained data. Furthermore, the MQ-8B may be utilized to perform the search mission depending on the operating area; the COBRA system is intended for shallow-water searching in sandy beach and other littoral areas. This data will be added to the post-mission analysis and will contribute to the AMNS battle plan.

Once mine locations are determined, it is up to the MCMC whether those mines require neutralization. If so, the MH-60S will be the best option (in the near term) for LCS to prosecute them. Other systems will become available as they are tested, validated, and ultimately delivered to the LCS. For now, the helicopter will launch and rendezvous with the supposed location of the mine to be neutralized. A key difference between the MH-53E and MH-60S is the method of deployment for neutralization systems. Where the MH-53E has options to drag mine sweeping gear and towed arrays through the water, the MH-60S is confined to utilize UUVs only. This means that the MH60S helicopter must hover over the area while lowering an apparatus (previously described as the "LHS") into the water using an on-board winch (CSTRS). From that LHS, up to four Archerfish vehicles can be deployed (one at a time) and operated by the aircrewmen located in the helicopter's cabin. The operator uses the sensors onboard the Archerfish to localize, perform final identification, and ultimately destroy the mine.

Alternative solutions may include utilizing EOD divers in some scenarios, but this has not been advertised as something that can be performed while the aircraft is in the AMNS configuration due to cabin space restrictions. Also, it should be noted that the aircraft is not capable of carrying both the ALMDS (mine searching) and the AMNS

(mine neutralization) equipment. This means that there will be a time delay between acquisition and persecution of a mine-like contact, which presents risk in the form of potentially not being able to positively reacquire the position of the mine (especially in the case of a floating or drifting mine) (Moton 2016).

#### **D. FUTURE MIW OPERATIONAL SCENARIOS**

##### **1. Operational Level CONOPS**

Currently, the LCS's towed systems are intended to be operational and available to the fleet in the relatively near future. This section presents a notional concept of operations for a near future situation where the MCM ships and MH-53E are no longer in service and no longer provide MIW capabilities, but LCS has its other programmed systems available to use.

##### **2. Tactical Level CONOPS: LCS MCMMP with upgraded systems**

In this scenario, the LCS is free to independently operate as necessary with its integrated MH-60S and MQ-8B air assets. Without relying upon the MH-53E's shore or large-deck ship requirements, there is no longer as high of a risk to a "high value" vessel. Also, the transit time for the airborne assets will be shorter (due to the ability for LCS, with its shallow draft, to get closer to the mine field) thus improving performance and decreasing the time necessary to execute a mission.

In this CONOPS, the same procedures as in the previous section are likely to be utilized. However, there will be additional capabilities that may be performed in parallel. For instance, the LCS will be capable of performing an improved search capability utilizing the towed sonar array (which was previously intended to be towed by the MH-60S). This information will be added to the post-mission analysis that will be obtained from the helicopters.

In terms of neutralization, there is an added capability for minesweeping to occur (again by towing gear behind the ship) and an added mine neutralization capability by deploying remote vehicles from the LCS. The deployment of the remote vehicles can occur in addition to (and simultaneously with) the Archerfish, expediting a neutralization effort but increasing complexity and coordination requirements. Finally, the Barracuda will add further capabilities to the neutralization equation since it is intended to be a platform agnostic subsystem that can be launched by the LCS, MH-60S, or perhaps other vessels. Unlike the current RMS vehicles or other Unmanned Surface Vehicles (USVs) being used, Barracuda is intended to be smaller, faster, more maneuverable, and more expendable (and therefore more cost-effective to utilize). Furthermore, part of the design process will allow it to be launched from the current MH-60R Sea Hawk sonobuoy launcher which will allow more neutralizers to be carried in the helicopter as opposed to AMNS's limitation of four rounds at a time.

#### **E. IMPLEMENTATION IN SIMULATION MODEL**

To have sufficient data to assess the relative efficacies of each mission variant, simulation runs were made utilizing each variant, at every possible performance variable value (defined using a full factorial design of experiments), for each employment configuration, against a single mine field model generated from EDP output as illustrated in Figure 19.

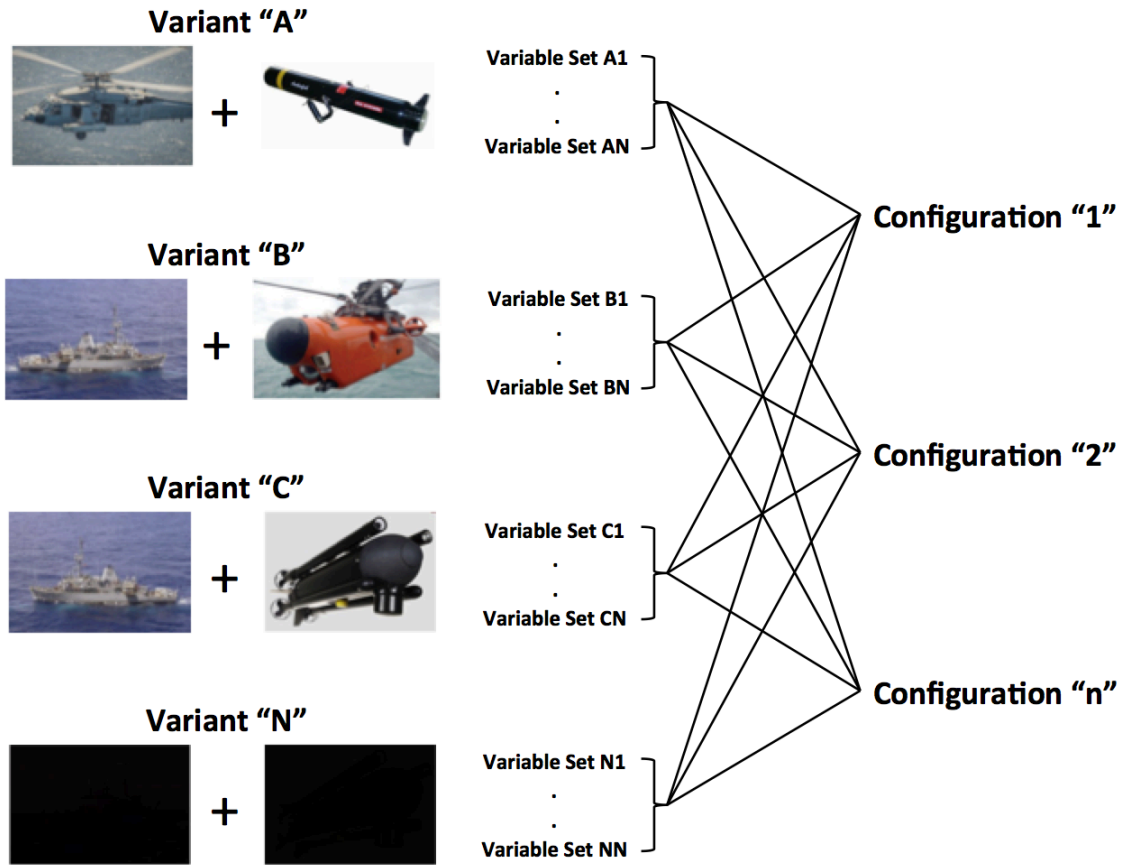


Figure 19. Simulation Framework. Sources: BAE Archerfish Mine Neutralization System (2016), Furey (2014), Hammond (2004), MarineLink (2012), Program Executive Office Littoral and Mine Warfare (2009).

This allowed for comparative efficacy evaluation between mission scenarios and key performance parameter sensitivity evaluations with single mission configurations. Details regarding the architecture of the simulation can be found in Chapter VII and details of the data analysis can be found in Chapter VIII of this capstone report.

## **VII. MODELING AND SIMULATION ARCHITECTURE**

### **A. OVERVIEW**

This chapter discusses the modeling and simulation (M&S) aspects of the project with respect to the development of the models design in accordance with the previously conversed SE process. Specifically, this chapter describes the analysis of modeling tool alternatives and subsequently the modeling areas requiring development using this modeling tool. Furthermore, this chapter provides an overview of the model aspects, configurations, inputs and outputs, required to address the project's problem statement. The assumptions that enable coherent evaluation of the model results within limitations to the scope of the model are also discussed. Finally, this chapter addresses the functionality and validity of the modeling analysis and provides a conclusion on capabilities of the M&S architecture.

### **B. MODELING TOOLS ANALYSIS**

#### **1. General**

The modeling and simulation effort was initiated by an analysis of available M&S tools. Specifically, Imagine That Inc.'s ExtendSim (a discrete event simulation) and Python Software Foundation's Python (an open programming language) were considered..

#### **2. ExtendSim**

ExtendSim is an M&S tool that enables dynamic model development through a combination of block diagram models that provide a set category of predefined actions and subcomponent manipulation through traditional coding of individual blocks. ExtendSim supports in-depth understanding of complex system models by enabling extensive feedback options during simulation executions based on a white-box programming model. This block diagram approach to modeling also allows for visual representation of simulation components as the simulation is running in an existing time-step model approach, allowing for the programmer to visually identify errors in the

execution of the model over a simulated and stepped time period. Additionally, the time required for model development can be reduced with ExtendSim by using modeling blocks with predefined actions to set up multiple functions quickly and the time required to simulate all the desired model scenarios can be reduced by creating adaptive loops of ExtendSim models to conduct data collection on various parameter inputs, which will reduce the overall time required to conduct the M&S development and execution (Imagine That Inc. 2008).

The primary drawback to the utilization of ExtendSim is the steep learning curve required to manipulate blocks with predetermined functions for multiple applications (something that is substantially different from traditional coding languages in model development). Having a set structure to each block, no matter how flexible, will also require non-standard applications of these blocks to accomplish desired results, preventing a streamlined functional flow to the data being manipulated by the model.

### **3. Python**

Python programming language is an M&S tool that enables dynamic model development through more traditional coding languages, though this specific language attempts to maximize readability and minimize the required lines of code in a modeled program. Python is an open-source programming language with extensive personal and professional applications beyond modeling which provides an extensive wealth of information for developing desired functions in a model and troubleshooting both common and unique bugs when problems arise. Additionally, the open-source nature of Python allows for the model to use third-party modules to perform specific functions with limited commands in the code. Python has limited interoperability with the internal mechanics of a model during simulation execution, though this does enable a cleaner black box approach to desired and variable performance parameter inputs through the model for a set sequence of programmed outputs (Python Software Foundation 2012).

The main disadvantage to Python as an M&S tool is the dedicated time required in model development and execution. Python only provides more detailed debugging feedback during program execution, requiring the program to be developed incrementally

by focusing on sections and components of the model individually before incorporating into the larger program for further debugging. Additionally, each operator in Python only performs a single action within the code, meaning that thousands of lines of code written by the programmer are required to perform the same notional actions as potentially a few dozen blocks in a block diagram modeling tool. In model execution, Python requires looping of the programming code with variable inputs that exponentially increases the run time of the simulation. Python has to be approached incrementally for data collection as well, establishing set performance parameters being manipulated before running the simulation loops, which will enable a more structured data collection over an extended period of time.

#### **4. Modeling Tool Conclusion**

While heavily swayed by previous experience with similar coding languages by the members of the MIW Team, the Python modeling tool was selected to enable a more adaptive and streamlined structure to the model. The Python programming language meets the requirements for desired input and output variables with the black box model design and provides the clearest functional flow of the information within the model for group coordination and future expansion in scope or application. While not organically designed as a time-step model, the Python model can be manipulated to apply this adaptive flow programming language in a looping pattern to simulate a time-step through a simulation. The excess of time required developing and performing data collection with Python compared to ExtendSim required advanced planning of development deadlines and incremental execution for data collection in a reasonable timeframe to mitigate the main risks associated with Python as the primary M&S tool.

### **C. AREAS FOR MODELING**

#### **1. General**

As discussed in Chapter II, the primary areas of concern for the mine neutralization scenarios are the environment and minefield layout as well as the platform and neutralization systems. To address these areas of the problem scenario, the model breaks apart these components and defines the environment, the red force composition

and the blue force composition for the model. The environment and red forces models develop the characteristics of the scenario for evaluation, while the blue forces model creates a time-step model to simulate the progression of the platforms and neutralization system in neutralizing the created minefield. To ensure unit consistency for all variables used in the models, inputs and outputs were standardized to meters for length measurements, seconds for time measurements, and meters per second for second order derivatives of these variables. The design architecture for each of these modeling areas is addressed below.

## **2. Environment**

The environment model was designed to follow the characteristics from the environment definition in Chapter II. The environment model simulates a littoral operating area in a constrained, shallow-water threat region centered on a priority shipping lane utilized by blue force, friendly, and/or neutral platforms. The mission space for the environment model consists of a square 10 nm by 10 nm grid, allowing for a three-dimension model with depths from the surface to 800 feet for the mines to be located. The specific depth is provided by a random, gradual gradient to the bottom of the water column across the 100 nm<sup>2</sup> operating area. Additionally, the mines that are tethered are subjected to a set current input, drifting their floating locations from the locations of the mines' anchors. These environmental characteristics are designed into a Python file that also developed the red force composition.

## **3. Red Force Composition**

The model for the red forces was designed with the assumption of combat theater dominance for the friendly forces, including no air, surface or subsurface red force platforms. The model was designed for red force mines being the only threat to the friendly forces. For designing these mines into the environment model, the red force model was designed to follow the characteristics of the minefield definition described in Chapter II and the specific minefield characteristics described in Chapter III. The red force model provides a saturated minefield, consisting of 100 mines of various types as well as 400 echo returns from surface and subsurface clutter, consisting of only 10%



mine-like echo returns for further analysis in the simulation. The red force model pulls the three-dimensional location information developed in the environment model to randomly place these mines and echo returns into the operating area. Additionally, each of these mines is randomly designated with the mine or clutter type when the location is selected. As stated above, the red force model is located in the same Python file as the environment model, enabling consistent environment construction and mine locations to be evaluated against various blue force compositions.

#### **4. Blue Force Composition**

The environment and red force models established the context and the threat environment utilized in the simulation. The blue force model performed most of the activities and provided the results for each scenario. Specifically, the blue forces model conducted the localization, identification, and neutralization portion of the mine neutralization mission, targeting mines with known locations within the minefield, reacquiring and re-identifying these known mines, neutralizing these mines, and evaluating the success or failure of the neutralization effort for each mine. This model was designed as a time-step model with discriminating loop functions utilized to simulate one second during each pass through the model's code. The blue forces model was designed to simulate the characteristics of the platforms, MCM Avenger-class MCM ships, MH-60S Knight Hawk and MH-53E Sea Dragon, and mine neutralization systems, AN/SLQ-48 Mine Neutralization System, AN/SLQ-60 SeaFox Mine Neutralization System, AN/AQS-235 Archerfish Airborne Mine Neutralization System and Barracuda Airborne Mine Neutralization System, from the platform performance parameters in Chapter IV and the mine neutralization system performance parameters in Chapter V. Additionally, these designated blue forces were designed to operate in accordance with the mine neutralization scenarios defined in Chapter VI.

### **D. MODEL CONFIGURATIONS**

#### **1. General**

For the model configurations, four separate Python M&S files were created to isolate unique and independent system reactions to comparable simulations. The first

modeling file executes a simulation for the environment and the minefield creation with a single run. Having the environment and red force models run in a separate modeling file than the blue force model provided a constant data sample input for the minefield during all simulation runs of blue force configuration and performance parameter permutations. The minefield was populated with a dense threat from the mines and other echo returns spread across the designated environment, maximizing the variety of situations encountered by the model to ensure a large sample size of various systems' responses to collect an adequate sample of data for system response normalization.

The subsequent three Python M&S files were designed to account for different blue force compositions using each of the designated platform and neutralization combinations. For these blue forces model files, the platform(s) begins in a set location to the west of the minefield along an extension of the shipping lane. This starting location's characteristics for the scenario depended on the associated platform being utilized for each model run. For the MCM ship this starting location signified a rendezvous location for the MCM ship with resupply vessels, while the helicopters started from a LCS or a land-based location depending on the respective platform. This location designated the location that the platform begins the simulation, resupplies when neutralization capabilities are depleted, and returns at completion of mine neutralization of the entire minefield to command the completion of the simulation.

Each of these blue forces modeling files was designed to minimize the mission time required to clear the most critical area of the minefield around the shipping lane through the center of the designated environment. These configurations accomplished this task by targeting the center sector of the minefield around the shipping lane first, then spreading outward to the less critical sectors of the minefield from the shipping lane. This methodology is depicted in Figure 20. The most critical area around the shipping lane is colored green, the moderately significant sectors adjacent to this critical area are colored yellow, and the lowest priority sectors with the furthest range from the shipping lane are colored red. The three different blue force M&S files were designated as Blue Force Configuration 1, Blue Force Configuration 2, and Blue Force Configuration 3. Their specific traits are broken out below.

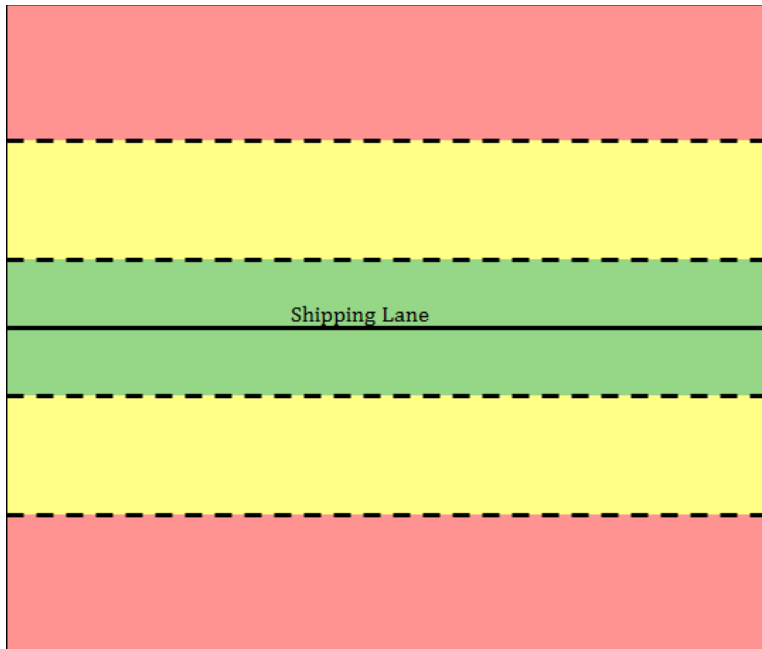


Figure 20. Threat Prioritization for Blue Forces Configurations

## 2. Blue Force Configuration 1

The first blue forces configuration, Blue Force Configuration 1, utilizes a single platform from the designated blue forces platforms with the respective mine neutralization systems associated with the platform. This single platform conducts the mine neutralization mission by prioritizing the shipping lane and subsequently the areas adjacent to the shipping lane. While this methodology was utilized to minimize the mission time required to clear the immediate area around the shipping lane, this also resulted in increased time to clear the entire minefield of all known mines. As the platform and neutralization systems completed neutralizing all the mines in each specific sector, the platform's neutralization route was designed to travel across the shipping lane to clear the next most priority sector, causing additional mission time squandered to accomplish these transits. Figure 21 depicts the designed operation for the Blue Force Configuration 1 model. Notice that the system begins to the left of Figure 19, neutralizes targets within the shipping route, then moves to targets between 20% and 40%, then moves to targets between 60% and 80%, then moves to targets between 0% and 20%, then moves to targets between 80% and 100%. Note that this will likely result in

increased time to clear the entire minefield because it prioritizes the areas in and around the shipping lane before moving to the outskirts of the potential minefield..

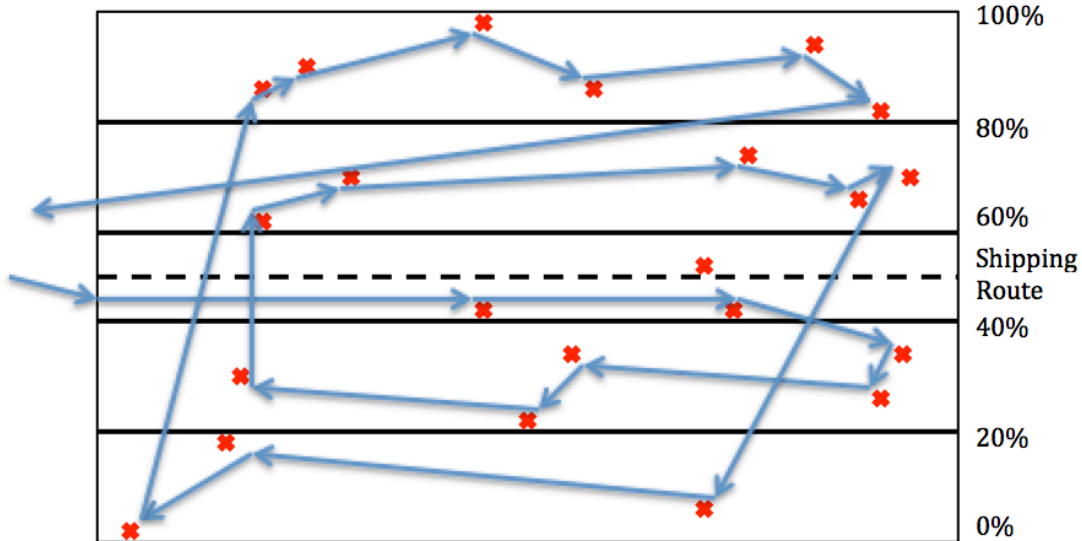


Figure 21. Blue Force Configuration 1 – Blue Forces Designed Route

### 3. Blue Force Configuration 2

The second blue forces configuration, Blue Force Configuration 2, utilizes two platforms from the designated blue forces platforms with the respective mine neutralization systems associated with the platforms. For all the simulated runs with multiple platforms and neutralization systems, the platforms and neutralization systems will be the same to ensure consistency for the data collection efforts. The issue created in Blue Force Configuration 1 with the platforms required to travel across the shipping lane to ensure priority sectors were cleared in the correct order was mitigated through the use of multiple platforms in Configuration 2. Once the two vessels initially clear the immediate area around the shipping lane of mines, one platform would continue clearing the sectors to the north of the shipping lane, while the other platform would clear the sectors to the south of the shipping lane. This method of neutralizing all the mines in the operating area will minimize mission time by preventing excesses transit times while still allowing mines proximity from the shipping lane to determine neutralization priority.

Figure 22 depicts the designed response for this configuration model with both platforms and their associated neutralization systems.

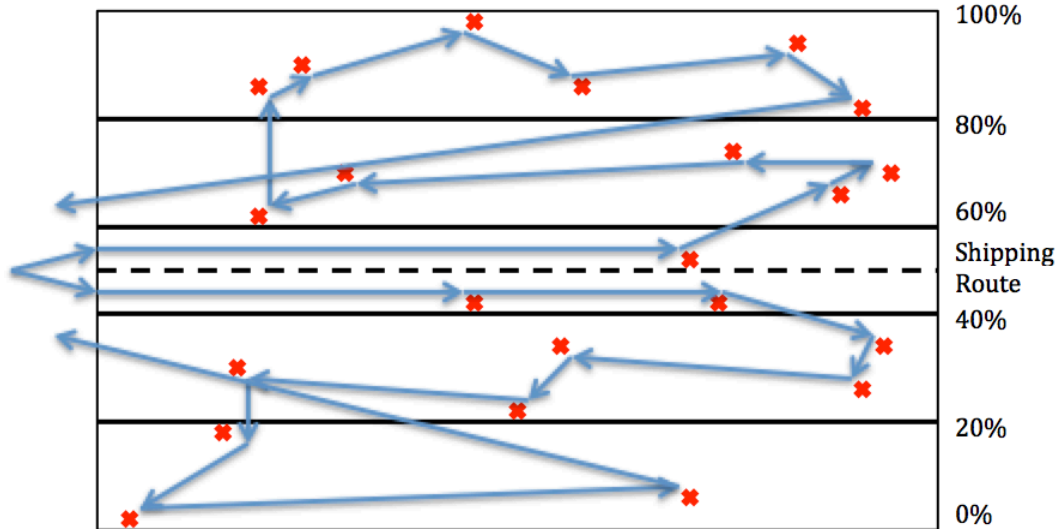


Figure 22. Blue Force Configuration 2 – Blue Forces Designed Route

#### 4. Blue Force Configuration 3

The last blue forces configuration, Blue Force Configuration 3, utilizes four platforms from the designated blue forces platforms with the respective mine neutralization systems associated with the platforms. As with configurations of two platforms, all four of these platforms and their associated neutralization systems are the same systems for data collection consistencies. Blue Force Configuration 3 takes the ideas of using multiple platforms to accomplish the intended mission quicker and more efficiently further by redoubling the number of platforms being utilized during the mission. Two of the platforms target clearing the mines immediately around the shipping area first, while the other two platforms begin by clearing the sectors positioned north and south of the shipping lane, respectively. Sharing the workload both north and south of the shipping lane between two platforms instead of one will substantially reduce the time required to complete the mission. However, this blue forces model provides the capability to bracket the mission problem to see if the mission effectiveness increases

proportionally with the number of assets being utilized. The simulation collects sufficient data to allow follow on analysis to compare the expected increase in mission efficiency with the associated increase in cost, manpower, and resource allocation. Figure 23 depicts the designed response for this configuration model with both platforms and their associated neutralization systems.

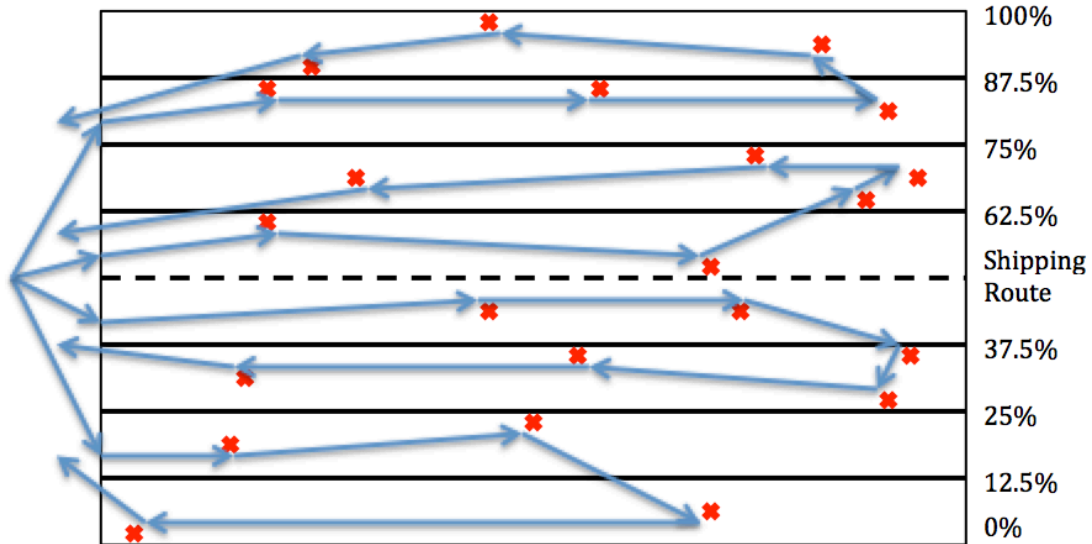


Figure 23. Blue Force Configuration 3 – Blue Forces Designed Route

## E. MODEL INPUTS

### 1. Constant Variables

Each of the models utilizes constant inputs to develop the model. The constant inputs provide consistent values to be used for all different configuration and parameter runs. These specific inputs remain constant based on the constraints established by the scenario definition or by the nature of the mission. These constant inputs include:

**a. *Environment Python File Constant Inputs***

run\_number: Integer to mark environment file outputs for reference.

x\_min: Minimum value along the x-axis of the operating area.

x\_max: Maximum value along the x-axis of the operating area.

y\_min: Minimum value along the y-axis of the operating area.

y\_max: Maximum value along the y-axis of the operating area.

gradient\_min: Minimum depth change per 1 meter of longitudinal or latitudinal change across the sea floor in the designated operating environment.

gradient\_max: Maximum depth change per 1 meter of longitudinal or latitudinal change across the sea floor in the designated operating environment.

depth\_min: Minimum depth of the operating area.

current: Constant environmental current to affect moored mines.

num\_of\_mines: Number of mines in operating area.

num\_of\_clutter\_returns: Number of echo returns for clutter in operating area.

types\_of\_mines: Number of mine types (Bottom, Surface Anchored, and Subsurface Anchored).

type\_of\_clutter: Number of echo returns from clutter (Ocean-Floor Non Mine-like Clutter, Floating Non Mine-like Clutter, Ocean-Floor Mine-like Clutter, and Floating Mine-like Clutter).

**b. *Blue Forces Configuration Python Files Constant Inputs***

scenario\_number: Integer to mark configuration file outputs for reference.

Ship\_Standoff: Range for platform standoff as a defensive posture to deploy and recover the neutralization system.

Engage\_Time: Time required by the neutralization system to engage an individual mine.

Resupply\_Time: Time required to resupply the neutralizing platform at the starting location.

Max\_Ammo\_Load: Expenditures available on the designated platform for the neutralization system before platform requires reloading.

Max\_Time: Time utilized to stop the scenario when the platforms do not successfully return to the starting point.

d\_t: Time interval utilized to establish the time-step loop for the blue forces progression.

Staging\_Area\_X: position along the x-axis that establishes the starting location for the beginning of the simulation and the location to be returned to for reloads and mission completion.

Staging\_Area\_Y: position along the y-axis that establishes the starting location for the beginning of the simulation and the location to be returned to for reload requirements and mission completion.

Entry\_Point\_Offset: Identifies the position along the y-axis where the platform enters the minefield. For configuration models with multiple platforms, entry point variable is required for each platform.

## **2. Time-Step Variables**

The time-step variables provide random values based on defined ranges and distribution characteristics to create input variables that change with each pass through a loop function. This means that these variables will change with each simulated run through the model's code within the desired loop function. These time-step variables will provide values within consistent ranges for all different configuration and parameter runs. These time-step variables include:

### ***a. Environment Python File Time-Step Variables***

gradient\_x: X-axis sea-floor gradient based on a random uniform distribution between the gradient\_min and gradient\_max.

gradient\_y: Y-axis sea-floor gradient based on a random uniform distribution between the gradient\_min and gradient\_max.

mine\_anchor\_x: X-axis location of mine for bottom mines or mine anchor for moored mines based on a random uniform distribution between the x\_min and x\_max.

mine\_anchor\_y: Y-axis location of mine for bottom mines or mine anchor for moored mines based on a random uniform distribution between the y\_min and y\_max.

mine\_type: Establishes mine type based on even probability of Bottom, Surface Anchored, and Subsurface Anchored mines based on a random uniform distribution across the type\_of\_mines value.



clutter\_bottom\_x: X-axis location of echo returns from clutter based on a random uniform distribution between the x\_min and x\_max.

clutter\_bottom\_y: Y-axis location of echo returns from clutter based on a random uniform distribution between the y\_min and y\_max.

clutter\_type: Established variation of detection characteristics in echo return types from clutter based on realistic probability of Ocean-Floor Non Mine-like Clutter (40%), Floating Non Mine-like Clutter (40%), Ocean-Floor Mine-like Clutter (10%), and Floating Mine-like Clutter (10%) echo returns based on a random uniform distribution across the type\_of\_clutter value.

clutter\_depth: Depth of floating echo return from clutter, both mine-like and non-mine-like, based on random uniform distribution of water-column depth at specified x-axis and y-axis location.

***b. Blue Forces Configuration Python Files Time-Step Variables***

Pd\_Min: Establishes logarithmic slope for the minimum probability of detection equation at the range between the detected contact and the sonar system for the respective platform or neutralization system.  $P_d$  determinations discussed in detail below.

Pd\_Max: Establishes logarithmic slope for the maximum probability of detection equation at the range between the detected contact and the sonar system for the respective platform or neutralization system.  $P_d$  determinations discussed in detail below.

Detection: Determine if a contact was detected when compared to the probability to detect ( $P_d$ ) based on a random uniform distribution for a probability up to 100%.

Manual\_Removal: Determined if sonar return was identified as mine-like echo returns from clutter when compared to the Radar\_ID\_Accuracy probability based on a random uniform distribution for a probability up to 100%.

Weapon\_Success\_Probability: Determined if neutralization effects were successful when compared to the Weapon\_Success probability based on a random uniform distribution for a probability up to 100%.

The probability of detection ( $P_d$ ) for the sonar systems of each platform and neutralization system was the most complicated time-step variable to be input in the mine neutralization system when attempting to reacquire known-location mines. However, the actual values for each system are classified, and when the standoff range is located within  $P_{d_{50}}$  (50% probability of detection) of the sensor as implemented in our M&S program

based on realistic operational scenarios then the  $P_d$  variable has minimal effect on the scenarios as designed. Therefore, the  $P_d$  value is approximated from expected results based on generic environmental conditions.

To create an equation for  $P_d$  based on the range between the sensor and the echo contact, three points are required, and with expected detection characteristics the equation will be logarithmic. Creating the most separation between equation points while selecting realistic detection ranges, ranges were selected for  $P_{d_{25}}$ ,  $P_{d_{50}}$ , and  $P_{d_{75}}$  for each platform's and neutralization system's sonar systems. To create expected variability in the  $P_d$  solution at each time-stepped range, two equations were created for each sonar system to create a minimum and maximum  $P_d$  results, providing controlled randomness to the sensor results. The resultant equations are displayed in Figure 24, specifically showing the minimum and maximum  $P_d$  curves for the MCM ship sonar. These  $P_d$  equations allowed  $P_d$  to be determined from a random uniform distribution between the minimum and maximum  $P_d$  curves based on the independent variable of any range between the platform or neutralization system and any echo contact.

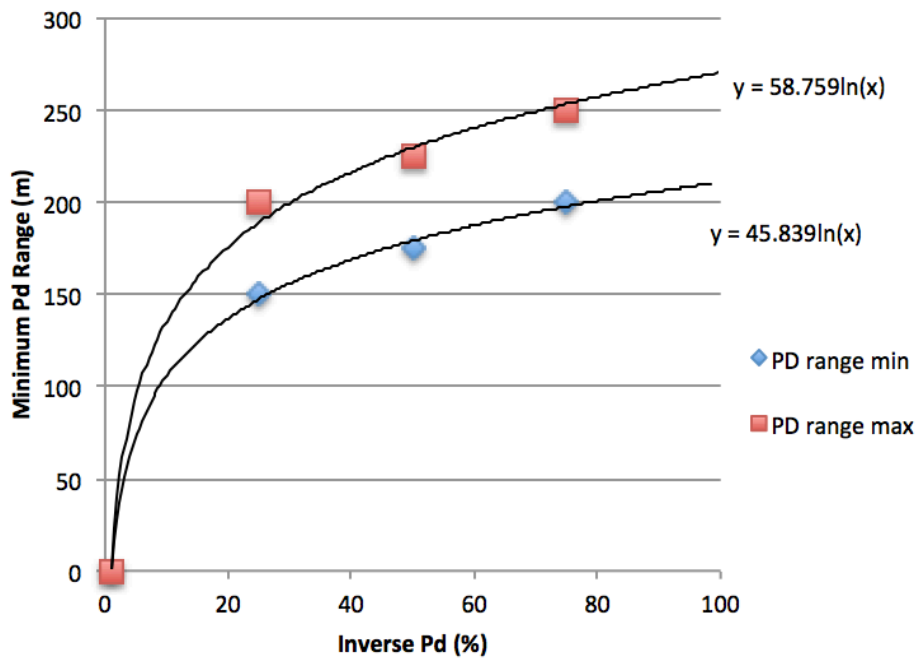


Figure 24. Minimum and Maximum  $P_d$  Equations for MCM ship

### 3. Simulation Variables

The simulation variables provide specific parameter values for inputs that have a direct impact on the results from different blue forces configuration and parameter permutation model runs. The parameters are unique for the platforms and neutralization systems that are being evaluated for the all the blue forces configurations. Additionally, these parameters have three levels, low, medium and high, for parameter permutations. The simulation variable inputs that were determined to have the most realistic impacts on the defined scenarios during M&S program development and experimental evaluation of the simulation's capabilities are:

Neutralizer\_Operating\_Speed: Neutralizer's maximum speed.

Ship\_Max\_Speed: Platform's maximum/cruise speed.

Weapon\_Success: Probability of successful neutralization of a mine by the neutralization system versus the probability of a failure or malfunction during neutralization of a mine as a percentage value.

Radar\_ID\_Accuracy: Probability of successfully identifying a mine-like echo return from clutter as such versus the probability of a mine-like echo return from clutter being identified as a mine, requiring neutralization system deployment, as a percentage value.

Deploy\_Time/Recovery\_Time: Time required to deploy or potentially recover the neutralization system from its associated platform.

The specific values identified for each of these inputs with each of the various scenarios are provided in the tables below. Table 6 provides the simulation inputs for the scenario of the SLQ-48 launched from a MCM vessel. Table 7 provides the simulation inputs for the scenario of the SLQ-60 launched from a MH-53E based on the shore. Table 8 provides the simulation inputs for the scenario of the SLQ-60 launched from a MCM vessel. Table 9 provides the simulation inputs for the scenario of the AQS-235 launched from a MH-60S embarked aboard a LCS vessel. Table 10 provides the simulation inputs for the scenario of the Barracuda AMNS launched from a MH-60S embarked aboard a LCS vessel.

Table 6. AN/SLQ-48 Mine Neutralization System Scenario Variable Inputs

<b>System of Interest:</b>		<b>AN/SLQ-48 Mine Neutralization Sys</b>		
<b>Launched Via:</b>		<b>Avenger Class MCM Ship</b>		
<b>Primary Functions:</b>		<b>Places charge on bottom mines, Cuts cable for moored mines (then requires EOD to neutralize)</b>		
<b>Parameters</b>	<b>Units</b>	<b>Low</b>	<b>Med</b>	<b>High</b>
Neutralizer_Operating_Speed	m/s	3.087	4.116	5.144
Ship_Max_Speed	m/s	5.402	7.202	9.003
Weapon_Success	[0,1] scale	0.375	0.5	0.625
Radar_ID_Accuracy	[0,1] scale	0.225	0.3	0.375
Deploy_Time/Recovery_Time	min	7.5	10	12.5

Table 7. AN/SLQ-60 SeaFox (1) Scenario Variable Inputs

<b>System of Interest:</b>		<b>AN/SLQ-60 SeaFox (1)</b>		
<b>Launched Via:</b>		<b>MH-53E Helicopter, shore-based</b>		
<b>Primary Functions:</b>		<b>Sacrificial explosive delivery ROV</b>		
<b>Parameters *</b>	<b>Units</b>	<b>Low</b>	<b>Med</b>	<b>High</b>
Neutralizer_Operating_Speed	m/s	2.315	3.087	3.858
Ship_Max_Speed	m/s	57.875	77.167	96.458
Weapon_Success	[0,1] scale	0.225	0.3	0.375
Radar_ID_Accuracy	[0,1] scale	0.1875	0.25	0.3125
Deploy_Time/Recovery_Time	min	7.5	10	12.5

Table 8. AN/SLQ-60 SeaFox (2) Scenario Variable Inputs

<b>System of Interest:</b>		<b>AN/SLQ-60 SeaFox (2)</b>		
<b>Launched Via:</b>		<b>Avenger Class MCM Ship</b>		
<b>Primary Functions:</b>		<b>Sacrificial explosive delivery ROV</b>		
<b>Parameters *</b>	<b>Units</b>	<b>Low</b>	<b>Med</b>	<b>High</b>
Neutralizer_Operating_Speed	m/s	2.315	3.087	3.858
Ship_Max_Speed	m/s	5.402	7.202	9.003
Weapon_Success	[0,1] scale	0.225	0.3	0.375
Radar_ID_Accuracy	[0,1] scale	0.225	0.3	0.375
Deploy_Time/Recovery_Time	min	7.5	10	12.5

Table 9. AN/AQS-235 AMNS Scenario Variable Inputs

<b>System of Interest:</b>		<b>AN/AQS-235 AMNS</b>		
<b>Launched Via:</b>		<b>MH-60S Helicopter Embarked aboard LCS Ship</b>		
<b>Primary Functions:</b>		<b>Sacrificial explosive delivery ROV</b>		
<b>Parameters *</b>	<b>Units</b>	<b>Low</b>	<b>Med</b>	<b>High</b>
Neutralizer_Operating_Speed	m/s	2.315	3.087	3.858
Ship_Max_Speed	m/s	60.190	80.253	100.317
Weapon_Success	[0,1] scale	0.075	0.1	0.125
Radar_ID_Accuracy	[0,1] scale	0.1125	0.15	0.1875
Deploy_Time/Recovery_Time	min	7.5	10	12.5

Table 10. Barracuda AMNS Scenario Variable Inputs

<b>System of Interest:</b>		<b>Barracuda Future System</b>		
<b>Launched Via:</b>		<b>MH-60S Helicopter Embarked aboard LCS Ship</b>		
<b>Primary Functions:</b>		<b>Sacrificial explosive delivery ROV</b>		
<b>Parameters *</b>	<b>Units</b>	<b>Low</b>	<b>Med</b>	<b>High</b>
Neutralizer_Operating_Speed	m/s	3.858	5.144	6.431
Ship_Max_Speed	m/s	60.190	80.253	100.317
Weapon_Success	[0,1] scale	0.0375	0.05	0.0625
Radar_ID_Accuracy	[0,1] scale	0.1125	0.15	0.1875
Deploy_Time/Recovery_Time	min	5.625	7.5	9.375

## F. MODEL OUTPUTS

The M&S Python files provide multiple outputs in various formats to ensure complete data collection for accurate analysis results. The outputs general fall into two main categories, test outputs for tracking and evaluation of model performance and analysis output for data analysis of all the scenarios based on the problem statement. The outputs are unique to each combination of variable inputs, neutralization system and platform of interest, and blue force configuration models. The model outputs include:

## 1. Test Outputs

Scenario Depth (#).csv file: Comma separated variable (CSV) file that results from the environment model, providing varying depth values over a two-dimensional grid across the simulated minefield at one meter intervals.

Echo Locations (#).csv file: CSV file that results from the red forces model, providing characteristics for each mine and echo return based on the number of inputs requested. The specific entries for each mine are:

- Echo Type
- X Anchor Location
- Y Anchor Location
- Depth
- Mine Cable Length
- X Mine Location
- Y Mine Location

Single Blue Ship Scenario (#).csv file: CSV file that results from the blue forces model, providing time-step outputs for the progression of both the platform and neutralization system. The specific entries collected during every time delta through the blue forces model are:

- Time
- Ship X
- Ship Y
- Ship Speed
- Ship Heading
- Neutralization System X
- Neutralization System Y
- Neutralization System Heading

## 2. Analysis Outputs

Time: Prints final time during the blue forces model simulation, which equates to all platforms returning to the starting point or the time counter equals the input maximum time value.

Weapon\_Expenditures: Prints total number of weapon expenditures that were utilized during mine neutralization efforts to include re-attacks.

Expenditure\_Failures: Prints total number of failures to neutralize, equating to the number of re-attacks required to neutralize all the modeled mines.

## **G. ASSUMPTIONS**

### **1. General**

There are several assumptions affecting all the components of the model. Several overarching limitations of scope of the project were discussed in Chapter III, while these specific assumptions address potential impacts or require mitigating circumstances directly on the model components or the data collection capabilities executed with the model. The assumptions impact all aspects of the model, including the environment, red forces, and blue forces models. The primary assumptions of the model are included in the following paragraphs.

### **2. Environment Model**

The environment assumptions result in consistent or similar results between the scenario runs, so not including these inputs and variables will have minimal impact on the run's results. The environment model does not incorporate abrupt or assertive changes in the sea floor gradient, environmental effects from water clarity, water temperature, sea state, wind speed, wind direction, and air temperature, or environmental characteristics from surface traffic and dynamic marine life. Additionally, the environment model did not include any simulation variables, containing only constant and time-step variable inputs, and the blue force model was only run against a single resultant of the environment model. While this architecture enables consistent and comparable results between the configurations and parameter permutation runs as well as preventing excessive time requirements to complete all the designated simulation runs, the environment being tested against will only have limited variety of three-dimensional areas for the blue forces to operate. To mitigate this risk, the environment was built to exhibit various depths throughout the design limits of the scenario to allow a more complex variety of locations for the mines in the environment.

### **3. Red Forces Model**

The assumptions of the red forces model result in consistent or similar results between the scenario runs, so not including these inputs and variables will have minimal impact on the run's results. For real-world representation, the threat tactics are limited for testing since the only threats designed against in the operating area are the mines. This assumption in the composition of the red forces limits the offensive and defensive postures against further threat implications, preventing a full scope comparison of the neutralization systems and associated platforms. The model is limited to the mine types outlined in Chapter III, though this is mitigated by using mine types that occupy all areas of the three-dimensional minefield and utilizing general mine neutralization tactics for time delays vice specific depictions of neutralization technics. As with the environment model, the red forces model only provided one picture of the mine's composition to the blue forces model. This architecture still enables consistent and comparable results between the configurations and parameter permutation runs as well as preventing excessive time requirements to complete all the designated simulation runs, though the same limitation is present by restricting the number of individual mine neutralization attacks. To mitigate this risk, the resulting minefield from the red forces model was built to exhibit various positions and configurations to test all the combinations for the blue forces model to evaluate.

### **4. Blue Forces Model**

The assumptions of the blue forces model result in consistent or similar results between the scenario runs, so including these inputs and variables will have minimal impact on the run's results. While the model neutralizes mines in a set pattern to address the closest mines with the highest probability of detection over established sectors of the minefield, the simulation logic is not a perfect simulation of the best order of neutralizing the known mines compared to human logic and deductive reasoning skills. The suboptimal neutralization route of the platforms will create increased mission time due to "doubling back" for mines not addressed as a priority while closer by the platform and neutralization systems. This assumption will result in increased transit times, though this



will have minimal impact to the overall mission time due to the speed of the platforms and the extensive time required to conduct the neutralization portions of the mission as well as increasing the transit distances evenly for all the mines in the same configuration models. The movements for the platforms and neutralization systems did not have fully realistic motions, since the systems performed immediate turns in response to required heading changes in the blue forces model. For evaluation of detected echo returns, the mine-like and non mine-like clutter returns were evaluated for their probability to be misidentified as actual mines, though the reverse was not true. The mines that were detected did not have a probability to be identified as a different echo return, but this assumption was not included in the design as a result of having the locations known for each mine, enabling direct comparison to mines that were relocated by the platforms. During these detections, the  $P_d$  was determined based on logarithmic functions with the range between the sonar systems and echo returns. This would indicate that the probability to detect was solely dependent on range separation, which is not true in the real world sonar applications. However, this is a valid assumption for modeling since these  $P_d$  equations enabled a consistent comparison between the scenarios, while the sonar return characteristics were outside the scope of this project. Additionally, the runs in each configuration with each performance parameter permutation are unique to set platform and neutralization system pairings. There were no mixed platform and neutralization system capabilities compared with multiple platform configurations. A limitation specific to the MCM ship is that the MCM platform performs the localization through neutralization functions of the mine neutralization mission in conjunction with the detection and identification functions, so the configuration using mines with known locations is not a true representation of the expected mission tactics of the MCM ship. However, this was determined to be the best representation of the MCM mission to maintain comparability to the other platforms that will execute the neutralization portion of the mines neutralization mission separately then the detection portion. As part of the time-step architecture of the blue forces conducting the mine neutralization tactics, the time to recover neutralization systems was assumed to be the same as the recovery time of the same neutralization system. Additionally, the time to attack for the neutralization

systems was assumed to be constant for all mine types and locations and from all neutralization systems. The time required to resupply was also assumed to be constant for all platforms and neutralization systems.

## **H. SIMULATION RUNS**

For executing the simulation runs, each aspect of the model was run during the simulations. As discussed above, a single run was conducted for the environment and red forces models. For the blue forces model, simulation runs were conducted for the five platform and neutralization system scenarios, the three blue force configuration models, and all 243 performance parameter permutations of the simulation variable inputs, resulting in 3,645 individual blue forces model runs. Depictions of the motion for the platforms and neutralization systems are displayed for Blue Forces Configurations 1, 2, and 3 in Figures 25, 26, and 27, respectively. The depictions of the motion for different platforms and neutralization systems will be distinctive by extending the separation between time-steps for faster platforms and return transits to the starting point for platforms that require resupplies of expenditures for their respective neutralization systems, but the general path of the platforms and neutralization systems will be the same as the figures below. The specific entries collected during every time delta through the blue forces model are:

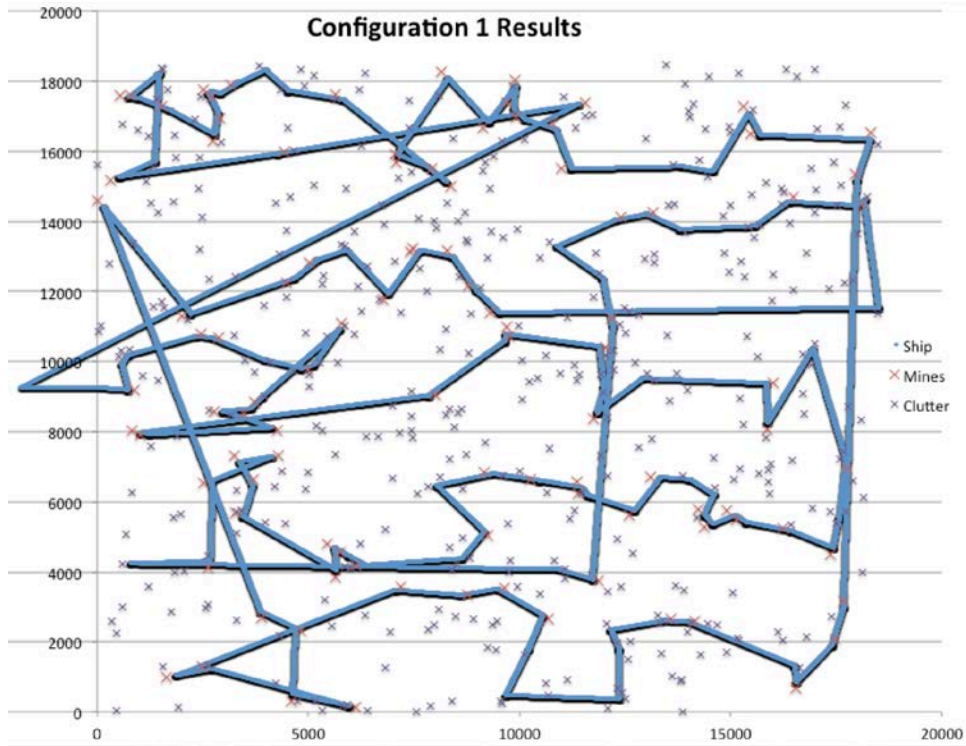


Figure 25. Blue Forces Configuration 1 Results

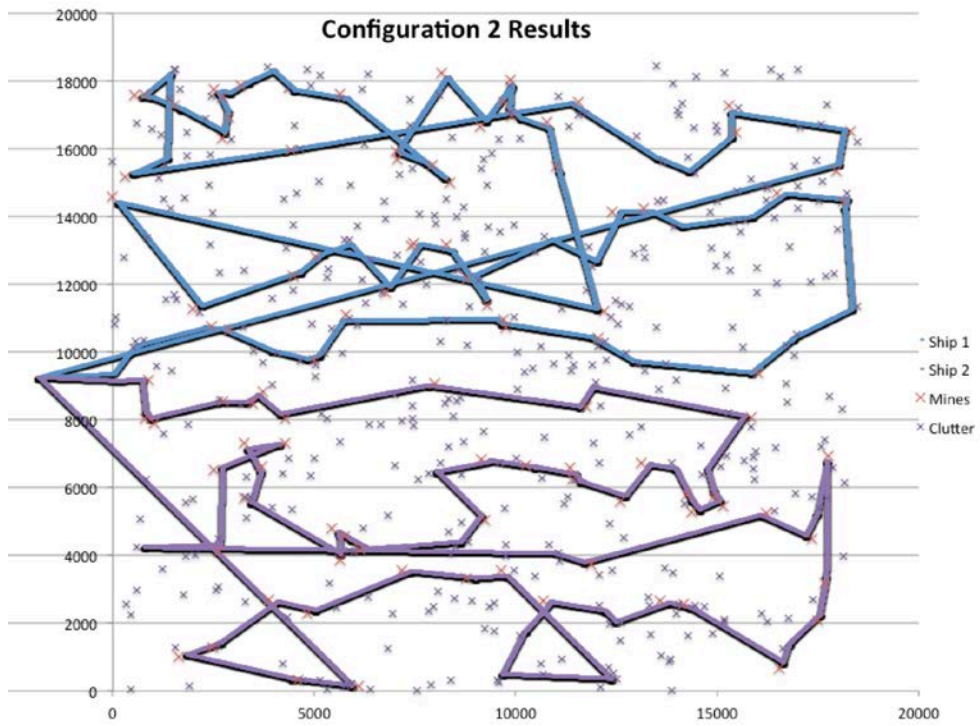


Figure 26. Blue Forces Configuration 2 Results

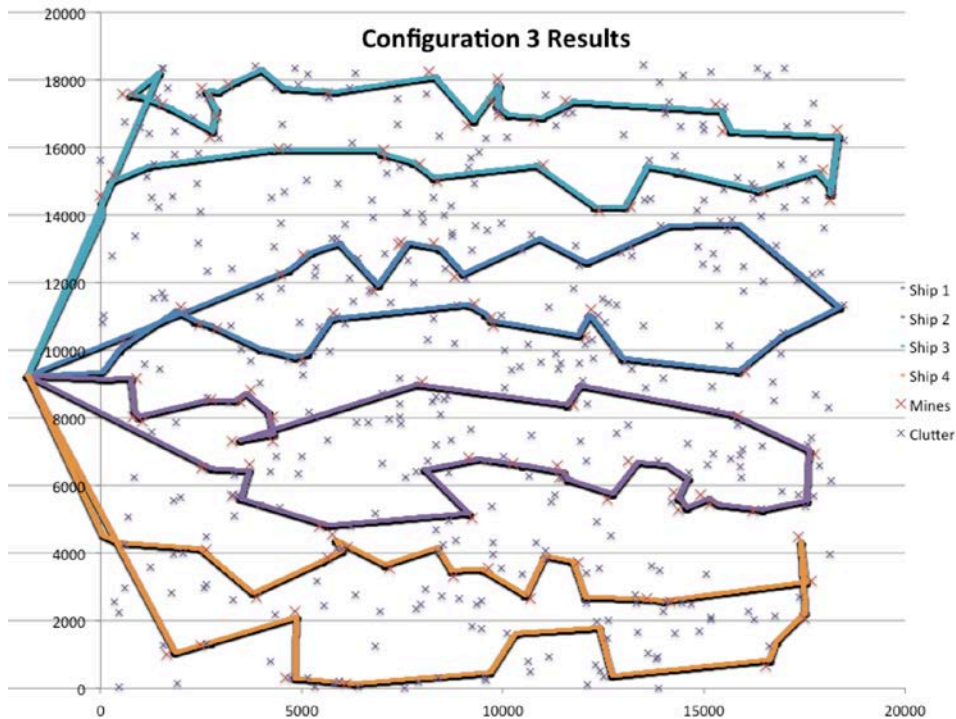


Figure 27. Blue Forces Configuration 3 Results

## I. VERIFICATION AND VALIDATION

### 1. Verification

The model was designed through an incremental and iterative process that resulted in the combination of various model components. Once the models were combined for a complete run-through of each scenario, the test outputs were verified for accuracy of the model's functionality and the analysis outputs were mathematically evaluated for approximate accuracy to expected system responses. These outputs were adjusted within the parameters of the simulation variables to verify the system response through various configurations to ensure model accuracy and adherence to design requirements prior to data collection.

## **2. Validation**

The inputs for the model were validated as acceptably representative of the stakeholder needs, providing outputs that corresponded to approximate real world system performance designs. Since the performance parameters and system configurations were limited to unclassified metrics as inputs for the model, the M&S results could only be evaluated for generalized expectations for performance parameters and system performance in established conditions. However, the model is designed to apply more accurate data inputs for these conditions in a classified setting to provide more highly tuned system responses.

## **J. CONCLUSION**

The M&S Python files provided an adequate model for the designed mission, slightly hindered by multiple assumptions and limitations that had little to no impact on the simulations' results as well as restrictions concerning system classifications, and successfully provided the appropriate data for further analysis with respect to the problem statement. The data analysis of the M&S run results is detailed in Chapter VIII.

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## VIII. DATA ANALYSIS

### A. OVERVIEW

Upon conclusion of model development and execution, the next step in this study was to conduct an analysis of the simulation results. Data analysis was conducted in accordance with the research questions outlined in Chapter I E:

What configurations, using current neutralization systems and platforms, are most effective (fastest) in clearing a minefield?

What configurations, using current and / or proposed neutralization systems and platforms, are most effective (fastest) in clearing a minefield?

What individual platform or neutralization system performance parameters (i.e., range, speed, probability of kill) have the greatest impact on the efficacy of current or proposed operational scenarios?

To answer these questions, an analysis was conducted by model scenario, model configuration, and individual performance parameters.

### B. MODEL VARIABLES

To complete this analysis, first, the most relevant variables with the highest likelihood of mission impact were identified as well as those that were most likely to influence the CONOPS described in Chapter VI. Neutralizer performance was measured via three dependent variables:

Mission Time (overall time elapsed for full minefield clearance of all mines). A low Mission Time is preferred.

Weapon Expenditure (neutralizers required to conduct full minefield clearance including failed attempts). A low Weapon Expenditure is preferred.

Mission Effectiveness (amount of neutralizers expended versus number of mines in the field). A Mission Effectiveness equaling or approaching a value of one is preferred; this equates to a one-for-one ratio of neutralizers used per mine.

For this analysis, Mission Time and Mission Effectiveness will represent the focus of analysis. Weapon Expenditure, with its inclusion in Mission Effectiveness, is accepted to represent Mission Effectiveness calculations. These dependent variables were chosen to establish a baseline for each neutralizer, to establish a means of differentiation when

multiple configurations (parallel operations of deployment platforms) are used, and to best report the efficacy of each neutralization system. Mission Time relates most easily to scenario and configuration changes while Mission Effectiveness, with its ability to show how the system performs over multiple mine clearances, best describes the neutralizer's efficacy for an entire minefield.

Multiple independent variables were tested and measured for their impact on neutralizer performance as outlined in Chapter II, and Tables 2–5 include the range of values used during model runs. Significant variables from these model runs included:

- Neutralizer Speed
- Platform Speed
- Probability of Malfunction (pM)
- Probability of Misidentification (pMID)
- Time to Deploy/Recover the Neutralizer (tD/R)

### **C. SCENARIO AND CONFIGURATION EFFICACY**

An analysis of each scenario and each configuration was conducted, resulting in fifteen unique configurations with 243 model runs within each. Each independent variable was modified from a “high” to “medium” to “low” estimate to represent a range of possible values. This resulted in a total number of 3,645 runs with unique outputs.

A comparison was conducted between each scenario and configuration, with results shown in Table 11, and illustrated in Figure 28. This data set represents each scenario, defined by its specific marker, and includes the three associated configurations. This table shows Mission Time in hours and Mission Effectiveness as a ratio (mines / weapon expenditure).



Table 11. Neutralizer Performance

System	Configuration 1 1 Neutralization Platform		Configuration 2 2 Neutralization Platforms		Configuration 3 4 Neutralization Platforms	
	Mission Time	Mission Effectiveness	Mission Time	Mission Effectiveness	Mission Time	Mission Effectiveness
SLQ-48	98.27	0.671	52.68	0.673	31.41	0.672
SLQ-60(1)	78.58	0.775	42.24	0.772	25.21	0.776
SLQ-60(2)	88.53	0.773	47.52	0.778	28.48	0.776
AMNS	65.77	0.915	34.92	0.914	20.71	0.912
Barracuda	52.97	0.958	28.02	0.959	16.49	0.957

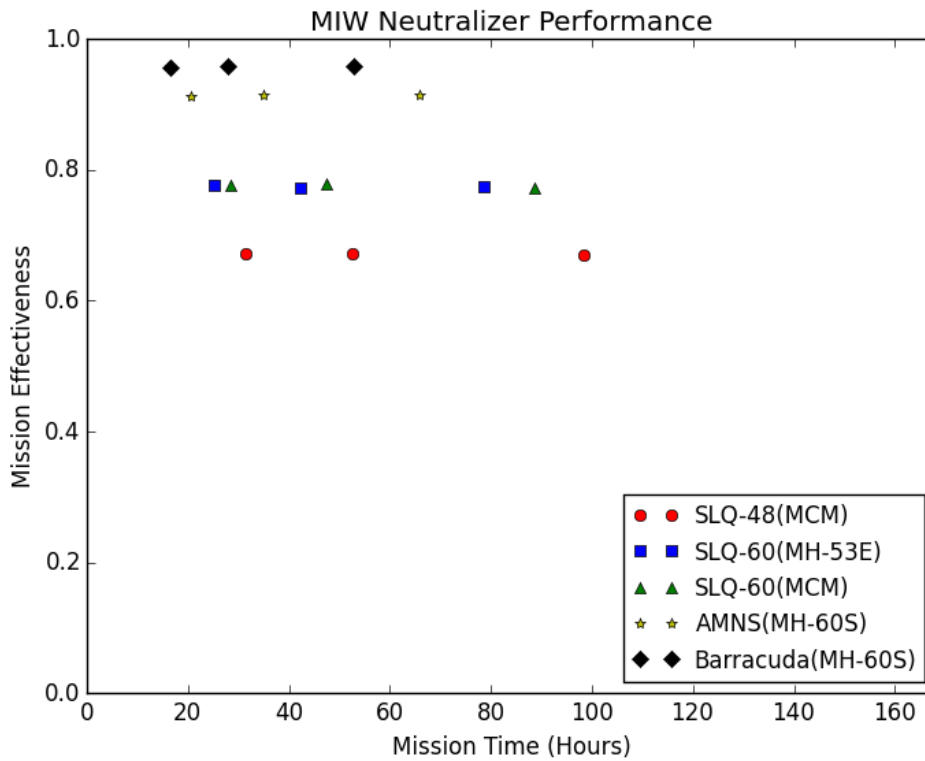


Figure 28. MIW Neutralizer Performance

These scenario results show a significant improvement from legacy systems, such as the SLQ-48 deployed from an MCM Avenger, to the proposed systems in development for MIW. While not explicitly stated, each configuration improvement also results in a Mission Time improvement, though possibly with diminishing results as multiple systems are brought into action. Though no significant change in Mission Effectiveness was anticipated between configuration changes, this hypothesis is now validated. Multiple platforms deploying neutralizers in the same operational area have a positive impact of the time required to clear a minefield, but do not change the effectiveness of the overall system.

It should also be noted that not only does the proposed “Barracuda” neutralizer appear to have the most impressive results of all neutralizers tested, but the neutralizers deployed from aerial assets appear to have better results on average. Correlation does not imply causation, though, and this is likely to be the result of increased performance parameters of the neutralizers themselves rather than solely the platforms they are deployed from.

#### **D. ANALYSIS OF PERFORMANCE PARAMETERS**

Performance parameter analysis consisted of regression testing between multiple independent variables and their associated dependent variable. This analysis was conducted within the Python open-source language and database management was conducted in Microsoft Excel. Within Python, several libraries were utilized including “pandas,” “numpy,” “statsmodels,” “openpyxl,” and “matplotlib.” The following interactive charts were generated using these products and present two independent variables, one dependent variable, a hyperplane representing the best computed linear representation between the variables using regression and Ordinary Least Squares (OLS), and a representation of which individual runs resulted in an above-average or below-average dependent variable result (data points are white for above and black for below). The hyperplane is color-graduated to represent the highest and lowest averaged results of the dependent variable.

## **1. Mission Time**

Figures 29–31 show similar planes used in each configuration – – the primary change is a near-linear drop in Mission Time when using multiple neutralizers and platforms in parallel; as more neutralizers are put into use and the minefield is divided into equal sections, Mission Time decreases. This shows that the positive relationship identified earlier between Mission Time and Configuration approaches a linear representation. While Figure 30 shows a significantly poor coefficient of determination (R squared and adjusted R squared), this implies that the relation of Neutralizer Speed and Platform Speed to Mission Time may be quadratic and not linear. The implications of configuration changes remain valid; however, it is noted that continuing to increase the number of parallel neutralizers in use in a minefield will not gain a perfectly linear drop in Mission Time. Other factors, such as human interaction and the number of command and control links available are likely to limit and degrade Mission Time. This is a known and accepted limitation of this model that presents an opportunity for further study. This analysis does not mean to imply that a categorical change in configuration will always result in a linear decrease in time, only that for the configurations listed in Chapter VII, Mission Time decreased when multiple neutralizers or platforms were added in parallel.

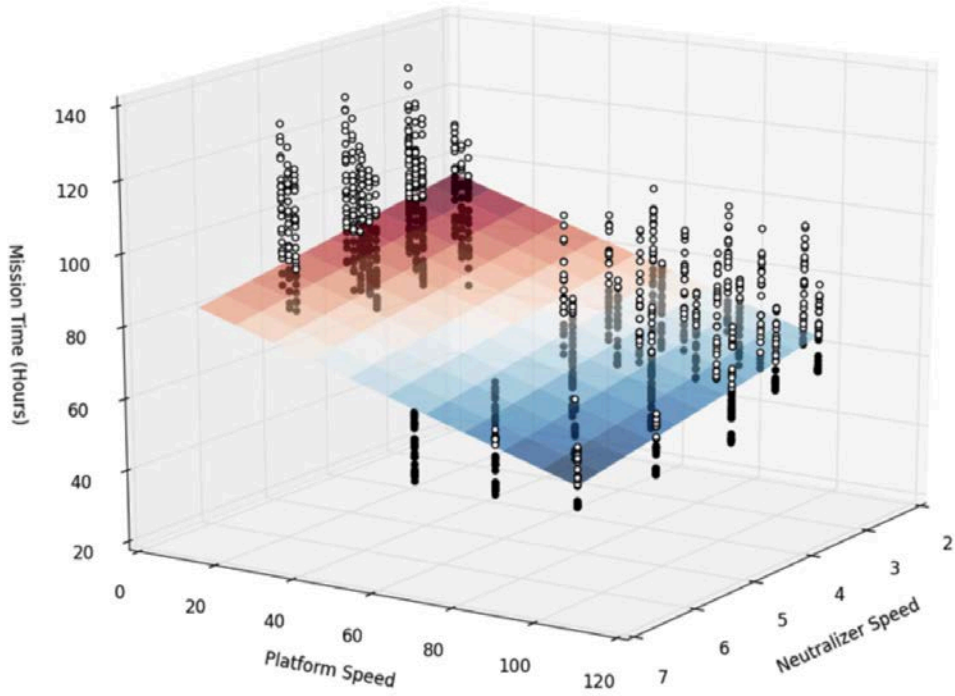


Figure 29. Speed vs. Time (Configuration 1)

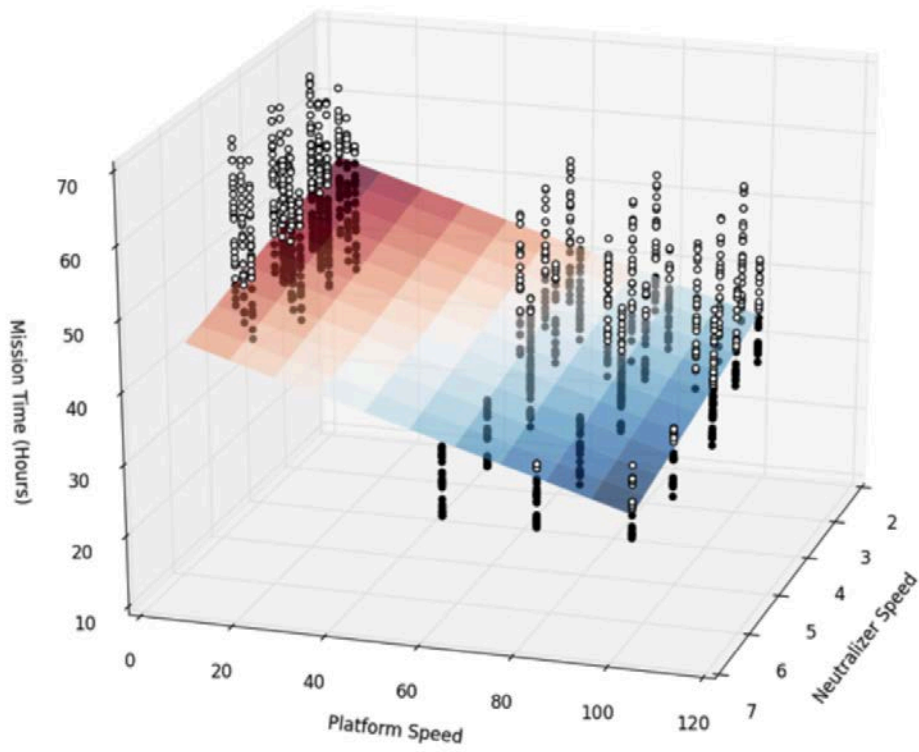


Figure 30. Speed vs. Time (Configuration 2)

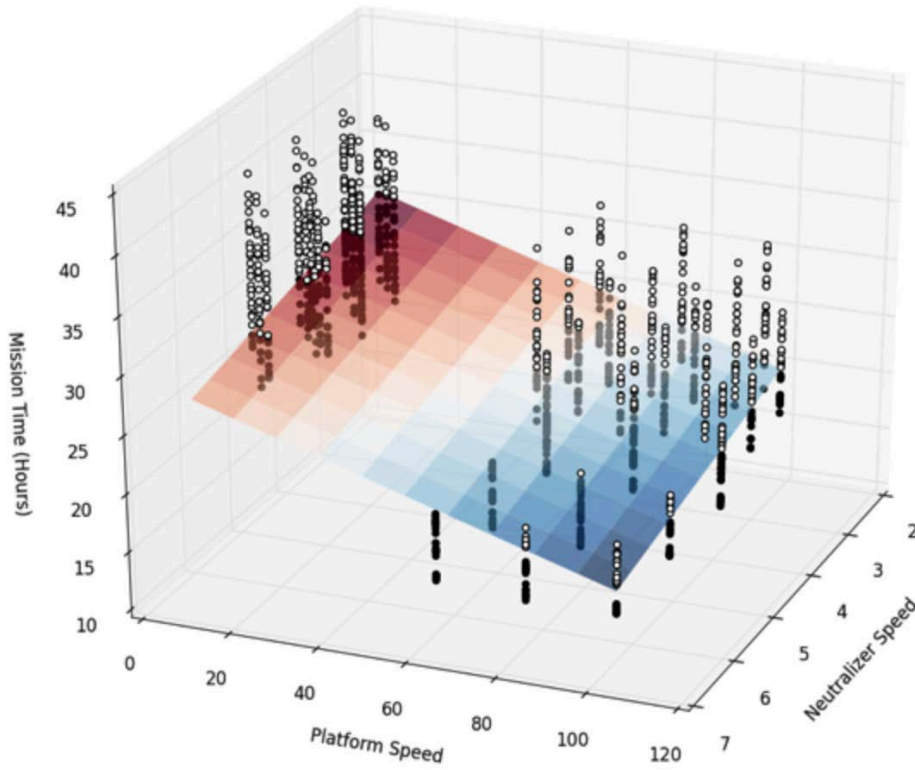


Figure 31. Speed vs. Time (Configuration 3)

```

=====
                        OLS Regression Results
=====
Dep. Variable:          MT1C      R-squared:                0.530
Model:                 OLS       Adj. R-squared:           0.529
Method:                Least Squares   F-statistic:              682.3
Date:                  Sat, 15 Oct 2016   Prob (F-statistic):       3.21e-199
Time:                  14:01:41         Log-Likelihood:           -4838.8
No. Observations:      1215          AIC:                      9684.
Df Residuals:          1212          BIC:                      9699.
Df Model:               2
Covariance Type:      nonrobust
=====
               coef      std err          t      P>|t|      [95.0% Conf. Int.]
-----
Intercept    107.3929      1.341      80.108      0.000      104.763      110.023
NS           -3.5873      0.331     -10.837      0.000       -4.237      -2.938
PS           -0.3428      0.010     -34.336      0.000       -0.362      -0.323
=====
Omnibus:                 32.449   Durbin-Watson:           1.492
Prob(Omnibus):           0.000   Jarque-Bera (JB):        33.196
Skew:                    0.382   Prob(JB):                 6.19e-08
Kurtosis:                 2.734   Cond. No.                  231.
=====

Warnings:
[1] Standard Errors assume that the covariance matrix of the errors is correctly
specified.

```

Figure 32. Impacts upon Mission Time (Regression Results)

This proof coupled with the results from Figure 28 directed future analysis to be limited to single configurations with the assumption that Mission Time would be decreased in a near-linear fashion with further configurations (within the mathematical limitations of this model previously mentioned). No significant change to Mission Effectiveness was proved (and therefore not documented in this analysis) by using multiple configurations. Further charts will focus primarily on single configuration runs.

Neutralizer Speed, Platform Speed, tD/R, and pMID were all evaluated against Mission Time. While Neutralizer Speed had the least impact on overall Mission Time, Platform Speed, tD/R, and pMID had similar effects, though pMID impacted Mission Time slightly more than tD/R, and both had a slightly greater effect than Platform Speed (Figures 33–35).

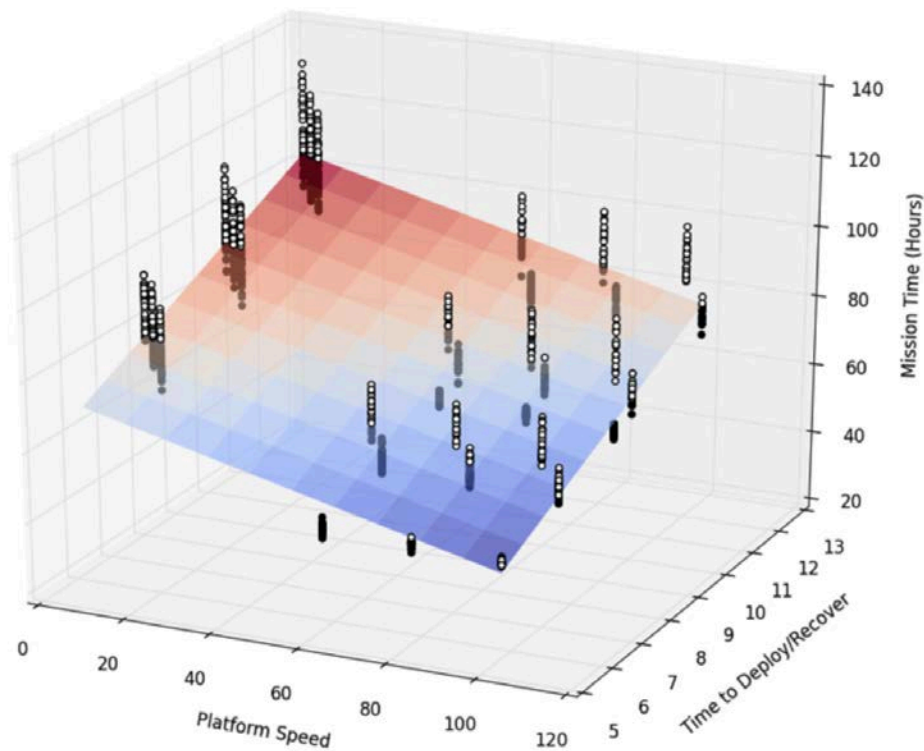


Figure 33. Impacts upon Mission Time (1)

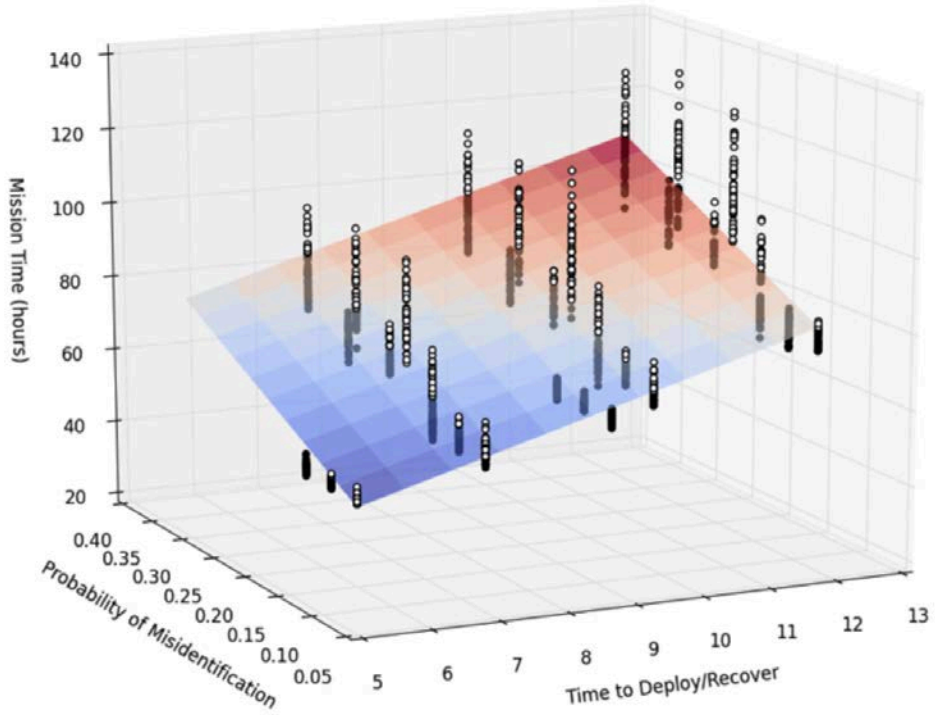


Figure 34. Impacts upon Mission Time (2)

```

=====
                        OLS Regression Results
=====
Dep. Variable:          MT1C      R-squared:                0.766
Model:                 OLS       Adj. R-squared:           0.766
Method:                Least Squares   F-statistic:              1985.
Date:                  Sat, 15 Oct 2016   Prob (F-statistic):       0.00
Time:                  15:22:07         Log-Likelihood:           -4414.3
No. Observations:      1215          AIC:                      8835.
Df Residuals:          1212          BIC:                      8850.
Df Model:               2
Covariance Type:      nonrobust
=====
                coef    std err          t      P>|t|     [95.0% Conf. Int.]
-----+-----+-----+-----+-----+-----
Intercept         1.0228      1.267         0.807     0.420     -1.463    3.508
tDtr              5.0216      0.123       40.839     0.000     4.780    5.263
pMID             122.1464     3.222       37.916     0.000    115.826  128.467
=====
Omnibus:            133.233   Durbin-Watson:           0.621
Prob(Omnibus):      0.000   Jarque-Bera (JB):        181.616
Skew:               0.851   Prob(JB):                 3.65e-40
Kurtosis:           3.832   Cond. No.                  122.
=====

Warnings:
[1] Standard Errors assume that the covariance matrix of the errors is correctly
specified.

```

Figure 35. Impacts upon Mission Time (Regression Results)

## 2. Mission Effectiveness

Probability of Malfunction (pM) had the most substantial impact on Mission Effectiveness. A polynomial regression analysis showed a strong correlation between probability of malfunction and the mission effectiveness (Figure 36). The coefficient of determination suggests that both linear and quadratic models provide an acceptable fit, but a visual analysis of the residual plots shows the quadratic polynomial as the best fit.

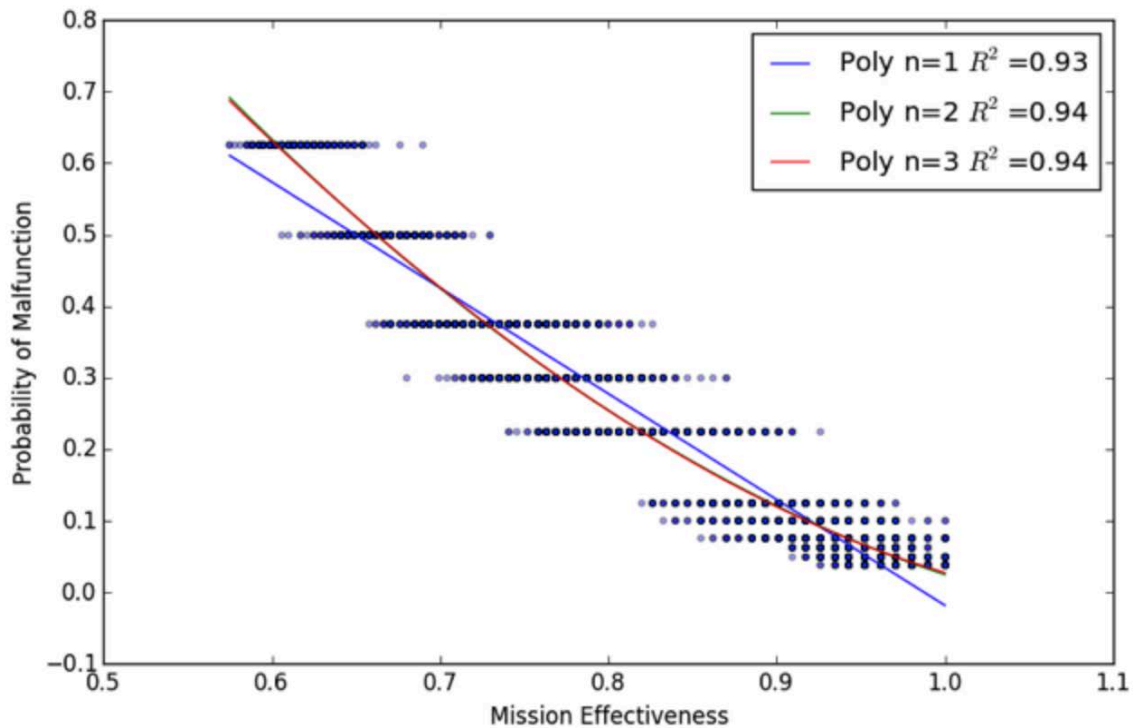


Figure 36. Polynomial Regression of Mission Effectiveness

## 3. Overall Mission Parameters

An overall relationship between the primary independent variables, pM and pMID, and the combined dependent variables, Mission Effectiveness / Time, showed a higher effect from pM – as pM decreases, Mission Effectiveness / Time increases substantially. The equivalent type of effect from pMID is significantly less substantial, as seen by the slopes indicated in Figure 37.



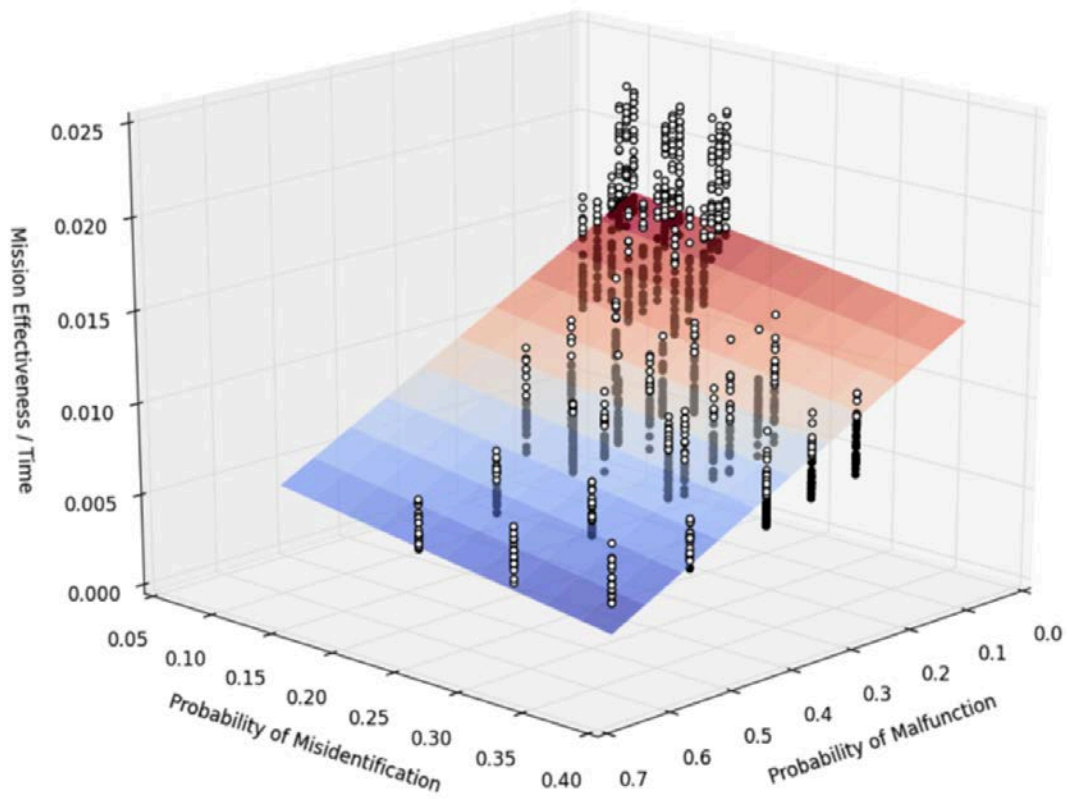


Figure 37. Overall Performance Effects

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## **IX. CONCLUSIONS**

### **A. SUMMARY**

As stated in Chapter I, this study, as a continuation of the MIW 2014 and 2015 capstone reports, was intended to: analyze the efficacy of current and future MNS, determine relevant performance parameters, and enhance and demonstrate the Systems Engineering methodology skills developed by the study team. These goals have been successfully accomplished through the design of experiments (DOE) detailed in this report and the engineering and analysis methods used to develop and test them.

A systems engineering process was employed that began with the definition of high-level requirements based on stakeholder and SMEs input, as well as the prior NPS MIW studies (Cohort 311–132M, 2014 and Cohort 311–132O, 2015). The process utilized a tailored “Vee” allowing for simultaneous and iterative, decomposition of detailed requirements across all of the three analysis domains of environment, platform and neutralizer performance, and operation configuration definition. The detailed requirements derived were the basis for the Python simulation model that allowed for experimental efficacy comparison across a range of performance and neutralization operational configurations.

The use of Python and associated module libraries as a modeling and data analysis tool provided an adequate basis for the DOE and subsequent analysis, within the limitations outlined in Chapter VI.

### **B. CAPSTONE CONCLUSIONS**

#### **1. Neutralizer and Platform Performance**

Overall, the performance of the “Improved Mine Neutralization System” or “Barracuda” currently in development presents an increase in capability over legacy systems and, if this neutralizer and its associated system components perform to the expectations set in this capstone model, it will be the preferred MNS for warfighter use.

In addition, model analysis shows a significant performance increase from aerial-deployed neutralizers and neutralizers deployed simultaneously in parallel configurations due to the decreased mission time required to clear a given minefield. This report suggests that, when possible, mine neutralization should be conducted in a parallel configuration from multiple platforms with the most capable neutralizer available. It is accepted, however, that operational limits may present an obstacle to the use of multiple MIW platforms simultaneously, and the increased presence of platforms may provide diminishing results as the number is increased. To this point, the following measures of effectiveness are presented as focus points for neutralization developers.

## **2. Measures of Effectiveness**

With regards to Mission Time, the Probability of Misidentification (pMID) played the largest role in influencing overall time required to clear a minefield. When possible, this neutralizer attribute should be improved upon in future development of neutralizers. While in operational use, the pMID cannot be modified (with the exception of limiting mine-like returns while in the classification and localization phases of mine hunting), but the time required to deploy and recover neutralizers (tD/tR) may be improved using TTPs as well as increased training to neutralizer operators. This second attribute (tD/tR) presented the next best option for Mission Time improvement.

Mission Effectiveness, as defined by weapon expenditure compared to mines neutralized, was most impacted by the Probability of Malfunction, though the DOE used in this report is somewhat limited in input variables that had a significant influence upon Mission Effectiveness. The expansion of these variables is presented in the recommendations section below.

## **3. Recommendations**

Recommendations for further study and improvement include the expansion of this model and its associated input variables to account for more MOEs that can be specified by future MNS acquisitions teams. To accurately account for the MOEs used in this model, it is recommended that the input variables used to represent neutralizer and platform capabilities be set as constants representing the actual capabilities of the

neutralization systems reviewed in this report. This information and the associated result would, however, require a classified environment.

For current MIW operations, it is recommended to update the proper TTPs for the use of parallel platforms and neutralizers, include the use of aerial platforms, and begin reviewing deployment and recovery procedures for neutralizers from both surface and aerial platforms. These measures present the most immediate benefit to the warfighter without significant modification to existing platforms and neutralizers.

Further study and development of the MIW field represents a significant step in protecting the warfighter from an effective and prolific threat that is present today. The benefits of this and future studies far outweigh the potential consequences of allowing this field to be dominated by adversaries who have access to and have demonstrated use of MIW.

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## **APPENDIX. MODELING AND SIMULATION FILES**

As discussed in Chapter VII, Python was used as the M&S tool of choice for this capstone project. For access to the configuration scenarios discussed in Chapter VII, please contact one of the following personnel:

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