



# **NAVAL POSTGRADUATE SCHOOL**

**MONTEREY, CALIFORNIA**

## **SYSTEMS ENGINEERING CAPSTONE REPORT**

**DEVELOPING THE MINE OF THE FUTURE —  
THE MADMAN (MARITIME AREA DENIAL MINE  
WITH AUTONOMOUS NAVIGATION)**

by

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June 2018

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| <b>REPORT DOCUMENTATION PAGE</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                                                         |                                                                                | <i>Form Approved OMB<br/>No. 0704-0188</i>                      |  |
| Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                                                         |                                                                                |                                                                 |  |
| <b>1. AGENCY USE ONLY<br/>(Leave blank)</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | <b>2. REPORT DATE</b><br>June 2018                                      | <b>3. REPORT TYPE AND DATES COVERED</b><br>Systems Engineering Capstone Report |                                                                 |  |
| <b>4. TITLE AND SUBTITLE</b><br>DEVELOPING THE MINE OF THE FUTURE — THE MADMAN<br>(MARITIME AREA DENIAL MINE WITH AUTONOMOUS NAVIGATION)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                                                         |                                                                                | <b>5. FUNDING NUMBERS</b>                                       |  |
| <b>6. AUTHOR(S)</b> Jose E. Balderrama, Alan Crocker, Mia Moore,<br>Stephen T. Pease, and Vincent J. Ragona                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                                                                         |                                                                                |                                                                 |  |
| <b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b><br>Naval Postgraduate School<br>Monterey, CA 93943-5000                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                         |                                                                                | <b>8. PERFORMING<br/>ORGANIZATION REPORT<br/>NUMBER</b>         |  |
| <b>9. SPONSORING / MONITORING AGENCY NAME(S) AND<br/>ADDRESS(ES)</b><br>N/A                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                                                                         |                                                                                | <b>10. SPONSORING /<br/>MONITORING AGENCY<br/>REPORT NUMBER</b> |  |
| <b>11. SUPPLEMENTARY NOTES</b> The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                         |                                                                                |                                                                 |  |
| <b>12a. DISTRIBUTION / AVAILABILITY STATEMENT</b><br>Approved for public release. Distribution is unlimited.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                                                         |                                                                                | <b>12b. DISTRIBUTION CODE</b><br>A                              |  |
| <b>13. ABSTRACT (maximum 200 words)</b><br><p>The Maritime Area Denial Mine with Autonomous Navigation (MADMAN) project provides a means for asserting maritime dominance through integration of intelligence into mines. This project identifies a path toward reinvigorating mine warfare innovation to develop the mine of the future, MADMAN. Modeling and simulation tools reveal that the highest mission success probabilities support an unmanned underwater vehicle (UUV) option. By integrating current, available systems, a resulting system of systems provides a cost-effective means to develop a mine that is capable of autonomously transiting to a location, arming itself, performing missions, and increasing personnel safety. Using a capability engineering approach, this study identifies an overall target probability of success for the system of systems. This overall success probability decomposes the individual systems and highlights their level of impact on overall success. Analyzing these impacts allows tailoring of each system to provide improved mining and cost savings while meeting project requirements. Resulting collaboration between UUV designers and military engineers ensures a modern arsenal for a modern world.</p> |                                                                         |                                                                                |                                                                 |  |
| <b>14. SUBJECT TERMS</b><br>unmanned undersea vehicle, countermeasures, mine laying, mine placement, UUV, autonomous, MADMAN, mine warfare, autonomous mine deployment                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                                                                         |                                                                                | <b>15. NUMBER OF<br/>PAGES</b><br>149                           |  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                                                                         |                                                                                | <b>16. PRICE CODE</b>                                           |  |
| <b>17. SECURITY<br/>CLASSIFICATION OF<br/>REPORT</b><br>Unclassified                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | <b>18. SECURITY<br/>CLASSIFICATION OF THIS<br/>PAGE</b><br>Unclassified | <b>19. SECURITY<br/>CLASSIFICATION OF<br/>ABSTRACT</b><br>Unclassified         | <b>20. LIMITATION OF<br/>ABSTRACT</b><br>UU                     |  |

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AREA DENIAL MINE WITH AUTONOMOUS NAVIGATION**

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Submitted in partial fulfillment of the  
requirements for the degrees of

**MASTER OF SCIENCE IN SYSTEMS ENGINEERING**

and

**MASTER OF SCIENCE IN ENGINEERING SYSTEMS**

from the

**NAVAL POSTGRADUATE SCHOOL  
June 2018**

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## **ABSTRACT**

The Maritime Area Denial Mine with Autonomous Navigation (MADMAN) project provides a means for asserting maritime dominance through integration of intelligence into mines. This project identifies a path toward reinvigorating mine warfare innovation to develop the mine of the future, MADMAN. Modeling and simulation tools reveal that the highest mission success probabilities support an unmanned underwater vehicle (UUV) option. By integrating current, available systems, a resulting system of systems provides a cost-effective means to develop a mine that is capable of autonomously transiting to a location, arming itself, performing missions, and increasing personnel safety. Using a capability engineering approach, this study identifies an overall target probability of success for the system of systems. This overall success probability decomposes the individual systems and highlights their level of impact on overall success. Analyzing these impacts allows tailoring of each system to provide improved mining and cost savings while meeting project requirements. Resulting collaboration between UUV designers and military engineers ensures a modern arsenal for a modern world.

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## LIST OF ACRONYMS AND ABBREVIATIONS

|                                    |                                                                     |
|------------------------------------|---------------------------------------------------------------------|
| A2AD                               | anti-access/area denial                                             |
| ACTUV                              | Anti-Submarine Warfare Continuous Trail Unmanned Vessel             |
| ADCAP                              | Advanced Capability                                                 |
| ANDES                              | Ambient Noise Directionality Estimation System                      |
| ASW                                | anti-submarine warfare                                              |
| CBA                                | <i>Capabilities-Based Assessment</i>                                |
| CRUSER                             | Consortium for Robotics and Unmanned Systems Education and Research |
| DANES                              | Directional Ambient Noise Estimation System                         |
| ELF                                | extremely low frequency                                             |
| EPA                                | Environmental Protection Agency                                     |
| ESGN                               | electrostatic gyro navigation                                       |
| FFBD                               | functional flow block diagram                                       |
| GPS                                | Global Positioning System                                           |
| INS                                | inertial navigation system                                          |
| LCS                                | littoral combatant ships                                            |
| MBARI                              | Monterey Bay Aquarium Research Institute                            |
| MCM                                | mine countermeasures                                                |
| METOC                              | Meteorological and Oceanographic Community                          |
| MIW                                | mine warfare                                                        |
| MTBF                               | mean time between failure                                           |
| OV-1                               | Operational Viewpoint                                               |
| $P_{\text{anchor}}$                | Probability of successful anchoring                                 |
| $P_{\text{avoid obstacle}}$        | Probability of successful obstacle avoidance                        |
| $P_{\text{evade countermeasures}}$ | Probability of successful countermeasure evasion                    |
| $P_{\text{fault recover}}$         | Probability of successful fault recovery                            |
| $P_{\text{kill}}$                  | Probability of kill                                                 |
| $P_{\text{launch}}$                | Probability of successful launch                                    |

|            |                                              |
|------------|----------------------------------------------|
| $P_{nav}$  | Probability of successful navigation         |
| POSYDON    | Positioning System for Deep Ocean Navigation |
| $P_{prop}$ | Probability of successful propulsion         |
| RF         | radio frequency                              |
| RLGN       | ring laser gyro navigation                   |
| SLMM       | submarine-launched mobile mine               |
| SUTRS      | Ship Underwater Threat Responses System      |
| UAV        | unmanned aerial vehicle                      |
| ULRM       | Universal Launch and Recovery Module         |
| USV        | unmanned surface vehicle                     |
| UUV        | unmanned undersea vehicle                    |
| UxV        | unmanned air/surface vehicle                 |
| VLF        | very low frequency                           |

## **EXECUTIVE SUMMARY**

The United States Navy does not currently possess the capability to deploy mines from either surface ships or submarines (Truver 2015). In the past, mine warfare acquisition focused on mine countermeasures. The Navy's current use of unmanned undersea vehicles (UUVs) is limited to countermeasures and mine detection. UUVs operate in shallow waters, but their limited size likely prevents them from playing a key role in mine deployment. Current acquisition programs for fielding a mine deployable from manned vessels during armed conflict do not exist. Combatant Commanders expressed a renewed interest in a versatile and broadly applicable naval mining capability. A cornerstone of this effort must be the development of an autonomous UUV capability that provides the clandestine deployment of naval mines in response to Combatant Commanders' needs.

The purpose of this project is to develop viable system alternatives for achieving naval mine offensive capabilities. This project addresses the current gaps in the U.S. Navy's undersea offensive mining capability, and proposes an autonomous delivery system architecture to enable improved offensive mining while reducing risks associated with manual deployment. A capability-based engineering analysis process focused on the current Navy and commercial capabilities to identify gaps that prevent such an autonomous delivery capability today. Thorough investigation of existing systems and the inability of those systems to meet mission needs resulted in a set of potential system candidates and recommended technology improvements. Evaluations focused on the capabilities required to establish autonomous systems architectures for mining operations in conflicted littoral areas.

Successful conduct of effective autonomous mine warfare hinges on the accomplishment of six key objectives. The system must not only provide access to target areas, avoid detection, and fit within current naval vessels but also arm/disarm mines following operator commands. This system must also dispose mines when commanded by disabling explosives in place after verification of an environment free of commercial and civilian traffic and achieve all of these goals with a significant reduction or

elimination of risk to human life. This risk reduction comes from adding in autonomous features to the system, preventing the need for human interaction in multiple parts of the mission activity. Ultimately, the system must meet all of these goals with acceptable suitability traits, such as system reliability, operational availability, and probability of mission success. With these key objectives in mind, a system context diagram helped scope the effort while extensive research revealed existing capabilities and gaps to provide a starting point for expanding those technologies to achieve the mission.

Maritime Area Denial Mine with Autonomous Navigation (MADMAN) is a mine that exerts explosive force on adversary vehicles that enter in range of any sensors. These sensors respond to proximity, acoustic signature, or magnetic field from the adversary vehicle. With the definition of MADMAN understood, the investigation shifted to its deployment. Three alternatives appeared during the study for the deployment of MADMAN, 1) UUV, 2) Wave Glider, and 3) Aircraft. OV-1s depicted these three alternatives of how the MADMAN reaches the target location and decomposed system capabilities. The concept of operations detailed the separate phases of the operational activities within the system and potential scenarios. The four operational phases, pre-deployment phase, deployment phase, engagement phase, and post-engagement phase, demonstrated where portions of the mission begin and end while displaying which segments contain autonomous features or requirements.

The hierarchy of capabilities describing what MADMAN must do to achieve mission success provided a better system understanding and identified the operational activities supported; navigation, deactivation, monitoring, detonation, propulsion, and communication. The MADMAN capability hierarchy highlighted areas for potential leveraging of current technology. The MADMAN project focuses on the integration of already existing systems into a functional system of systems weapons, navigational, monitoring, propulsion, anchoring, communication, and autonomous systems all currently exist. The results contained in this study provided an assessment of three viable alternatives for deploying MADMAN. All three of the alternatives addressed the requirements for:

- transporting the mine, autonomy, system integration, and incorporation of mine sensors
- operational range, communication capability, position accuracy, and stealth

While all three alternatives addressed the requirements, each alternative addressed requirements at varying levels. Examining technical capability, performance, cost, and risk provided clarity and set the stage for comparing the alternatives. Simulations using Microsoft Excel in conjunction with the Real Options Valuation Risk Simulator add-in, Microsoft Visio, and SPEC Innovations Innoslate systems engineering toolkit provided success metrics for each portion of the deployment chain for each alternative, resulting in a final success likelihood of mine deployment. Initial simulation results of simulations demonstrated that the UUV option outperformed the Wave Glider and aircraft options. From a basic modeling perspective, this meant that the UUV successfully placed more mines, more frequently, with fewer failures than that of the other options. Once identified as the better option, a sensitivity analysis revealed potential probability leniency for the individual systems in the deployment chain. This leniency translates to cost savings, allowing for less restrictive system requirements on certain systems. By lowering the stringent probability requirements, systems do not need to attain unreasonable probabilities to reach a final goal. The redesign additionally resulted in the UUV performing better in simulations when faced with high-density obstacle environments.

From the resulting research performed and simulation results, the team recommended developing the MADMAN using the UUV deployment option. The team also recommended enlisting support from the designers or engineers from the company of the selected UUV model because integration of existing systems with the offensive mining aspect still needs development. Early involvement of designers and engineers ensures first-hand support and experience with any integration issues encountered throughout the lifecycle of the system. The most alluring aspect of this project is the ability to use existing autonomous systems. Where possible, improvements in launch success probability and automated obstacle avoidance capability increases MADMAN mission success probability. Once integrated, these improvements provide autonomy for

the overall system and create a safer system by removing the human element in the deployment, delivery, and placement of the mine.

In today's environment, funding is a constant concern and the MADMAN is an ideal candidate to minimize cost while maximizing operational effectiveness. Reuse affords minimal need for new design or system development. Many UUV architectures provide "plug and play" system capabilities. Many such UUV systems are already in use performing mine countermeasure activities; repurposing these UUVs as offensive, mine delivery systems requires relatively little effort.

The UUV option demonstrated a consistently high probability of mission success when deploying mines and, from a purely simulation perspective, was the clear leader. From a technical perspective, the UUV contains the systems capabilities necessary for mission success and requires minimal effort to rework into an offensive mining capability. The performance of the UUV from a transit and mission perspective requires minimal testing because the systems operate successfully in missions similar those of MADMAN. This known functionality, minimal need for testing, evaluation, and integration lowers cost significantly. Finally, from a risk perspective, these UUVs perform for long periods allowing them to travel far beyond dangerous proximity to personnel. Keeping our personnel free from harm is paramount in warfare and this alternative increases that safety by allowing personnel to initiate mine deployment from a significant distance.

Pioneering into undeveloped technologies presents risk. Throughout all military history, project development does not have a perfect success rate. This risk forces leadership and stakeholders to be more discerning in their procurement and project decisions. This project is low risk in development and cost. The components necessary to construct MADMAN exist and evaluation in this study provides the Navy alternatives for the maritime warfare.

## Reference

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## **ACKNOWLEDGMENTS**

Sincere appreciation is due to our families. Our families and loved ones provided tremendous support during this process, and without it, we could not have accomplished this. The capstone process is arduous and requires great amounts of focus, time, and critical thinking.

The patience and understanding of our colleagues and senior leaders at work has been invaluable.

The Naval Postgraduate School professors, advisors, and fellow students have guided and mentored us through this effort and deserve our gratitude. Thank you, Professor John Green and Professor Mark Rhoades, for direction, guidance, and mentorship. You have challenged us to perform above even our own expectations.

Team Stingray would also like to give special recognition for Rear Admiral (ret.) Rick Williams' thoughtful insight, expertise, and questioning nature.

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## **I. INTRODUCTION**

The United States Navy currently depends upon aircraft to deploy mines because it lacks mine delivery systems on surface ships and submarines. This dependency places U.S. Navy personnel at risk of attack when deploying mines, especially in the shallow water regions surrounding many key points of military interest. Naval mines have the ability to shape naval battle space through strategic channeling, denying passage, and disabling enemy vessels during conflict. Naval mines can also slow or completely stop movement through restricted waters or approaches to restricted land sites.

Current mine warfare (MIW) research mostly focuses on mine countermeasures (MCM). The U.S. Navy is increasing its capabilities in MCM, but the combatant commanders continue to lack the operational capability to covertly deliver and place naval mines. Examination of this capability need provides a concept for an intelligent offensive mining system. The Maritime Area Denial Mine with Autonomous Navigation, or MADMAN, is a proposed system that provides an offensive mining capability, utilizing autonomous features to complete mission objectives.

### **A. BACKGROUND**

United States Naval MIW began with the development of the drifting mine by Mr. David Bushnell. While studying at Yale, Mr. Bushnell invented the Bushnell Keg as shown in Figure 1 (Naval Mine Warfare Engineering Activity 1985). The National Research Council (2000) stated, the Bushnell Keg “consisted of a wooden keg filled with gunpowder and fitted with a primitive contact fuse.” While the Bushnell Keg was not very effective, “it provided a successful psychological deterrent to British Naval operations.”

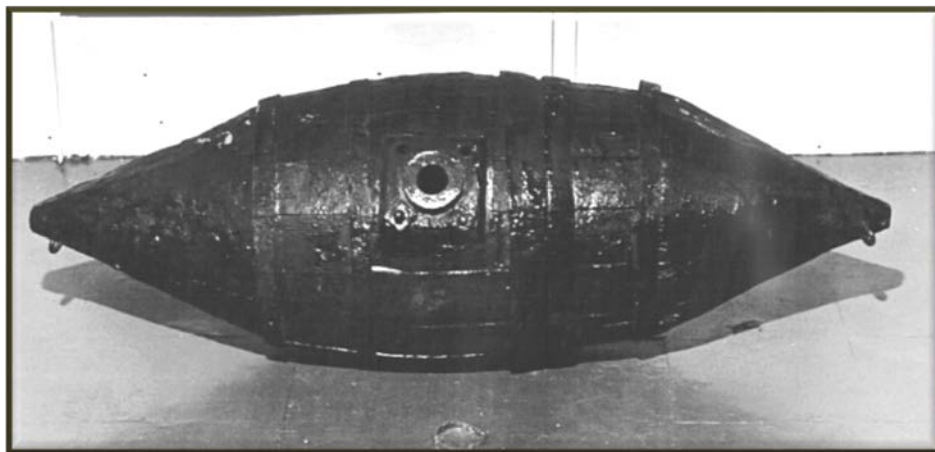


Figure 1. The Bushnell Keg. Source: Naval Mine Warfare Engineering Activity (1985).

The Bushnell Keg mine was a form of contact mine. These mines did not need human intervention to explode and ignition occurred through any form of contact, usually with a ship. On 12 December 1862, USS Cairo (Figure 2) was the first U.S. Navy ship sunk by a naval mine.

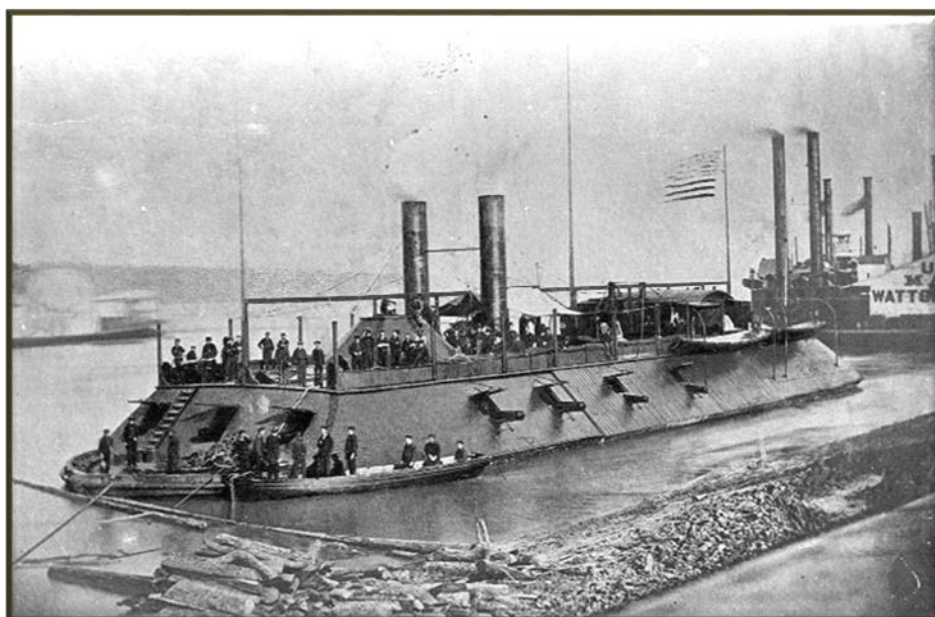


Figure 2. USS Cairo. Source: Learning Lincoln Online (2017).

The USS Cairo event intensified the psychological impact of underwater minefields. Naval forces became acutely aware of the dangers that mines presented to their ships and personnel. In times of conflict, this perceived and very real danger translated to a battlefield advantage for those laying the minefields. Retaining this advantage naturally led to improvements in mines. Design iteration over many years resulted in nine general types of mines, six depicted in Figure 3 and the explanation for the remaining three later in this chapter.

## B. NAVAL MINE TYPES

As seen in Figure 3, modern mining utilizes a broad spectrum of features.

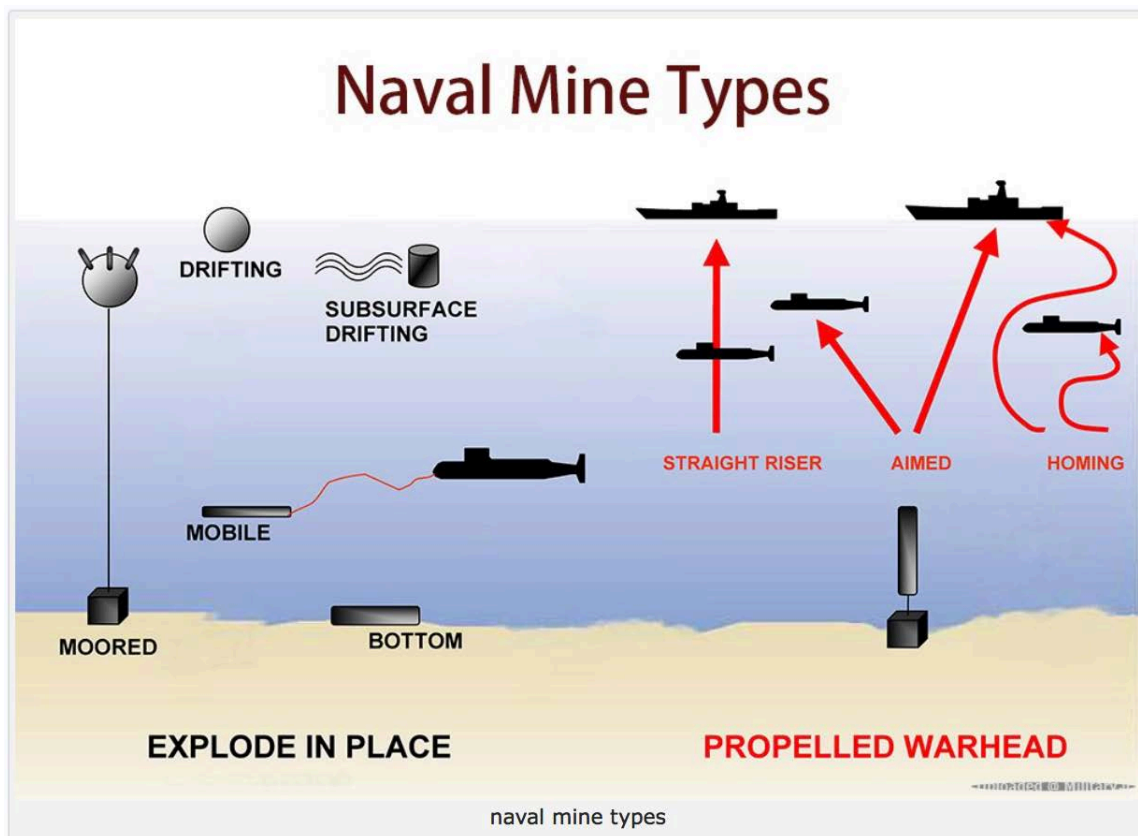


Figure 3. Naval Mine Types. Source: Picard (2017).

- **Moored Mines.** These mines anchor to the seabed. With early versions relying on contact, modern versions can use acoustic, magnetic, and pressure sensors to detect when an enemy is nearby.

- Short Wire Moored Mines. Short wire moored mines are almost identical in capability and structure to moored mines as seen in Figure 4 (Farrington 2017). They have a shorter wire to keep them well below the surface, creating a more dangerous hazard to both ships and submarines.

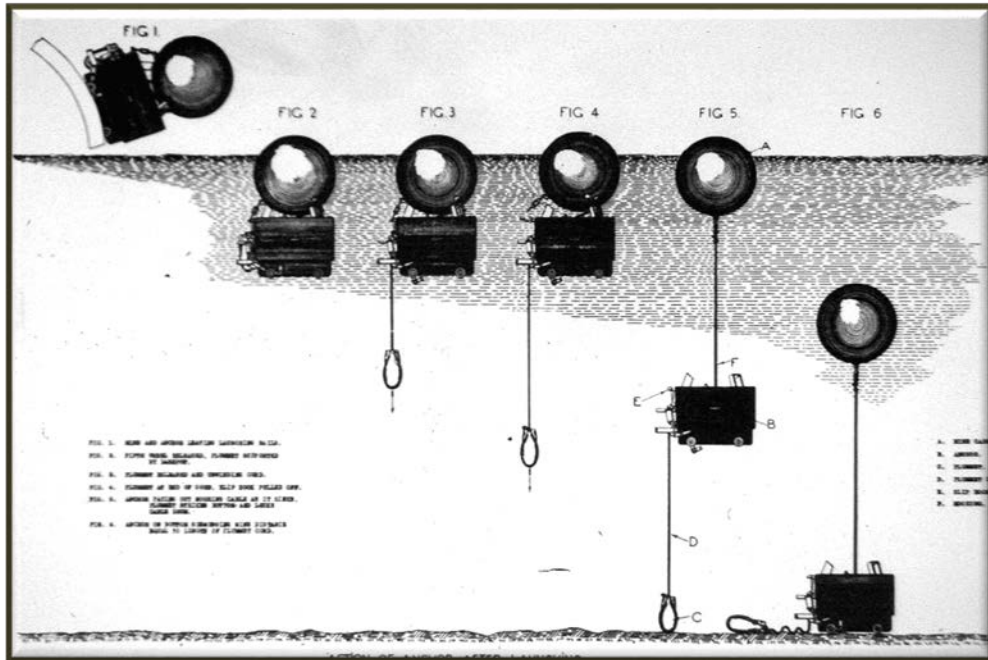


Figure 4. Short Wire Moored Mine. Source: Farrington (2017).

- Drifting Mines. As the name implies, a drifting mine is a mine without a tether and moves through the water using the sea current and wind as seen in Figure 5. The use of untethered mines is incredibly dangerous and against maritime law. Once a drifting mine deploys, it is very difficult to monitor its position. These types of mines are obsolete. These mines, used mostly during World War 1 and II, are no longer relevant. However, modern tethered mines become drifting mines if their tether breaks.

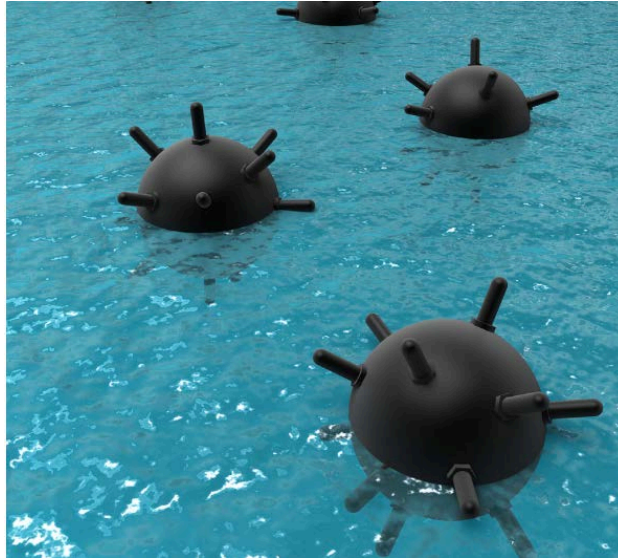


Figure 5. Drifting Mine. Source: Warfaresims.com (2016).

- Subsurface Drifting Mines. These mines are similar to drifting mines, but their negative buoyancy prevents them from reaching the surface. In dark waters, they are difficult to see, making them even more dangerous than drifting mines that lay on the surface of the water.
- Mobile Mines. A mobile mine uses a two-phase approach. In its first phase, the mobile mine uses some form of propellant to reach a location. In the second phase, the mine settles to the bottom and becomes a bottom mine.
- Bottom Mines. Bottom mines placed on the seabed lie covered in sediment, either intentionally or over time. These mines most closely resemble landmines and are more difficult to detect. These mines are most dangerous to submarines and ships transiting shallow waters.
- Rising Mines. Rising mines, similar to torpedo mines, uses buoyancy instead of propulsion to rise to a passing enemy ship or submarine.
- Torpedo Mines. Torpedo mines, as seen in Figure 6 (Proshkin 1999) are more intelligent than a standard moored mine and can directly seek out enemies. The mine is tethered, and using onboard sensors for enemy detection, propels the explosive warhead to the target.

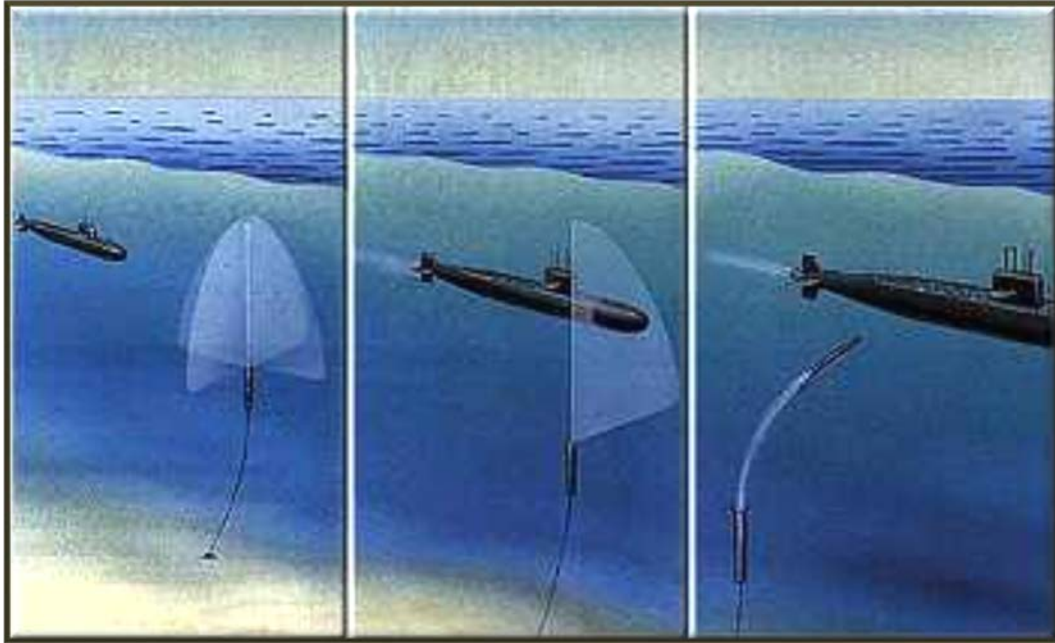


Figure 6. Torpedo Mines. Source: Proshkin (1999).

A notable mine not mentioned above is the dummy mine. Although a dummy mine does not contain explosive materials, the general mine construction remains the same. Use of dummy mines results in the expenditure of enemy resources to inspect and or remove them before allowing friendly shipping or combatants' passage due to the fear that they might be active mines. Dummy mines do not explode, but they serve as a psychological deterrent in warfare, particularly when intermingled with live mines. Mixing dummy mines with active mines limit the overall cost of laying a minefield over a sizable area. The mines listed above all require personnel involvement for deployment. Personnel involvement potentially puts human lives in direct danger during deployment. Unmanned vehicles and systems can provide a means to remove the risk.

Removing the element of risk to humans for a mining system requires the use of autonomy. Autonomy, for the purpose of this endeavor, is the ability of the system to complete the mission without assistance from external entities. Specifically, the system completes the tactical deployment mission without the need for human-in-the-loop control after deployment from a host aircraft, ship, or submersible. Studies and examples

of autonomous unmanned submarines exist, yet little effort focuses on mine delivery from an unmanned undersea vehicle (UUV).

The Navy's current use of UUVs in mine warfare is limited to countermeasures and lies in a small vehicle, the Swordfish UUV, which supports only mine detection. In the past, mine warfare acquisition focused on MCM as seen in the acquisition and development of the Bluefin-21 autonomous underwater vehicle and littoral combatant ships (LCS) MCM package. Development of the Kingfish and Knifefish UUVs addresses only countermeasures and focuses on vehicles that detect mines. Although these vehicles can operate in shallow waters, their limited size likely prevents them from playing a key role in mine deployment. Larger UUV development projects, including the large displacement UUV and extra-large UUV, present more potential for mine deployment missions but are still in early development stages.

The U.S. Navy does not currently possess the capability to deploy mines from either surface ships or submarines (Truver 2015). Current acquisition programs to develop and field a mine deployable from unmanned vessels during armed conflict do not exist at this time. Nonetheless, Combatant Commanders have expressed a renewed interest in a versatile and broadly applicable naval mining capability. A cornerstone of this effort must be the development of an autonomous UUV capability that can provide the clandestine deployment of naval mines in response to Combatant Commanders' needs.

### **C. PROJECT PURPOSE**

The purpose of this project is to define a system that increases naval mine offensive capabilities. This project addresses current capability gaps in the U.S. Navy's undersea offensive mining mission area and exploits autonomy capabilities to narrow the gap between unmanned and manned underwater warfare systems to minimize human risk through autonomy. This project examines the capabilities of such an autonomous systems architecture to perform mining operations in conflicted littoral areas. This study not only defines enhanced UUVs abilities to deliver and place naval mines in response to

combatants but also enables the integration of unmanned mining systems with other current and future unmanned systems.

With a focus on offensive mining, this project attempts to expand a collection of capabilities from currently existing systems into a complete system, comprised of a combination of features. The resulting system will provide a mine that can locate a geographical area and engage an enemy target without risking human involvement in dangerous waters.

#### **D. PROBLEM STATEMENT**

Most U.S. naval maritime mine delivery and placement efforts carry out overt operations with inherent and inordinate risk to delivery personnel and counter detection by enemy forces. UUVs may provide means of mine delivery and placement to reduce both of these risks, but no fully autonomous UUV mining capability currently exists. The emergence of this system requires a structured and technical capability assessment to develop a fully autonomous architecture.

#### **E. SCOPE**

Combatant Commander's growing interest in mining provides the foundational boundaries for this project. Stakeholder involvement with Naval Postgraduate School advisors and substantial team involvement support further refinement of boundaries. The project scope includes evolving all aspects of MIW down to focusing on autonomous mine laying capability improvement.

As Kossikoff (2011) notes, "Constructing a diagram such as the system context diagram can be invaluable in communicating the boundary of the system. The picture clearly and easily identifies the external interfaces needed" (Kossiakoff et al. 2011). This high-level view provides an overview of potential factors that are most likely to affect MADMAN, or that MADMAN is most likely to affect. As seen in Figure 7, the context diagram developed for MADMAN illustrates external factors that reside outside the scope of system development.

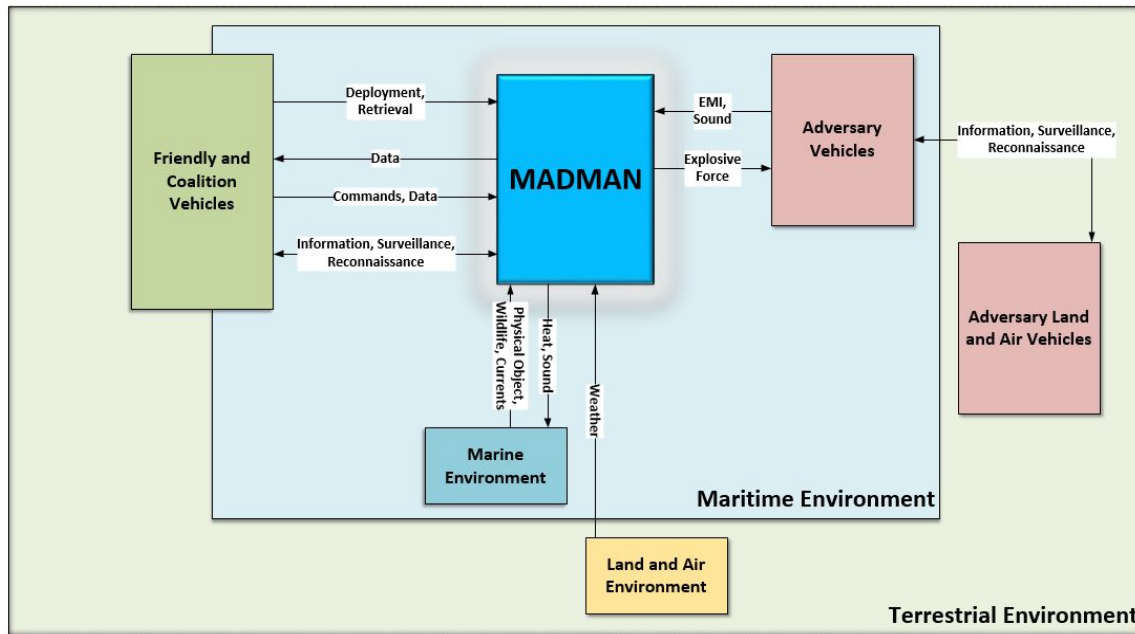


Figure 7. Layered Context Diagram.

While discussion of the specifics of the MADMAN subsystems exists in Chapter IV, the purpose of this diagram is to highlight external elements. The first noted element includes friendly and coalition land and sea vehicles that provide transport to a general area in preparation for deployment. These vehicles can exchange bidirectional data with MADMAN. When stealth is a requirement, the vehicles will likely only transmit data. The MADMAN will also interact with the marine environment and must avoid obstacles when transiting to a final anchor point. The terrestrial environment should only interact with the MADMAN before entering the water. The MADMAN is a mine, and, as expected, exerts an explosive force on adversary vehicles that enter in range of any sensors. These sensors respond to proximity, acoustic signature, or magnetic field from the adversary vehicle. Finally, though indirect, the land and air adversary vehicles affect the MADMAN by providing data to the maritime adversary vehicles to identify and neutralize the threat.

When refining the scope of the project, key questions posed include:

- What are the critical capabilities for a successful system?
- Are these capabilities an improvement on those existing?

- Are there specific geographical boundaries for the system?
- What are viable methods for MADMAN deployment?
- What level of human involvement is required and acceptable?
- What capabilities will adversaries use now or in the future to counter the system?

Research and simulation can help answer these questions and identify potential alternatives for deployment and mining. Naval Postgraduate School capstone advisors, who act as subject matter experts, also helped shape the direction and scope of the project based on this research. Examination of assumptions, limitations, and constraints of the surrounding environment and systems serve to define the system boundaries further.

## **1. Assumptions**

The items below are important assumptions the project team incorporated during the research phase. These assumptions assist in further defining system requirements and ensure the system remains within a clearly defined scope.

- Current U.S. Navy vehicles can support system delivery. The chosen delivery must be able to place the system within range of its target location. Choice of the delivery method considers covertly delivering the mine while minimizing the ability for interdiction during the delivery phase by outside forces.
- Existing technologies are sufficient to meet location determination needs. MADMAN development can leverage one of the many available location determination technologies such as Global Positioning System (GPS) electronic dead reckoning, inertial navigation systems, or augmented terrain-based navigation
- The MADMAN will autonomously navigate to its mission location by using uploaded navigational data points before deployment. In turn, the MADMAN will have a positive means of reporting its location after deployment, increasing battlespace awareness of naval forces.
- Current communications technologies can support the remote activation, deactivation, and potential recall of the MADMAN system. Deactivation of MADMAN allows U.S. forces to control the scale of warfare. This capability could enable U.S. forces to transit the mine laid areas; such transit would be a significant change from current practice.

- Present technologies can meet MADMAN's internal power and propulsion needs. Exploiting existing power and propulsion technologies is important. Leveraging demonstrated technologies (i.e., Swashplate piston engine or chemical storage system) provides a starting point that with enhancements may meet system requirements.

## **2. Limitations and Constraints**

The project team separates limitations and constraints into different concepts for this project. While similar, limitations report something that the system cannot do within the boundary of natural or manufactured laws. Constraints bound the system to increase capability only to the point of mission success. For this project and eventual mission success, it is prudent to abide by and operate within the noted limitations and constraints. A non-exhaustive list of limitations includes:

- MADMAN uses autonomous mobility only in the relative mission area.
- MADMAN cannot weigh more than the deployment system can handle.
- MADMAN does not contain nuclear devices.
- System design of MADMAN depends on available 2018 technology.

The following constraints demonstrate that the system remains bounded within the scope set through requirements interesting to stakeholders.

- MADMAN detects the location and detonates mines autonomously.
- Development meets budget limits using current equipment on naval vessels to release mines for mission activity.
- The project remains at the unclassified level.

## **F. RESEARCH**

The project team conducted extensive literature research and reviews of current efforts addressing mining technology. Results of the literature research combined with a review centered on the use of MIW technology in adversarial port areas with a focus on autonomous deployment of mines. In littoral warfare, mobility is a necessary advantage for vessels that require clear paths through sea-lanes. Offensive mining diminishes or denies these advantages to enemy forces by reducing freedom of movement and preventing enemy vessels from controlling the battlefield. When attempting to avoid a

minefield, enemies experience a delay in offensive maneuvers, providing friendly naval forces with more time to shape the battlefield and move into advantageous locations (National Research Council 2000). At this time, the greatest challenge for the U.S. Navy is the deployment of anti-access/area denial (A2AD) (Naval Research Advisory Committee 2012). This challenge validates the offensive system even further due to the area denial side effects that mining naturally exhibits.

Each year, a vast amount of documentation refines the use of mines. There was no beneficial information found regarding the use of autonomous UUV in the deployment of mines. In a previous NPS capstone project report, “Ship Underwater Threat Responses System (SUTRS): A feasibility Study of Organic Mine Point Defense,” the Dahlgren Team (2012) established UUVs as operating in a “full maritime environment inclusive of the littoral regions in the face of the anti-ship mine threat.” While focusing on filling the gaps in MCM in the U.S. Naval forces, the information from SUTRS provides the team an established baseline for incorporating an offensive autonomous mine deployment into these already existing vehicles and capabilities.

## **G. SYSTEMS ENGINEERING APPROACH**

The study implements a capability-based engineering analysis process focusing on the development and evolution of capabilities, as depicted in Figure 8. The capability-based engineering analysis process is a tailored version of the U.S. Air Force Office of Aerospace Studies (2014) process defined in its *Capabilities-Based Assessment (CBA) Handbook*.

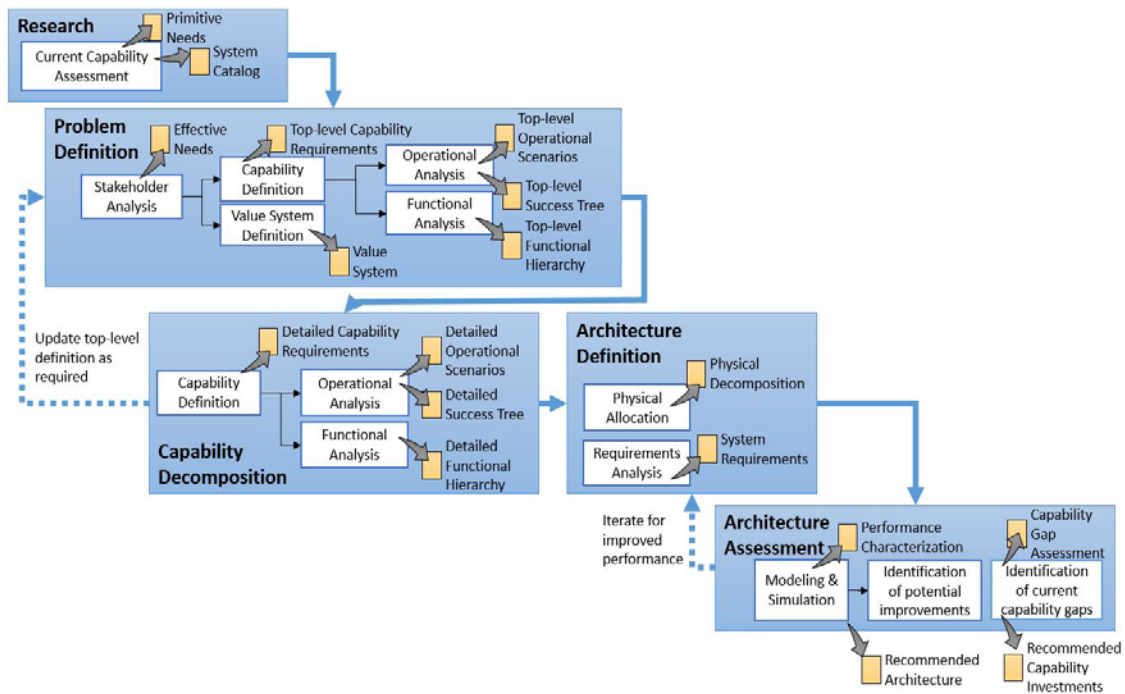


Figure 8. Expanding Mine Warfare Systems Engineering Process.

The systems engineering process consists of five phases: research, problem definition, capability decomposition, architecture definition, and architecture assessment. Although these five phases occur serially, previously defined assumptions found to be invalid or overly constraining may be re-examined and improved through phase iteration.

### Phase 1: Research

The initial research phase identifies the U.S. Navy’s current mining capabilities and generates a catalog of relevant weapon systems that were either in development or already operational. Capability gaps focused on offense, noted through this research, provide an initial set of primitive needs used in subsequent problem definition. The weapons system catalog provides a basis for later comparison to the required system capabilities identified by this study.

### Phase 2: Problem Definition

The problem definition phase begins with identification and analysis of stakeholders to determine the effective needs. This analysis supports the subsequent definition of a general set of required operational capabilities and a value system used in

quantifying the degree to which the operational capabilities are satisfied by a candidate design. Operational and functional analysis of the detailed capability requirements defines detailed operational scenarios, physical decompositions, and an objective hierarchy for the design solution.

### **Phase 3: Capability Decomposition**

During the capability decomposition phase, the general operational capabilities decompose into detailed capability requirements. Similarly, additional operational and functional analyses define the detailed functional architecture and operational scenarios. The products from this phase provide sufficient detail to support the definition and assessment of specific architectural solutions.

### **Phase 4: Architecture Definition**

Development of comprehensive system architecture and clear definition of technology needs validate Navy's requirements and needs in the naval MIW arena. During the architecture definition phase, the physical allocation of functions and capabilities to specific system components create architecture options. This allocation identifies all of the required system components such as UUVs and mines, and the quantities of each component.

### **Phase 5: Architecture Assessment**

Exercising system architecture in the simulation during the architecture assessment phase predicts system performance. The value system created in the problem definition phase allows scoring of the various architecture options based on performance simulation results. Analysis of performance results identifies opportunities for improvement in both the overall architecture and the requirements allocated to each system component. Each architectural design iteration and simulation result confirms the effectiveness of these improvements. Next, a comparison between allocated requirements and capabilities identified in the weapons system catalog developed during the research phase provides a current capability overview. Finally, documentation of capability gaps highlights them for the proposed system architecture.

## **H. CHAPTER I SUMMARY**

The U.S. Navy mining capability is long overdue for an upgrade. While the technology to improve mining capability exists, no efforts are underway to integrate these technologies into a better weapon. This project examines a path forward for integrating current technologies such as autonomous transit, navigation, and detonation. Extensive research provides an understanding of the current capability gaps in naval mining. A thorough investigation of current systems and their inability to meet the needs leads to an analysis of alternatives designed to produce a set of potential candidate systems and improvements to existing systems.

Each chapter builds on the previous as the sections lead to a final, detailed path. Chapter II describes stakeholders important to the project and the associated interests in developing MADMAN. Next, the requirements demonstrate alignment to overarching objectives serving the needs of the stakeholders. The chapter concludes by highlighting available technology and providing a current capability assessment. Chapter III details the design of MADMAN by beginning at a high-level view and then decomposing the system into subsystems. This decomposition provides a foundation for developing a concept of operations, mission scenarios, and vignettes. These artifacts describe the functionality of the system in an operational environment. Chapter IV begins with a look at the functional architecture of MADMAN and then provides a detailed explanation of the modeling and simulation used in this project. Chapter IV also describes the methods for qualifying the system in quantitative terms. Chapter V assesses the characteristics of each design option and summarizes the comparative viability of each option through statistical analysis. Finally, Chapter VI provides conclusions on the leading alternative and recommendations from the team toward future development.

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## **II. PROBLEM DEFINITION**

Reaching a defined problem statement is always difficult. “It is not uncommon to first identify some ‘perceived’ need which, in the end, doesn’t solve the problem at hand” (Blanchard and Fabrycky 2011). Only through multiple iterations of problem statement redefinition can a concise focus on actual needs result in a system foundation that is realistic and supported by all stakeholders. This section breaks apart that process and examines stakeholder wants top-level requirements, and an overview of the current capabilities as they relate to the MADMAN.

### **A. STAKEHOLDERS ANALYSIS**

Stakeholder analysis is a valuable step in the problem definition phase. Stakeholder analysis examines the expressed and implied needs required of the MADMAN. The first task of the stakeholder analysis is to identify the project’s stakeholders and their interests associated with the study. After identifying the stakeholders, each separates into primary, secondary, or tertiary categories. Weighting for primary stakeholders’ is highest among the three categories.

It was necessary to obtain stakeholder needs through extensive documentation review. Table 1 provides a summary of several key stakeholders for the MADMAN mission. Stakeholder categorization assisted in the prioritization of stakeholder feedback and the level of influence and involvement of each in the MADMAN effort. Table 1 provides an overview of the identified stakeholders, primitive needs/wants, goals/objectives and brief concerns of each.

Table 1. Primary Stakeholders Analysis Overview.

| Priority  | Stakeholder                                                                  | Primitive Needs/Wants                                                                                                                                                                                                                                                                      | Concerns                                                                                                                        |
|-----------|------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|
| Primary   | Operators                                                                    | <ul style="list-style-type: none"> <li>- <b>Remotely controlled</b></li> <li>- <b>Pre-programming of missions</b></li> <li>- <b>Mission termination</b></li> <li>- <b>Shallow water, active warzone accessible</b></li> </ul>                                                              | <ul style="list-style-type: none"> <li>- Difficulty of operation</li> </ul>                                                     |
| Secondary | U.S. Navy                                                                    | <ul style="list-style-type: none"> <li>- <b>Autonomy</b></li> <li>- <b>Mine delivery and deployment</b></li> <li>- Identification of alternatives</li> <li>- Evaluation of alternatives</li> <li>- Application for future expansion</li> <li>- <b>Reduced risk to personnel</b></li> </ul> | <ul style="list-style-type: none"> <li>- Protecting technological capabilities</li> <li>- Addressing capability gaps</li> </ul> |
|           | Department of Defense                                                        | <ul style="list-style-type: none"> <li>- <b>National security: Counter detection by enemy forces</b></li> <li>- <b>Defense of waterways</b></li> <li>- <b>Low cost with high effectiveness</b></li> </ul>                                                                                  | <ul style="list-style-type: none"> <li>- Survivability</li> <li>- Maintainability</li> </ul>                                    |
|           | Designers, Manufacturers, and Developers                                     | <ul style="list-style-type: none"> <li>- Design and manufacturing of system-programming of mission real-time decision-making</li> </ul>                                                                                                                                                    | <ul style="list-style-type: none"> <li>- Feasibility</li> <li>- Technology readiness</li> </ul>                                 |
|           | Enemy Forces                                                                 | <ul style="list-style-type: none"> <li>- Deny passage</li> </ul>                                                                                                                                                                                                                           | <ul style="list-style-type: none"> <li>- Effectiveness</li> </ul>                                                               |
|           | Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) | <ul style="list-style-type: none"> <li>- Advancement of <b>autonomy</b> educational endeavors</li> </ul>                                                                                                                                                                                   | <ul style="list-style-type: none"> <li>- Applicability</li> </ul>                                                               |
| Tertiary  | Engineers                                                                    | <ul style="list-style-type: none"> <li>- <b>System reliability</b></li> <li>- <b>System functionality</b></li> <li>- <b>Successful integration of system components</b></li> </ul>                                                                                                         | <ul style="list-style-type: none"> <li>- Poor system integration</li> <li>- Requirements not properly defined/met</li> </ul>    |
|           | Trainers and Maintainers                                                     | <ul style="list-style-type: none"> <li>- Ease of operation and maintenance</li> <li>- <b>Parts and materials costs</b></li> </ul>                                                                                                                                                          | <ul style="list-style-type: none"> <li>- Maintainability</li> <li>- Parts obsolescence</li> </ul>                               |
|           | Environmental Protection Agency                                              | <ul style="list-style-type: none"> <li>- Protection of environment, humans, and animals (free from harm)</li> </ul>                                                                                                                                                                        | <ul style="list-style-type: none"> <li>- System disposal</li> </ul>                                                             |
|           | Meteorological and Oceanographic Community (METOC)                           | <ul style="list-style-type: none"> <li>- Maritime data reading potential</li> </ul>                                                                                                                                                                                                        | <ul style="list-style-type: none"> <li>- System maritime environmental influence</li> </ul>                                     |
|           | Natural Resources Defense Council                                            | <ul style="list-style-type: none"> <li>- Protection of underwater wildlife</li> </ul>                                                                                                                                                                                                      | <ul style="list-style-type: none"> <li>- System maritime environmental influence</li> </ul>                                     |
|           | Beneficiaries                                                                | <ul style="list-style-type: none"> <li>- Military and commercial traffic</li> <li>- Safe passage</li> </ul>                                                                                                                                                                                | <ul style="list-style-type: none"> <li>- Conducting missions in a safe environment</li> <li>- Safe transportation</li> </ul>    |
|           | Taxpayers                                                                    | <ul style="list-style-type: none"> <li>- <b>Protection of naval forces and domestic safety</b></li> </ul>                                                                                                                                                                                  | <ul style="list-style-type: none"> <li>- Value of investment</li> </ul>                                                         |

**Bold** text denotes linkage to key objectives for the MADMAN system.

While stakeholders have varying perspectives, motives, and requirements, the majority of stakeholders have a direct interest in placing underwater mines successfully and safely. The key overall need is to identify and evaluate the alternatives addressing the inherent and inordinate risk to delivery units and avoiding detection by enemy forces.

## **1. Primary Stakeholders**

The central stakeholders for this project are system operators. Their interest is in addressing the lack of a fully autonomous UUV mining capability. The National Research Council (2000) states, “Continued dialogue between naval operators and academic scientists is essential to ensure that researchers are aware of the current needs and capabilities of the mine warfare community.” The chief goal of the primary stakeholders is a structured and complete assessment of the necessary technical capabilities needed to develop a fully autonomous mining system that significantly reduces or eliminates danger to ships, delivery units, and personnel. Primary stakeholders are also interested in ensuring analysis includes the necessary attributes and mine payloads of the vehicles, possible mission sets, the range of operations, and an effective concept of operations.

Deriving operator needs from the National Academic Press publication allows insight into why a mine with remote controlled activation and deactivation and mission deactivation is necessary (National Research Council 2000). Operator needs directly link to the fundamental aspects of having an autonomous mine delivery system with the ability to remotely deactivate as necessary.

## **2. Secondary Stakeholders**

Literature research provides insight into secondary stakeholders’ primitive needs (Blanchard and Fabrycky 2011). Secondary stakeholders consist of the U.S. Navy, Department of Defense, trainers and maintainers, designers, developers and manufacturers, and CRUSER. These stakeholders have varying needs and concerns. Among the concerns discussed in Table 1, a deployable, viable, autonomous mine delivery and deployment system is important to the secondary stakeholders.

### **3. Tertiary Stakeholders**

Tertiary stakeholders consist of engineers, trainers, and maintainers, the Environmental Protection Agency (EPA), the Natural Resources Defense Council, beneficiaries, and taxpayers. Direct communication does not occur with silent stakeholders, thus extensive research provides insight into the role each stakeholder plays in this evaluation and the primitive needs and wants.

A report from the Defense Science Board (2016) provides the basis for establishing tertiary stakeholders and associated desires for reliability, functionality, and integration. Tertiary stakeholders also support an emphasis on protecting the natural undersea wildlife and oceans from contamination (Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics 2016). Oceanography and Mine Warfare (2000) also provided needs for having a deployable autonomous delivery and deployment system with reduced risk to delivery units and armed forces personnel.

#### **B. TOP-LEVEL OBJECTIVES**

The objectives for MADMAN derives from the stakeholders' primitive needs. These primitive needs started as simple statements of desired abilities and functions for a mining system. To develop a clear path, these statements translate into key traceable and realistic objectives. Table 2 illustrates the translation from primitive needs to the resulting overall objectives for MADMAN's architecture. Stakeholders' primary concern is a general need for more autonomy and stealth capabilities. However, discussion determined that there would be six distinct needs resulting in six key objectives. Mapping top-level objectives to stakeholder primitive needs allow for a clear association of the necessary functions needed to meet requirements and defining the top-level objectives. –

Table 2. Top-Level Objectives

| Primitive Need                           | Key Objectives                  |
|------------------------------------------|---------------------------------|
| Shallow water, active warzone accessible | Access littoral target area     |
| Prevent enemy interference with mission  | Avoid detection                 |
| Should fit on current naval vessel       | Deployable                      |
| Can arm the system and deactivate        | Control mission start and abort |
| More autonomy throughout the system      | Reduce or remove human risk     |
| Keep costs low with high effectiveness   | Suitable                        |

Successful conduct of effective autonomous mine warfare hinges on the accomplishment of these six key objectives. First, the system must provide access to target areas; the system must be capable of reaching enemy littoral regions under its own power and guidance. Second, the system must avoid enemy detection by the enemy by presenting a small—or nonexistent—radar cross section and emitting little or no acoustic signature. Third, the system must fit within current naval vessels and not require additional equipment to deploy mines to the designated mining area.

The system must also arm and disarm mines per operator commands and, when armed, must attack detected targets. Similarly, the system must dispose of mines when commanded by disabling explosives in place after verification of an environment free of commercial and civilian traffic. As compared to current MIW capabilities, the system must achieve all of these goals with a significant reduction or elimination of risk to human life. This reduction comes from adding in autonomous features to the system, preventing the need for human interaction in multiple parts of the mission activity. Finally, the system must meet all of these goals with acceptable suitability traits, such as system reliability, operational availability, and the probability of mission success.

### C. TOP-LEVEL REQUIREMENTS (EFFECTIVE NEEDS)

To build the right system, combining stakeholder analysis, primitive needs and the resulting top-level objectives lead to the development of defined requirements for the system. These requirements provide a path to system specification. All lower-level elements of the system are traceable up to these requirements, providing stakeholder needs satisfaction and a correctly built system. Table 3 lists these requirements.

Table 3. Top-Level Requirements

| <b>MADMAN System Requirements</b>                                      |
|------------------------------------------------------------------------|
| The system shall be capable of entering shallow littoral areas         |
| The system shall avoid detection while in the active mission area      |
| The system shall be deployable                                         |
| The system shall be able to accept engage and disengage commands       |
| The system shall autonomously navigate to a pre-defined destination    |
| The system shall use existing naval mine warhead and influence systems |
| The system shall reduce the risk of human casualty                     |

The first requirement is the capability to enter shallow littoral areas. Entering shallow water requires a system of minimal size with the ability to maneuver, detonate, and meet proper distance requirements. In addition, it is important to understand the three major aspects of coastal environments when entering littoral areas. The National Research Council (2000) describes these three aspects as 1) 95% of the world's population lives within 600 miles of the sea, 2) 80% of all countries border the coast, and 3) 80% of the world's capitals lie within 300 miles of a shoreline. Warfighters and METOC have special interest in these unique location deployments. It is critical to plan and execute mine warfare successfully. A key to this success lies in understanding that “virtually every environmental parameter in the dynamic near shore environment

influences military operations” (National Research Council 2000). This required shared knowledge facilitates necessary cooperation between these communities of interest.

As the system enters the littoral area undetected, it must also avoid detection while in its designated area. One opportunity to meet this requirement is the use of low profile shapes mimicking creatures of the sea and attempting to stay within ambient noises during movement through the littoral areas. Ambient noise databases, such as the Historical Temporal Shipping database for commercial shipping supports the use for modeling discrete shipping noise, while the Ambient Noise Directionality Estimation System (ANDES) and Directional Ambient Noise Estimation System (DANES) models supports the use for the deep-water diffuse noise levels (National Academy of Engineering 2003). These databases allow for a distinction between seasonal trend noises like industrial fishing boats and the crashing of waves. The use of this database provides a better understanding of how to mask the acoustics of the mine propelling through littoral areas.

The mine must be deployable from current Navy vessels. The system must conform to a size limitation for naval vessels, taking into account load weight, quantity, and on-vessel transportation. Be able to fit on a naval vessel and then reach a pre-determined location for release. To support cost-effectiveness, there should be no special equipment required to move mines on naval vessels. The deployment operations should use current equipment on naval vessels to release mines for mission activity. Use of familiar equipment and on-vessel transport facilitates risk reduction through minimal human involvement.

In addition to deployment, the engagement and disengagement process will require communication and human intervention to some degree. System operators must arm mines in preparation for its mission activity. Human intervention disarms or disengages the mine remotely once the mission activity concludes. These commands may come in any form, provided the mine responds in an acceptable period to prevent risk to non-adversary human life. The ability to arm the mine is critical to providing offensive capabilities; however, the ability to disengage and reengage can provide a means of safe passage for friendly forces through active mission areas. Disengage and reengage

functions may be considered a last resort because any weapon that was once live could pose risk that friendly vehicles may not be willing to accept.

Once deployed, the mine transits to a target location autonomously using pre-defined or dynamically updating navigation. No human involvement will be required for the mine to reach a target location. The mine will utilize existing methods for location determination. Autonomous vehicles of many forms provide propulsion, location, and obstacle avoidance capabilities required for such a transit. Before deployment, uploading topographical maps of the littoral area to the mines facilitates successful navigation and increases the chance of success.

Stakeholders desire the use of existing hardware and software elements to incorporate into the system. Reuse of current warheads and influence systems constrain the ability to produce new components. However, the reuse of elements provides greater supportability and maintainability for the overall system. Lastly and most importantly, the system shall reduce the risk of human casualty. Incorporating as many autonomous characteristics and functions within MADMAN reduces risk to human casualty.

The seven high-level requirements incorporate mobility of the mines to establish verification and validation to specific design and development criteria early on in a project's lifecycle. Early verification and validation of specific design and development criteria allow performance traceability of requirements while tailoring down to the subsystem level specifications. Requirement traceability captures the relationships between the requirements, specifications, and design. These seven system requirements will create the foundation for the project with lower level system requirements appearing in Chapter III of this capstone.

#### **D. CURRENT CAPABILITY ASSESSMENT**

A system's primitive needs come from many different types of sources, and as their name implies, they have not yet matured into actual requirements. Many times, they come from a vision and stakeholders who may not understand the depth of their primitive needs. Additionally, there are situations where functionality or capability already exists in

some form. Examining the relationship between current capabilities and stakeholder needs allows for a better understanding of development feasibility.

Presently, an autonomous mine delivery system does not exist, and none are in development. Previous mine acquisition programs of record are no longer operational. Among the programs was the Mk 67, an improved submarine-launched mobile mine (SLMM), the Littoral Sea Mine, a proposed replacement for the Mk 60, and a planned target detection device for Mk 71 to replace sensors and fusing options for the Quickstrike series of mines (National Research Council 2001). None of these programs incorporates the autonomous delivery of mines. Understanding the current naval capabilities in mining, propulsion, navigation, communications, influence, UUV/USV, detection, mine deployment, and autonomy allows determination of applicable capabilities that can meet system requirements.

***a. Mining Capabilities***

United States naval mining capabilities are currently non-existent for autonomous delivery of sea mines. Current capabilities support air delivery of the Quickstrike series (Mk 62 (500 lb.), Mk 63 (1000 lb.), and Mk 65 (2300 lb.) mines. In combat, enemy forces will deploy aircraft and anti-aircraft batteries to prevent placement of mines. Additionally, when using the current deployment system to airdrop a mine, a human must fly the aircraft into contested zones, increasing the risk of attack from enemy anti-aircraft measures. Mine deployment precision is another issue faced by current Navy systems. While an aircraft can drop a weapon precisely in a particular area, the mine interacts with the water as it settles to its deployed location. A mine dropped from the air may not land on the seafloor at its intended location because sea currents interact with the mine as it falls from the surface.

***b. Propulsion Capabilities***

Different underwater vehicles use different means of propulsion. Each existing vehicle or weapon presents an option for MADMAN's means of transit. MADMAN could benefit from using current propulsion technology to make the required transit. The U.S. Navy's primary torpedo systems are the Mk 46 and Mk 54, air-dropped torpedoes

and the Mk 48 Advanced Capability (ADCAP), fired from submarines. All of these torpedoes use a swashplate piston engine fueled by OTTO Fuel. The range of these two torpedoes is limited to the amount of monopropellant fuel carried onboard (WeaponSystems.net 2002). When ignited, monopropellant fuel decomposes into hot gas, which supports driving the engine.

Another example of U.S. naval torpedoes is the Mk 50 Barracuda, which is a lightweight anti-submarine warfare (ASW). The Mk 50 uses a different propulsion technique with a chemical storage system. This type of propulsion uses sulfur hexafluoride gas sprayed onto a block of lithium and produces a low radiated noise level due to no exhaust gasses (Pike 1998). Again, fuel tank capacity limits this propulsion system range.

Before the Mk 48 ADCAP torpedo, U.S. submarines carried either the Mk 37 or the Mk 14 torpedoes. Each torpedo used different propulsion systems. The Mk 14 used an engine fueled by methanol and contained a pressurized air tank allowing the combustion engine to function underwater. The Mk 14's limited range is due to the tanks required for both the methanol and the compressed air. The Mk 37 used silver-zinc batteries that connected to a two-speed electric motor. Using the electric motors for the Mk 37 greatly increased range of the U.S. torpedoes; however, when vibrated they could overheat and explode (Milford 1997).

Most propulsion capabilities employ some form of motor or engine. However, an emerging technology allows the harvest of propulsive energy from current and wave motion. Wave Glider converts the ocean's kinetic motion to move the system through the water as shown in Figure 9. Should the float also contain solar cells, the energy gathered can also power UUV propulsion and sensors (Manley and Wilcox 2010). The Wave Glider's dependence on wave motion limits its motion to a slow speed through the ocean.

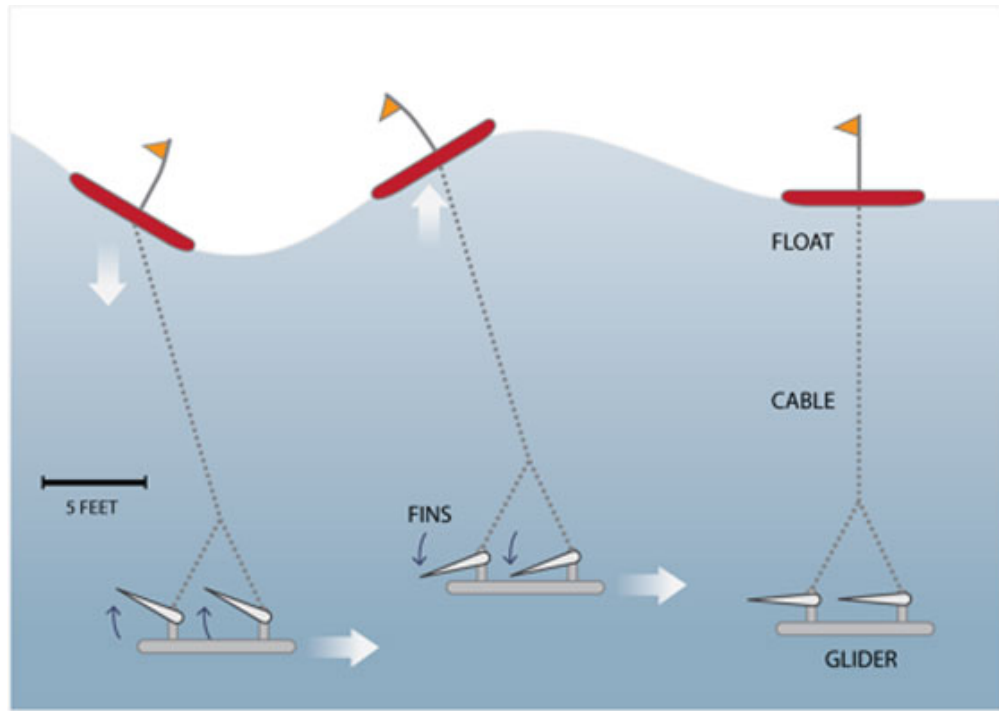


Figure 9. Wave Glider Principles of Operation. Source: Manley and Wilcox (2010).

### c. *Navigation Capabilities*

One of the inherent requirements for a mining system is precise positioning at the deployment location. Navigation is a critical function that ensures that friendly forces know the mine location. Precise positioning allows friendly forces to transit near or even through a mined area, while at the same time denying the enemy force access to the same areas.

Many inertial navigation systems provide the added option of using external fix sources such as GPS to determine location. Inertial navigation is most likely the best source to ensure covert delivery. While inertial navigation varies in precision, as the navigation tool becomes more precise, it also becomes more expensive. United States submarines use one of two primary methods to determine position while underway; either electrostatic gyro navigation (ESGN) or a ring laser gyro navigation (RLGN). The relatively large size of the ESGN and RLGN prevents successfully deploying or transferring of smaller systems. Redundancy, which provides their capability for sustained operations, causes the large size of these systems. Torpedoes such as the

ADCAP utilize a turn count based dead reckoning system that determines position. Other forms of inertial navigation systems include fiber optic gyros, pendulous accelerometers, quartz rate sensors, and timing and inertial measurement sensors. The inertial measurement method's short deployment life cycle and the potential to use outside sources for portions of the deployment allows for possibly scaling down the size of existing systems used on submarines (King 2017).

#### **d. Communications**

United States Navy submarines communicate covertly using multiple methods. Figure 10 shows different frequency bands used by submarines (Pike 2011). While range, detectability, and actual frequencies are classified, a multitude of active radio communication systems exists. The system requires either an antenna system or a deployable buoy for the required position report.

| CORE                                                                                                                          |                                                                                                                                                                                      | LOW RISK                                                                                                                                                              | OVERT                                                                                                                                                                  |
|-------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| STEALTH                                                                                                                       | COVERT                                                                                                                                                                               |                                                                                                                                                                       |                                                                                                                                                                        |
|  <p>ICE</p> <p>COPY</p> <p>VLF<br/>ELF</p> |  <p>ESM COMMS</p> <p>P/D</p> <p>EHF LDR/MDR<br/>SHF<br/>UHF</p> <p>VHF<br/>HF<br/>VLF<br/>ELF</p> |  <p>BROACHED</p> <p>EHF MDR<br/>SHF<br/>UHF</p> <p>VHF<br/>HF<br/>VLF<br/>ELF</p> |  <p>SURFACED</p> <p>EHF MDR<br/>SHF<br/>UHF</p> <p>VHF<br/>HF<br/>VLF<br/>ELF</p> |
|                                                                                                                               | LOW-MED                                                                                                                                                                              | HIGH                                                                                                                                                                  | HIGH                                                                                                                                                                   |

**Communication Capabilities for Submarine Operations**

Figure 10. Submarine Communication Capabilities. Source: Pike (2011).

Extremely low frequency (ELF) used during the Cold War, provided communication with Polaris class submarines. ELF requires a large infrastructure no

longer available for submarines today (Altget n.d.). Submarines currently use very low frequency (VLF) for communications; however, depth and environmental effects limits VLF. VLF, although a viable method of communication, presents limitations for the system's operational capability.

Acoustic underwater communication sends and receives information under water but also requires hydrophones. Underwater acoustic communication presents some challenges that may affect operational capability, but its small infrastructure makes this a viable alternative to radio frequency communications. The ocean environment affects underwater communication greatly. Water transmits sound better than air. While the communication range is greater, it is important to address the detrimental effects of bottom type, salinity, water depth, and multi-path propagation. The characteristics of the undersea environment heavily influence underwater communications. The undersea environment limits the long-range ability to activate the system since it requires a transmitter nearby. The use of an underwater telephone provides a suitable alternative for addressing long-range communications.

The AN/WQC-2 underwater telephone system is a good example of militarized long-range underwater communication (Shinego et al. 2001) but primarily used on manned submarines and surface ships. Another viable option includes the man-portable systems employed by divers.

Although the demonstration of radio frequency (RF) communications at very shallow depths and short separations between UUVs, RF-based UUV communication is not practical. UUVs are constrained to use of acoustic data links for primary communications. Transducers sized for UUVs are typically constrained to higher frequencies—10 kHz and above—and half-duplex protocols in which the UUV cannot simultaneously receive and transmit (Partana, Kurosea, and Levine 2016).

USVs and Seagliders can provide satellite-to-seafloor communications links; USVs support continuous satellite links, while Seagliders may only provide intermittent satellite communication while at or near the surface. Monterey Bay Aquarium Research Institute (MBARI) has demonstrated a Wave Glider-based communications “hot spot”

that employed both acoustic and Wi-Fi modems to communicate with both submerged and surfaced UUVs. Although MBARI's hotspot used a traditional cellular phone network for shore communications, use of a satellite link is feasible (Hanrahan and Cardoza 2017).

***e. Influence***

United States naval mines employ different influence types. Influence mines utilize acoustic, magnetic/seismic, pressure, or a combination of detonation types. CAPTOR (a torpedo type for the uninitiated) uses acoustic influence while the MK 67 SLMM uses magnetic/seismic influence, and the Quickstrike series uses a combination of magnetically/seismically and pressure influence. Other countries use multiple influence mines such as Spain's MINEA and Italy's MURENA mines, which both use pressure, acoustic, and magnetic/seismic influence triggers (RWM S.p.A. 2013) (Electronica Submarina SAES 2011). Previous exercises demonstrate these influence types not only exist but also function as intended. An important aspect not yet in development is the discrimination of targets from traffic before detonation. Table 4 provides an overview of the common U.S. naval mine types from 1890 to 2010.

Table 4. Mine Applicability and Influence.

| Name                | Type/Influence                               | Period of Use    |
|---------------------|----------------------------------------------|------------------|
| MK2/MK3             | Moored/Contact                               | 1890-1917        |
| MK6                 | Moored/Contact                               | 1914-1964        |
| MK16                | Moored/Contact                               | 1917-1945        |
| MK13/MK25           | Bottom/Magnetic                              | 1940-1974        |
| MK18                | Bottom/Magnetic                              | 1950s            |
| MK49                | Bottom/Magnetic/Acoustic/Pressure            | 1951-1960s       |
| MK52                | Modular/Acoustic/Magnetic/Pressure           | 1954-1978        |
| MK55                | Bottom/Magnetic                              | 1961-1980s       |
| MK56                | Moored/Magnetic                              | 1966-Present Day |
| Destructor (DST)    | Converted Air-Dropped Bomb/Magnetic/Acoustic | 1967-1985        |
| MK60 (CAPTOR)       | Moored Torpedo/Acoustic                      | 1979-Present Day |
| MK62/64 Quickstrike | Bottom/Magnetic/Pressure/Acoustic            | 1980-Present Day |
| MK67 SLMM           | Bottom Torpedo/Magnetic/Seismic              | 1983-2010        |

Adapted from Friedman (1998) and Hartshorn (2011).

Green shaded denotes the influence types presently used.

Presently, mines utilize three influence types consisting of moored/magnetic, moored torpedo/acoustic, and bottom/magnetic/pressure/acoustic.

#### ***f. Current UUV/USV Capabilities***

It may be necessary to employ unmanned surface vehicles (USVs) as well as UUVs to achieve required navigation and communications capabilities. Figure 11 compares trends in key performance characteristics across applicable classes of unmanned surface and underwater vehicles. The subsections below further describe current UUV capabilities and limitations in achieving top-level objectives.

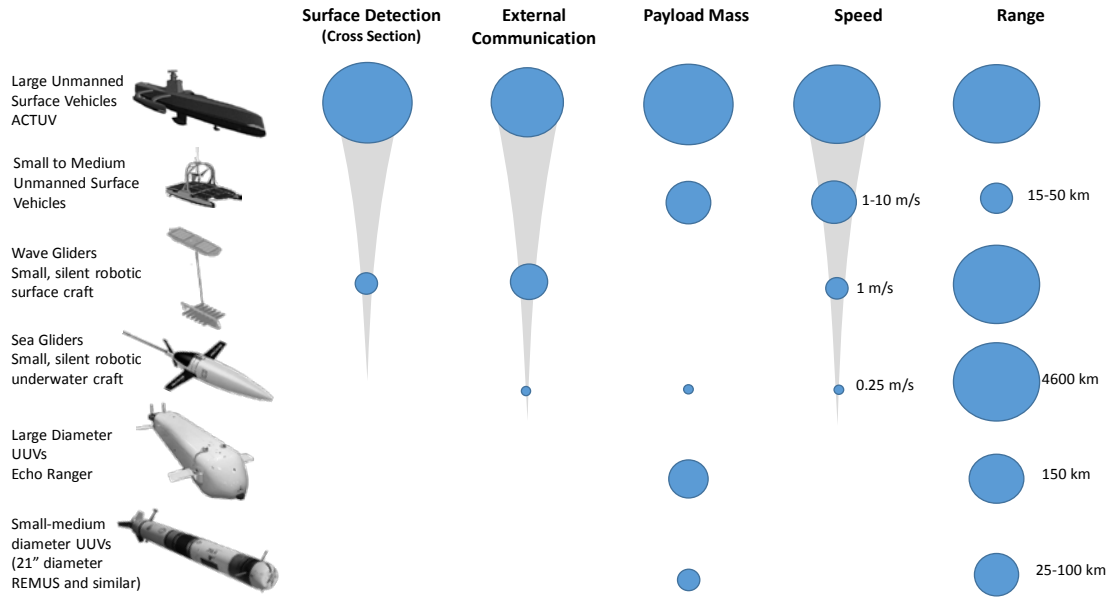


Figure 11. Comparison of Current and Near-Term Unmanned Marine Vehicle Capabilities

Commercial and research UUV launch and recovery operations generally use a manned surface vehicle or a dock. Neither of these platforms is appropriate for the MADMAN solution, as they would require direct exposure of humans to enemy attack during mine deployment. Renilson (2014) proposed a simple recovery method using a catching mechanism connected by wire to a submarine moving forward. A proposed “wing” would steer the catching mechanism to contact the UUV as the submarine traveled past it (Renilson 2014).

An alternative approach, proposed by Barlow and Hardy, would extend a recovery arm from a torpedo tube to capture the UUV and retract the UUV into the torpedo tube (Barlow and Hardy 2008). Either of these techniques may be applicable not only to large named submarines but also to larger UUVs that carry mines into littoral regions.

The Virginia class submarine USS North Dakota (SSN-784) in 2015 first demonstrated the submarine-based underwater launch and recovery of a REMUS 600 UUV (Gady 2015). This demonstration likely marked the first field demonstration of the Universal Launch, and Recovery Module (ULRM) illustrated in Figure 12. This system,

Virginia class submarine compatible, can launch and retrieve UUVs up to 1.5 m in diameter, 7 meters in length, and 13,600 kg in mass (Naval Drones 2017). It is notable that the REMUS 600's 21-inch diameter could also enable the use of one of the Virginia class's four standard torpedo tubes for launch (Vandenberg 2010).

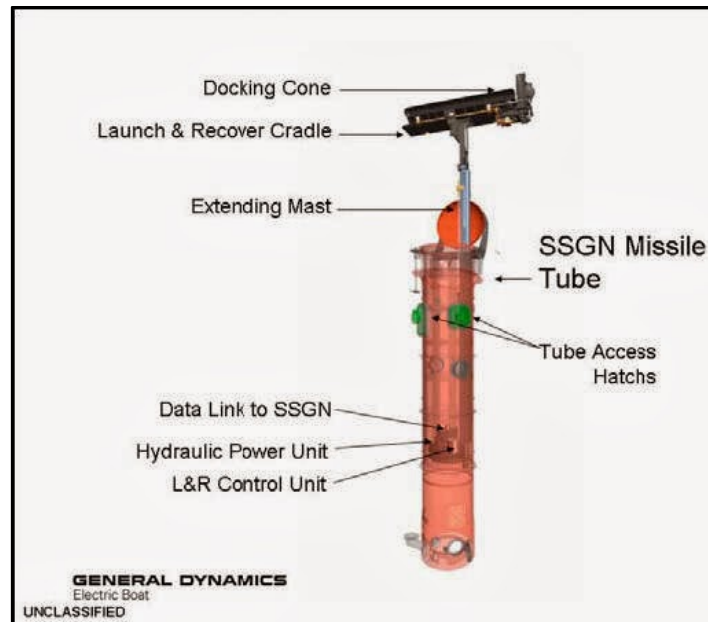


Figure 12. Universal Launch and Recovery Module. Source: Navaldrone.com.

The UUV navigation system relies on inertial navigation system (INS) instrument suites. Current INSs, when paired with Doppler Velocity Log systems, demonstrate a position error of approximately 2% of the distance traveled (Tang et al. 2013). Thus, longer deployment reaches will incur greater errors in the distribution of mines within the target region. External navigational references have demonstrated improved navigation. USVs equipped with GPS equipment may provide navigational references. The Defense Advanced Research Projects Agency has initiated an effort to develop an underwater equivalent of the GPS navigational capability.

The proposed Positioning System for Deep Ocean Navigation (POSYDON) would provide fixed reference points that emit acoustic signals to determine position relative to those fixed references. Such a system may provide a distinct advantage by

allowing a UUV to determine its precise location without emitting any detectable signal of its own (Draper Labs 2016).

***g. Detection Avoidance***

It is possible to detect system components at or near the surface by visual or radar means. Below the surface, acoustic signatures from UUV propulsion and communications systems may be detectable. Communications with external assets such as aircraft, satellites, and other surface craft may require vehicles that can operate at or near the surface. However, this communications capability comes at the increased risk of visual or radar detection due to the exposed surface area of the vehicle. Small USVs and Wave Glider's present an exposed cross section of a few square meters or less—orders of magnitude less than any manned surface vehicle or the Anti-Submarine Warfare Continuous Trail Unmanned Vessel (ACTUV) USV. Seaglidors further reduce surface exposure by surfacing only briefly before diving below the waterline. This temporary resurfacing can support periodic, but not continuous; communication links to navigation beacons and other external systems.

To avoid detection underwater, the UUV must also minimize its acoustic signature. Of particular concern are vehicle-to-vehicle communications using acoustic modems. These communications may serve as a clear sign of approaching UUVs, alerting enemy forces before mines are in place. A Norwegian test of covert acoustic modem communications demonstrated communication across a 9 km distance using difficult to detect modulations in the range of 1.5 to 5.1 kHz (Van Walree et al. 2018).

***h. Mine Deployment Capabilities***

Mine deployment involves the transport and accurate placement of a warhead in a specific target area. Key capabilities supporting this objective are the carrying capacity to accommodate the warhead payload, the endurance to travel the required distance, and the ability to navigate precisely.

UUV payload capacity decreases as overall vehicle size decreases. Vehicle speed and range also tend to decrease with decreasing vehicle size. Most naval mines use a

warhead section of 150 kg or greater mass; this significant payload mass may exceed the capability of most small-to-medium size UUVs. Technology improvements in propulsion efficiency and energy storage density (battery capacity) may be necessary to enable conversion of a small, commercially available UUV into a mine with sufficient range.

*i. Autonomous Capabilities*

Autonomous control software developed for the ACTUV has demonstrated the ability to identify collision risks and re-calculate vehicle trajectories to avoid such hazards on the surface (Antanitus 2016). Analogous projects for UUV swarms have demonstrated not only collision avoidance capabilities but also the ability to coordinate swarm motion to meet a common goal.

A group of UUVs traveling along a similar trajectory constitutes a swarm. Swarm control focuses on cooperative navigation and communication to ensure that each mine avoids collision with objects (including geologic features, biologics, and other vehicles), arrives at its target location, and can maintain communications capability.

Research into the behavior and control of such UUV swarms has focused on a mission such as underwater search and monitoring; these missions typically rely on a small USV as a navigation reference and communications relay. The CoCoRo projects studied the combined capabilities of multiple identical UUVs with the goal of “self-organization” to cooperatively complete tasks. Such self-organization may provide a benchmark for the definition of realizable goals (Schmickl 2011). Swarm control research in other domains may be applicable as well. Technology demonstrations using Unmanned Aerial Vehicle (UAV) and small satellite systems have proven basic cooperative navigation, communication, and command and control techniques.

Reliability in autonomous vehicles remains a challenge. A recent study of failure rates in commercially available REMUS 100 UUVs discovered a mean time between failure (MTBF) of 1 to 1.5 hours and a mean distance traveled between failures of approximately 8 km (Griffiths et al. 2009). The REMUS 100 UV is a relatively simple UUV, however complex naval mine placement systems may be even more susceptible to failures.

Although advanced onboard fault management software may improve vehicle reliability, expansion of a system to include multiple such vehicles can still experience a significant failure rate. A 2016 study found a wide range of MTBF values—from 50 to 1000 hours—for highly autonomous marine vehicles systems (Brito et al. 2016). Achieving system suitability requires significant UUV reliability improvement.

## **E. CHAPTER II SUMMARY**

To make MADMAN a mining system that meets or exceeds operational capabilities of traditional mines, effective mine delivery, navigation, propulsion, and communication become key. Traditional mining systems lack the autonomous capability to access the target area and deploy mines safely. Current technologies and systems offer leveraging capabilities providing a sufficient starting point for the MADMAN system.

The ability for MADMAN to deploy to its desired location autonomously could solely define MADMAN as a “smart mine” system. MADMAN must have the means to transit from the deployment site to the desired target location autonomously. Autonomously transiting requires the use of propulsion and navigation functions suitable for achieving mission requirements. Current capabilities may partially achieve some of MADMAN’s mission requirements, but no autonomous mine delivery system exists to achieve all of the requirements.

### **III. DESIGN**

Stakeholder analysis provides a path toward development of a system through defining requirements and identifying top-level objectives of the system. Upon reaching an agreement on a set of objectives for the system, decomposition helps generate a clear picture of the final system. Many aspects of what the system will and should do drive the early stages of system development.

It is at this early stage of the system life cycle that major decisions are made relative to adopting a specific design approach and related technology application. Accordingly, it is at this stage that the results of such decisions can have a great impact on the ultimate behavioral characteristics and life-cycle cost of a system. (Blanchard and Fabrycky 2011)

Developing a set of alternative systems for comparison helps reduce bias and avoid choosing a pre-conceived design. The decomposition effort begins by examining four distinctly different, albeit linked areas as defined.

1. Visual depiction. The visual depiction provides a high-level visual graphic of the system. In Department of Defense Architecture Framework syntax, the operational viewpoint (OV-1) provides a graphical depiction to display how the system functions operationally (Chief Information Officer U.S. Department of Defense 2010). The OV-1 separates MADMAN's potential deployment options into three alternatives for reaching the target location.
2. Capabilities. The visual depiction helps identify system capabilities and decomposes them down to essential parts of the system.
3. Operations. With the necessary capabilities identified, the concept of operations, details the separate phases of operational activities within the system.
4. Scenarios. Potential scenarios supports highlighting how the system responds to internal and external influences while conducting a standard mission.

#### **A. OPERATIONAL VIEW (OV-1) DEVELOPMENT**

In the early stages of development, an OV-1 serves as a viewpoint that makes sense to all the stakeholder perspectives. "The intended usage of the OV-1 includes providing a tool for discussion and presentation" (Chief Information Officer U.S.

Department of Defense 2010). Multiple discussions and iterations of requirement definitions generated three unique OV-1 drawings.

## 1. MADMAN Deployment Using UUV

The first drawing, Figure 13, demonstrates a balance between stealth, safety, and speed using a UUV-delivered mine.

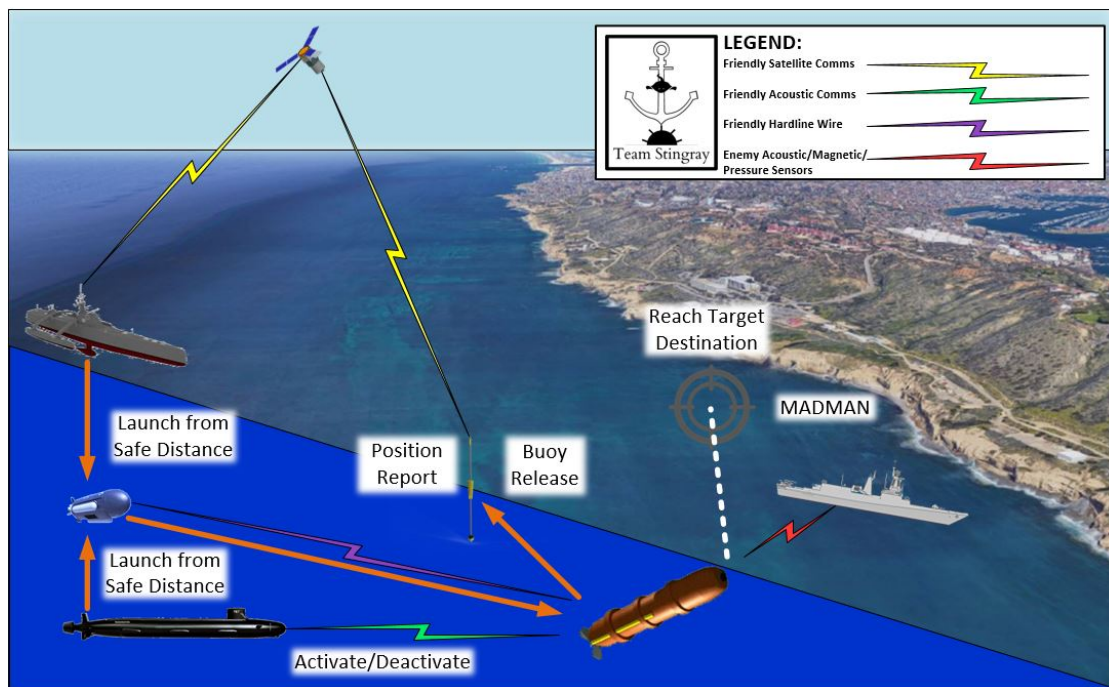


Figure 13. MADMAN Deployment Using a UUV.

In this viewpoint, the operator loads MADMAN onto a UUV from a carrier ship or submarine and then the UUV transports the mine into littoral waters where the mine autonomously reaches a set destination. The MADMAN may use active and passive communications between nearby submarines or satellite-linked buoys. Using a UUV ensures that personnel remain at a safe distance before the mine enters into contested waters.

## 2. MADMAN Deployment Using Wave Glider

Figure 14 depicts a viewpoint focused on stealth. Using wave glider technology, the delivery of the mine creates a minimal acoustic signature. The Wave Glider is also unmanned removing the risk to personnel. A drawback for using Wave Glider as a deployment method is the speed of delivery. While relatively silent, the technology uses the sea current to rise and fall to reach a destination, creating a longer path to mine placement in comparison to other alternatives.

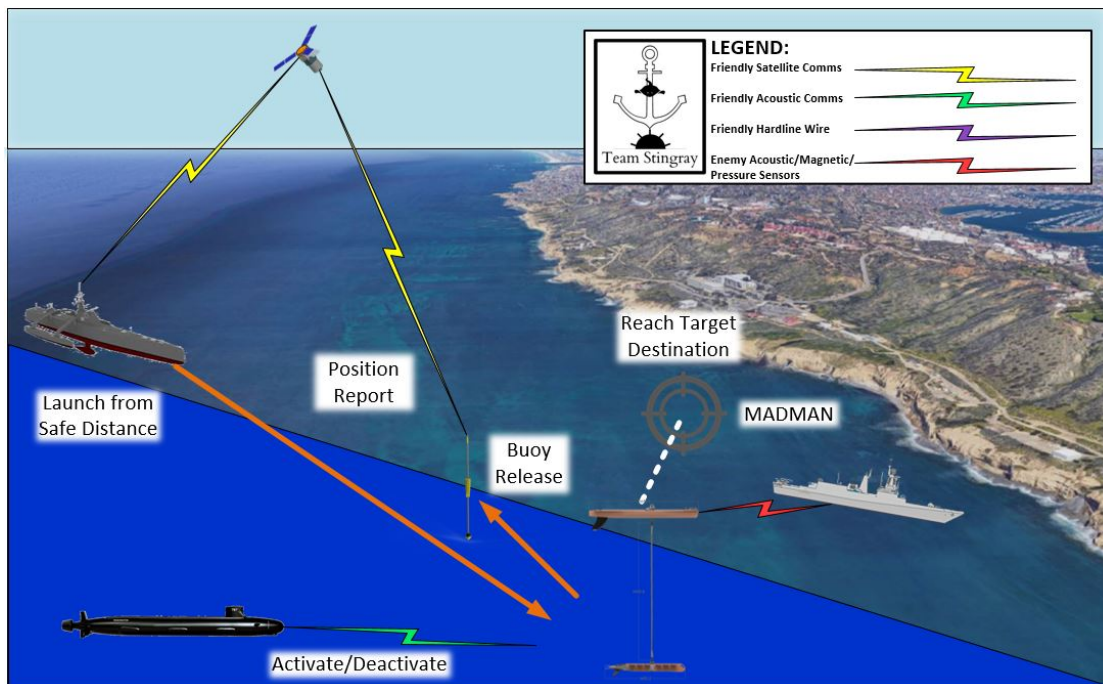


Figure 14. MADMAN Deployment Using Wave Glider.

## 3. MADMAN Deployment Using Air Drop

Air dropping MADMAN into littoral waters as shown in Figure 15, is the most similar example of current mining capabilities; however, it provides the most risk to personnel.

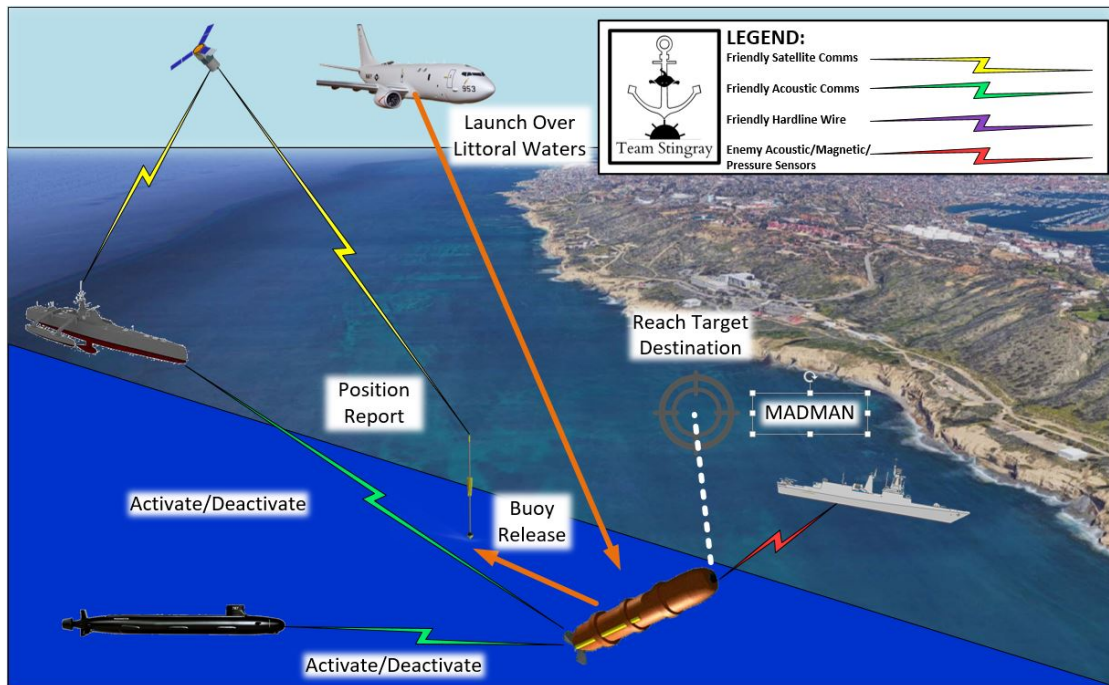


Figure 15. MADMAN Deployment Using Air Drop.

Aircraft equipped with mines pass over or near littoral waters and release mines in the general area for deployment. Once entering the water, the mines autonomously reach their final destination for arming. An aircraft's noise level combined with the mines striking the water creates a noticeable acoustic signature in a specific area making this a poor example of stealth. Additionally, pilots must get close enough to the intended minefield location for deployment, increasing personnel risk. This proximity increases the chance of enemy identification and response to the aircraft.

These high-level operational views provide a broad perspective on the MADMAN system. While the principle of operation is visually clear, specifics regarding the functionality of the system are minimal. A single image does not detail system elements. However, examining necessary capabilities supports an understanding of mission success.

## B. CAPABILITY DEFINITION

MADMAN's defined scope guides high-level requirements previously discussed in Chapter I. Chapter II explored current capabilities for subsystems with the potential to exploit. The next step is identifying "...the characteristics of design that relate to the technical performance of the system; that is, the technical characteristics that are required for the system to accomplish its intended mission(s)" (Blanchard and Fabrycky 2011); (National Research Council 2001). The functional capability hierarchy provides an overview of the necessary capabilities for the MADMAN. By starting with higher-level capabilities, a clear picture shows where further decomposition may highlight what gaps may exist. Figure 16 identifies this capability hierarchy, consisting of navigation, deactivation, monitoring, detonation, propulsion, and communication.

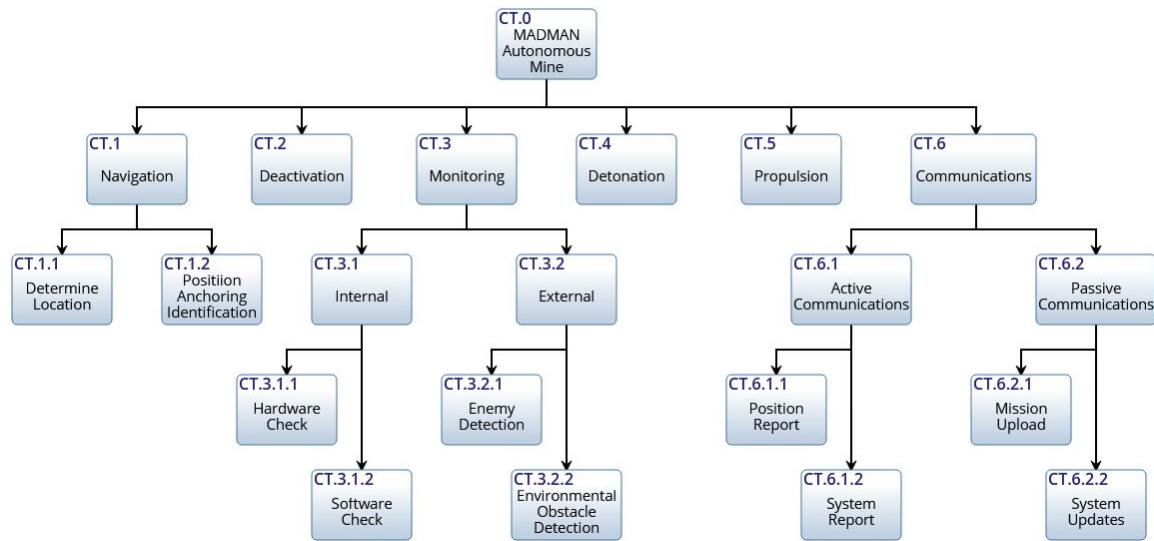


Figure 16. Capability Hierarchy of the MADMAN.

### 1. Navigation

Early stakeholder analysis indicates that MADMAN's design should include transit to the mission location autonomously. Multiple options exist for MADMAN to determine location, ranging from external fix sources such as GPS or inertial navigators. Regardless of the method employed, MADMAN must be able to determine its location

upon reaching the final deployment area within mission parameters to facilitate knowledge of the deployment sites by external entities, and recovery of MADMAN following the conclusion of its mission. The desire for communicating position data with the operational commander once MADMAN reaches its deployment location allows for real-time mission adjustment if necessary.

## **2. Deactivation**

Autonomous deactivation of MADMAN provides a greater margin of safety to outside entities that might have to interact with the deployed system. Autonomous deactivation and activation will provide operational commanders flexibility to transit known mined areas during the conflict aiding in psychological warfare and increasing safety upon changes to the scope of armed conflict. Remote deactivation of MADMAN also improves safety for personnel deployed to deactivate and dispose of deployed systems with the added benefit of minimizing the time required to restore free navigation of the seas post-conflict. However, personnel would transit minefields only in an emergency regardless of claimed deactivation.

## **3. Monitoring**

Autonomous monitoring systems support the storage and deployment of armed systems. Before deployment, MADMAN will perform self-checks of all internal critical subsystems. These systems will include the arming, fusing, and firing circuitry, navigation systems, portions of the propulsion systems, and communications. Satisfactory self-checks executed before deployment improve mission effectiveness by ensuring the reliability of stored and deployed systems.

External monitoring systems are required as MADMAN interacts with its deployed environment. MADMAN continuously monitors for nautical vessels that meet its pre-programmed mission criteria for target ships. During the deployment phase of the mission, MADMAN will also have to navigate through the underwater environment avoiding detection by minimizing interaction with undersea objects.

#### **4. Detonation**

Historical purposes of mines lie in asymmetrical warfare. Autonomous detonation is a requirement for naval mines. The MADMAN will have the means of arming, fusing, and firing the installed explosives once it meets the monitoring systems mission thresholds. Depending on the pre-programmed mission parameters, MADMAN functions similarly to an anchored or deployed mine by in place detonation or by the deployment of an encapsulated torpedo to increase the range of the MADMAN's mission effectiveness.

#### **5. Propulsion**

The MADMAN requires the need to covertly mine areas behind enemy lines. Covert mining requires MADMAN to have a means of moving through the water-space undetected by outside entities. MADMAN requires the means of storing energy and employing that energy to move from the deployment area to the mission area. The MADMAN uses navigation systems to determine its location and autonomously changes the propulsion methods as needed to remain in its programmed mission area.

#### **6. Communications**

Communications with MADMAN will occur in two different phases. Pre-deployment communications will occur when personnel are preparing MADMAN for deployment. Personnel conducting preparations to include loading mission profiles up to the system monitor communications conducted during the pre-deployment phase via a hardwire connection to facilities. The MADMAN will autonomously upload self-ran test data and system status to the pre-deployment facilities upon connection.

During the deployment phase, MADMAN will be capable of active and passive communications. Passive communications occurs when personnel are uploading mission parameters and system updates. Personnel conducting preparations to include loading mission profiles and system updates provides MADMAN the means of conducting active communications. The MADMAN will pass location data and activity autonomously to satellite communication systems upon reaching its deployed area. MADMAN continuously runs self-tests while deployed. Should MADMAN fail internal monitoring

tests, the option for active communication abilities to inform combatant commanders of mission failure should be in place. While deployed, MADMAN will also retain the ability to receive passive acoustic communications to facilitate the autonomous deactivation and activation of MADMAN.

## **7. Capabilities Summary**

From defining requirements to decomposing capability taxonomy, a potential system begins to unfold. By highlighting each capability, it is clear that there are certain functions required to enable the system to achieve mission goals. From this breakdown of capabilities, a general design appears. This demonstration of capabilities provides a look at the hierarchy of elements; however, an important aspect of the design is the integration of these capabilities.

### **C. SUBSYSTEM INTEGRATION DESCRIPTION**

Grouping the capabilities described in the previous section into four central systems and underlying subsystems allows for further delineation. By grouping the capabilities into four main systems, it is easier to develop a picture of how these systems relate to one another. Figure 17 highlights the main systems with the subsystems detailed within each of the four blocks.

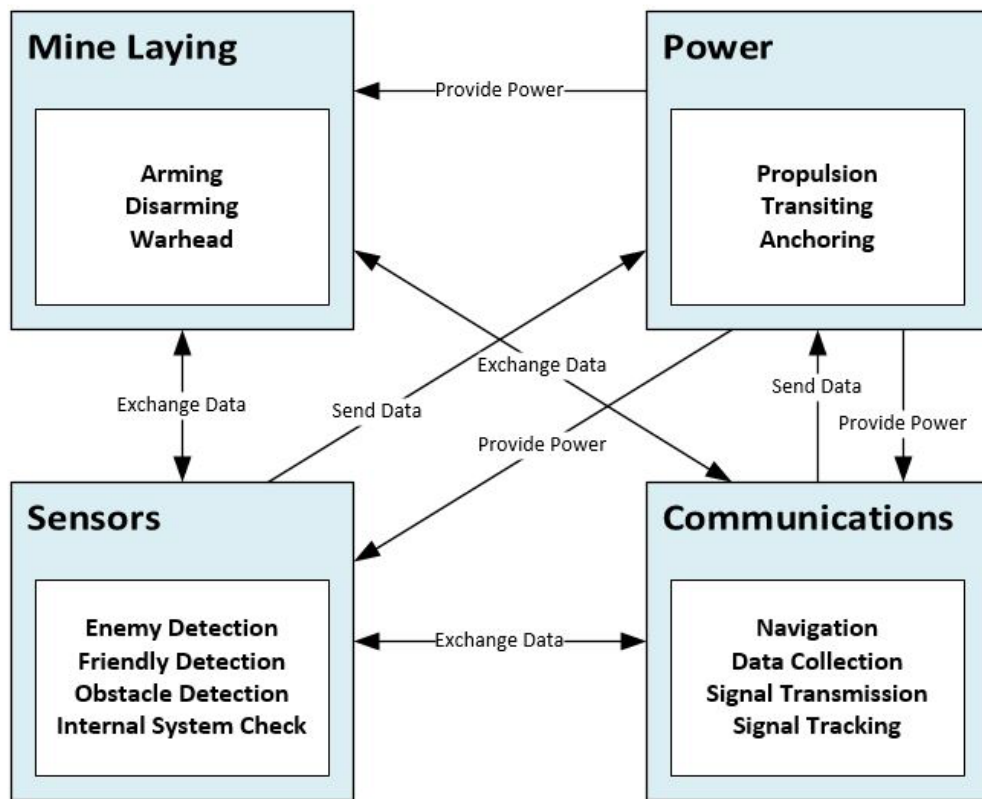


Figure 17. MADMAN Subsystem Diagram.

The mine laying system is crucial to ensuring accurate live mine placement and activation. The subsystems contained within mine laying must receive power to function. The sensor system will exchange data with the mine laying system to ensure that the mine arms at the appropriate time, and for the appropriate reasons. Minelaying also exchanges data with the communications system to determine appropriate signal reception for arming, and in the event of an emergency disarming. The power system provides power to the elements that require some form of power, which is critical to the success of the MADMAN. The power system does not receive any data from the minelaying system. However, both the sensors and communication systems provide data to the power system, triggering MADMAN to provide power for other systems.

The sensors system determines when the MADMAN should perform autonomous actions. Identifying targets of any kind and performing system checks require power delivered from the power system. The sensors system will use the responses from the

sensors to provide data to the mine laying system and communications system. Additionally, it will receive data from these same two systems. The mine laying system will provide sensor data with kill confirmation or mine deactivation data. The communications system will provide the sensors system with updates to area maps, software, or mission details. The communications system, while one-way between external command systems during covert operations, remains bi-directional internally. The communications system will require power to send data between the other three systems. During non-covert operations, the communications system will additionally exchange data between external sources if needed. This system is critical to providing a link outside of the autonomous aspect of MADMAN for any situations requiring involvement beyond initial programming.

A simple high-level list of requirements and capabilities does not refine needs to the point of reaching a design decision. Examination of the concept of operations for the MADMAN and potential mission scenarios is the next step toward agreeing on preferential system design and alternatives.

#### **D. CONCEPT OF OPERATIONS**

MADMAN functions through four separate phases of operation: 1) pre-deployment, 2) deployment, 3) engagement, and 4) post-engagement. The pre-deployment phase includes all activities occurring before deployment of MADMAN. The deployment phase includes all activities occurring between deploying MADMAN from the unit that transported the system to the deployment site until MADMAN autonomously reaches the mission area. The engagement phase includes the activities that occur while MADMAN is in the mission area to include monitoring of the system and environment. The post-engagement phase includes either MADMAN communicating a status of “mission complete” or a loss of signal.

#### **E. MISSION SCENARIO**

The typical mission scenario consists of the elements identified in Figure 18. Each of the four missions has distinct functions associated with it.

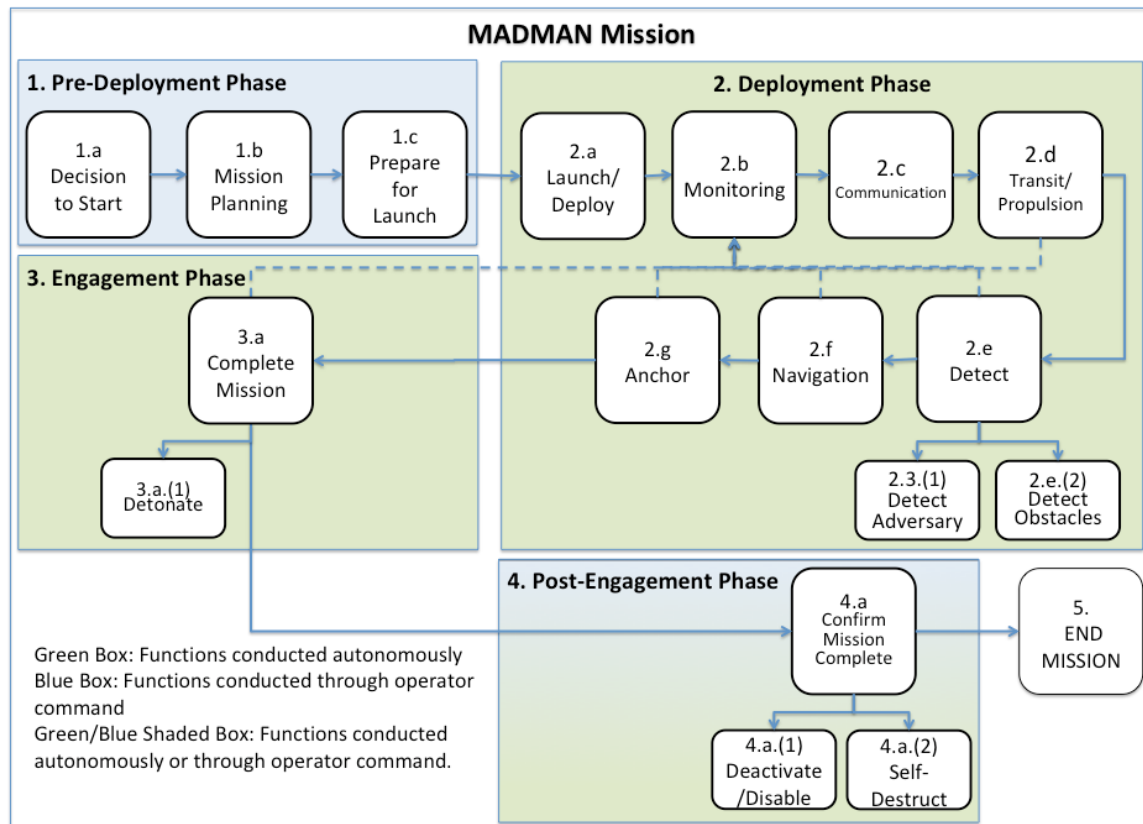


Figure 18. Typical Mission Scenario.

## 1. Pre-deployment Phase

During the pre-deployment phase, MADMAN is located onboard a manned vehicle in storage. The operator removes MADMAN from storage and transfers it to a transfer unit upon selection for mission activity. When installed in the transfer unit, MADMAN powers up upon installation and runs self-monitoring tests. If self-monitoring tests fail, MADMAN alerts operators of failed test and failure condition. Operators will then take appropriate troubleshooting actions to either correct the failure or select another MADMAN system.

Following completion of initial self-monitoring, operators upload mission parameters to the MADMAN system utilizing compatible software. Mission parameters include the geographic waypoints and mission data set including target ship identification (acoustic, pressure, magnetic, and seismic influence parameters) and mission parameters (ship count, waypoints, deployment area coordinates, communication codes, crypto

communication data, and mission timeline). Following successful completion of data upload, MADMAN will remain installed on the transfer unit [an unmanned air/surface vehicle (UxV)] until reaching the deployment area and subsequent deployment of MADMAN.

**a.      *Decision to Start a Mission***

A mission begins when leadership provides a decision to start to the operator. This decision influences the mission-planning step with the necessary planning information.

**b.      *Mission Planning***

The mission-planning step includes identification of the launch dates, times, location, and purpose. The mission-planning phase also includes the pre-planning of software for its mission.

**c.      *Prepare for Launch***

Preparing for launch is crucial to the success of the mission. Mission parameters pre-programmed into the MADMAN ensure accuracy and the latest available data.

**2.      *Deployment Phase***

The transfer unit starts the deployment process. MADMAN, upon notification of impending deployment, obtains location data from the transfer unit, and other external sources. If MADMAN is unable to receive position data, operators attempt to correct the issue or delay deployment operators in the manned vehicle can relay changes to the UxV. The MADMAN will run pre-deployment monitoring tests and must pass them before allowing deployment to continue. If MADMAN's pre-deployment monitoring fails, operators can troubleshoot the issues before deployment. MADMAN must pass all pre-deployment self-monitoring prior to deployment unless overridden by the operator.

MADMAN deploys from the UxV into the water. After deployment away from the UxV, MADMAN performs self-monitoring for all propulsion systems, mission-critical systems, and arming functions. Should this self-monitoring fail, MADMAN can

self-destruct upon operator command. Upon successful completion of waterborne self-monitoring, MADMAN will swim away from the transfer unit until obtainment of the minimum separation distance. After reaching minimum separation distance, and if pre-mission data allows, the initial arming of the device will occur.

MADMAN will autonomously transit through the water using the pre-loaded positional data and dead reckoning to make way to waypoints. It obtains an external fix at each waypoint if MADMAN has the means of obtaining external navigational fixes. MADMAN makes its way toward the mission area monitoring the environment via acoustic data and uses influence capabilities to avoid interaction with undersea obstacles. Once at the final waypoint, MADMAN reports its final position via active communications. If MADMAN is unable to obtain a required fix at any time, its internal position monitoring provides feedback indicating it is unable to maintain the programmed track and MADMAN self-destructs. MADMAN only self-destructs if it is within the safe distance required by the convention of biological diversity to assure civilian safety in these areas.

During the transit, MADMAN needs to overcome ocean currents and sea temperatures. If MADMAN is unable to overcome environmental currents and sea temperature, MADMAN enters a holding pattern for 24 hours, continuously monitoring sea current. Once sea currents lower to the point at which MADMAN can resume track, MADMAN does so. If 24 hours elapse and MADMAN is unable to continue transit, MADMAN self-destructs. Self-destruct only occurs if MADMAN is cleared under international standards for Humanitarian Mine Clearance Operations from affecting ecosystems and non-threatening civilian bystanders near littoral areas, after communicating the inability to follow the programmed mission.

***a. Launch-Deploy***

During the launch-deploy phase, MADMAN performs scenarios under simulation to assure the system is working properly before release from the UxV. The UxV assigns a bay for each MADMAN it carries along with any other issued equipment to complete the

mission. After the transfer of MADMAN onto the UxV, MADMAN accepts orders from the UxV.

***b. Monitoring***

MADMAN periodically monitors system status using the operator's pre-programmed parameters. While monitoring begins in the deployment phase, it continues throughout the engagement phase. Monitoring includes both internal MADMAN system components as well as external environment monitoring. Internal monitoring focuses on hardware and software checks performed throughout the deployment and engagement phases. External monitoring provides detection of adversarial and environmental factors.

***c. Communication***

As the UxV transits to its predetermined location, communications occur with the manned vehicles through the UxV. MADMAN only sends status updates to the UxV to provide assurance of proper configuration and ability to receive orders from the UxV.

***d. Propulsion***

At the designated location, the UxV releases MADMAN to begin transit to the preprogrammed location. Autonomous transit requires navigation and propulsion to work in conjunction with the monitoring function to reach its intended location. MADMAN must autonomously transit to its point of interest. During the transit phase, the mine will have a positioning system guiding as well as a programmed sensor that ensures it does not collide with other objects.

***e. Detect***

MADMAN uses its sensors to detect its surroundings and informs UxV that there is an obstruction in the way of the anchoring point. Once the team knows that MADMAN requires orders for deviation of the route, the mission continues.

(1) Detect Obstacles

During this step, the mine works autonomously around the obstacle with constant communication to the UxV to understand location and status for rerouting. Once informed, MADMAN can begin detour recognition.

(2) Detect Adversary

In addition to obstacles, MADMAN continuously monitors the environment for adversaries. If MADMAN identifies an adversary, additional protocols trigger.

***f. Navigation***

MADMAN navigates through the littoral area with the capability of being undetected throughout the mission. Navigation is the ability to sense, locate, and maneuver around obstacles.

***g. Anchor***

Once MADMAN anchors to the sub-terrain surface, it relays a message of touchdown and requests activation of the mine. Once activation has concurred, MADMAN monitors influence capabilities such as acoustics, pressure, seismic, and magnetics to engage pre-programmed target class.

**3. Engagement Phase**

After MADMAN reaches the final waypoint, it communicates its position. MADMAN completes the arming sequence and commences mission monitoring. Mission monitoring will include internal self-checks in addition to influence monitoring. During a critical failure, such as the inability to maintain power levels, MADMAN requires disposition if within the parameters under International Standards for Humanitarian Mine Clearance Operations. MADMAN continues to monitor acoustics, pressure, seismic, and magnetics. It is necessary to program MADMAN for influence types to ensure it looks for a combination of influences according to target ship classes. Obtaining a combination of thresholds for a pre-programmed target class, MADMAN deploys the encapsulated torpedo to explode under the target ship. While in the mission area, MADMAN will also

monitor for acoustic deactivation signals, either the signal to deactivate for a moment allowing friendly forces to transit the area or an end of mission signal discussed in the post-engagement phase.

**a. *Complete Mission***

MADMAN's three primary missions: 1) Detonate, 2) Deactivate, and 3) Self Destruct contributes to different objectives.

**(1) Detonation**

The purpose of detonation is to cause damage or destroy an adversarial ship or submarine. Detonation occurs in response to input received from detection systems to arm, fuse, and fire the installed explosives after meeting the monitoring systems' mission thresholds.

**4. Post-engagement Phase**

The post-engagement phase begins at the conclusion of the engagement phase. If MADMAN loses communication system operators confirm mission status before proceeding.

**a. *Confirmation of Mission Complete***

Confirmation of mission complete occurs when there is a loss of signal, due to the successful execution of mission when self-destructing or verification of mine deactivation or disabling.

**(1) Deactivate**

The deactivate mission requires MADMAN to disable a mine allowing U.S. forces to control the scale of warfare. By deactivating the mine, U.S. forces can transit the minefields safely for access to and deception from enemy forces. After remote deactivation, reactivation can occur by system operators. Deactivation occurs when the firing system components no longer receive a signal from the arming device.

## (2) Self-destruct

International standards for humanitarian mine clearance operations include disposal and destruction of the mine far from humans. It may be necessary to remove the mine from the littoral area if self-destruct is not an option in the area. This decision, made before deployment, consists of establishing preprogrammed routes so that the mine would detach from the anchor and move to a cleared location for self-destruction. Self-destruct is an option when there is no longer a need for the mine.

## 5. End of Mission

After the mission is complete, data and analysis begin supporting the reporting phase. It is necessary to assess the execution of MADMAN throughout all phases to highlight any issues that may occur. Various alternatives may occur during MADMAN mission, so it is necessary to consider vignettes throughout execution.

## F. VIGNETTES

The following two vignettes provide the basis for developing the concept of operations.

### 1. Vignette 1 – Obstacle Avoidance

During the transit portion, MADMAN detects an obstacle. Using a preplanned alternate route, MADMAN attempts maneuvering around the obstacle and is not successful. If the preprogrammed detour setting cannot execute, it reverts course. MADMAN communicates with the UxV to determine the best route to proceed. Once programmed into MADMAN, the positioning system takes over and creates an alternate route. Once MADMAN proceeds on track, the mission can continue.

### 2. Vignette 2 – Enemy Detection

During the detect function; MADMAN confirms the target as an adversary through ship identification. Detecting an adversary triggers the activation and release of the warhead toward the adversary target (military or commercial). Once the warhead has hit its target, loss of ship identification signals provide confirmation of the kill. If the

signals are still present, the delivery UxV recognizes it failed to eliminate the target. In this situation, the UxV commits other assets to eliminate the target or standby for information from the manned vehicle.

## **G. CHAPTER III SUMMARY**

With specifics of the system understood, the system decomposes into a hierarchy of capabilities, describing what the MADMAN must do to reach mission success. This capability hierarchy highlights areas that should incorporate current technology and areas where gaps may exist, which feed alternatives analysis. The concept of operations provides detail of the MADMAN system to highlight performance from an operational capacity perspective. The concept of operations divides the mission into four phases consisting of a 1) pre-deployment phase, 2) deployment phase, 3) engagement phase, and 4) post-engagement phase. These phases demonstrate where portions of the mission begin and end while displaying which segments contain autonomous features or requirements. Finally, mission scenarios provide examples of MADMAN reacting to potential situations during an active mission.

## IV. FUNCTIONAL ANALYSIS

### A. FUNCTIONAL ARCHITECTURE

This chapter discusses the architectural approach employed in the development of MADMAN. The functional analysis begins with the incorporation of stakeholder needs into key objectives. A functional hierarchy decomposes the typical functions of the MADMAN and aligns them with requirements.

#### 1. Functional Flow Block Diagram (FFBD)

The functional flow block diagram depicted in Figure 19 allows the MADMAN to meet the mission described in the three versions of the OV-1.

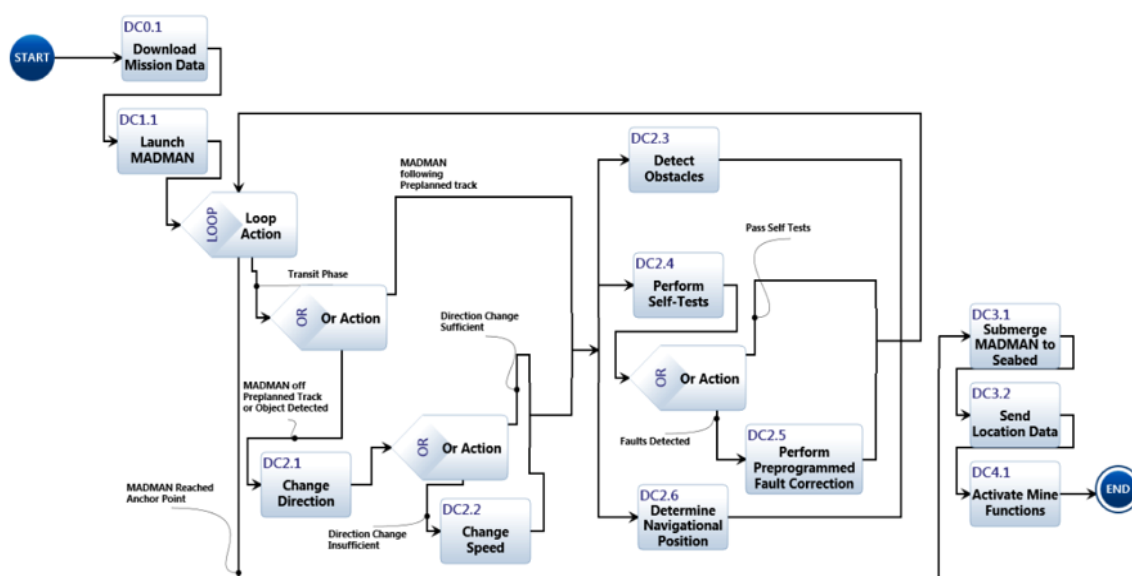


Figure 19. Functional Flow Block Diagram of MADMAN.

The deployment chain shown in modeling and simulation contains three phases 1) Launch, 2) Transit, and 3) Anchoring), however, the FFBD must include the prelaunch activities and after-anchoring milestones. The FFBD shows these activities as “Download Mission Data” (DC0.1)) and “Activate Mine Functions” (DC4.1). Each phase of the FFBD depicts the following.

MADMAN's pre-launch activities are external to MADMAN and occur before the Launch activity. Mission planners must determine the mission profile to include waypoint data. The operator enters waypoint data in a similar process to other autonomous platforms such as Tomahawk cruise missiles. Tomahawk's vehicle changes modes/direction at assigned waypoints. For an underwater device such as MADMAN, each waypoint consists of a location, depth, and speed. Once MADMAN reaches the waypoint, MADMAN changes parameters as required to match the waypoint data. MADMAN uploads mission plan in DC0.1 at the commencement of the FFBD.

Following mission data upload; MADMAN launches. DC1.1 shows the launch function for MADMAN. Modeling and Simulation show launch from multiple launchers; however, launch functions for MADMAN are the same regardless of which side of the launch vehicle the release occurs. The Launch phase includes any clearance maneuvers as well as the deployment of all sensors required for transit. Main motor start occurs following the launch, allowing MADMAN to maneuver away from the launching device. The launch phase ends, and the next phase begins when MADMAN enters the water and moves under its own force with all sensors activated.

The Transit phase encompasses the major portion of the FFBD and contains the majority of all functions that must occur in the FFBD. The transit phase is a feedback loop to allow for external factors such as sea currents as well as external actors such as shipping, sea life, and debris in the water to interact with MADMAN as it follows its route. MADMAN commences transit by determining any direction changes from its previous feedback from Determining Navigational Position (DC2.6) or Detect Obstacles (DC2.3). Should DC2.6 state that MADMAN is off course; it will send required data to Change Direction (DC2.1) to force MADMAN to turn left or right. If DC2.3 senses an obstacle, it would override the input from DC2.6 into DC2.1 to cause a course change away from the object. DC2.1 could also cause MADMAN to change depth as required following reaching a new waypoint. After changing direction, if the navigational demands are large enough, MADMAN could also change speed to assist in regaining track or obstacle avoidance. Regardless, as MADMAN continues to transit, iterations of the transit functional loop DC2.3, DC2.6, "Perform Self Tests" (DC2.4), and "Perform

Preprogrammed Fault Correction” (DC2.5) continually run to detect issues. The transit loop will reiterate at the preprogrammed navigational interval specified by permission planners; this interval will be between 0.25-5min. Once DC2.6 determines that MADMAN has reached the anchor location, the transit loop ends, and the next phase commences.

The Anchoring phase contains two distinct functions “Submerge MADMAN to Seabed” (DC3.1) and “Send Location Data” (DC3.2). DC3.1 causes MADMAN to sustain current depth using propulsion but causes a change in buoyancy resulting in MADMAN to sink to the bottom. Sinking to the bottom is not a recoverable function; once MADMAN is on the seabed, MADMAN will not move again until disposal. MADMAN will sink in such a fashion that all of the deployed sensors required to influence the mine are properly oriented to function. Following, DC3.1 and DC3.2 will release a communication device to transmit the final position of MADMAN back to combatant commanders.

Completing successful release of the communication device, MADMAN enters the deployment phase. The deployment phase requires the activation of mine sensors with “Activate Mine Functions” (DC4.1). At this point, MADMAN completes its mission and the mine portion commences.

## **B. MODELING AND SIMULATION**

There are three potential alternatives identified as candidate MADMAN systems. These alternatives provide different strengths and weaknesses. Identifying the most crucial elements for stakeholders allows modeling and simulation to reveal the system with the highest chance of success. “Models contain increasingly more mathematical and physical details of the system as the design portion of the development phase ends” (Buede 2009). This section presents mathematical details that demonstrate which alternatives perform better and why the results are meaningful to stakeholders.

## 1. Approach

The deployment phase's mathematical model uses Lusser's product law. As illustrated in Figure 20, seven key activities occur as part of MADMAN mine deployment: 1) launch, 2) navigation, 3) propulsion, 4) recovery from internal fault, 5) obstacle avoidance, 6) countermeasures evasion, and 7) anchoring.

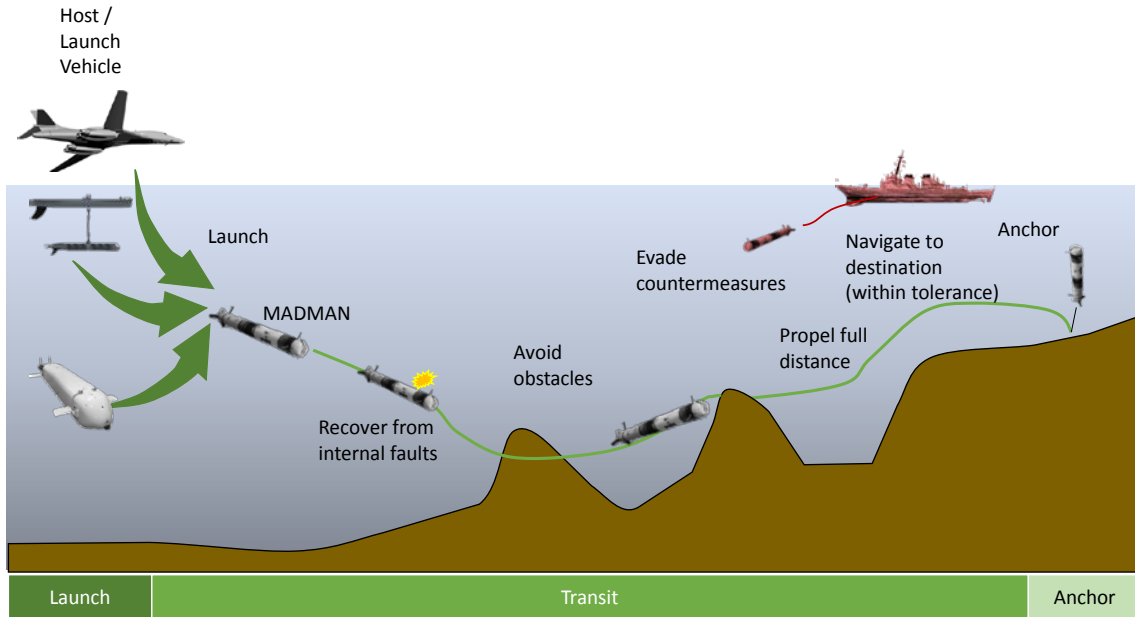


Figure 20. The Deployment Phase.

$P_{\text{deploy}}$ , the overall probability of success in completing deployment, models a chain of serial probabilities associated with each of the key activities. The resulting “deploy chain” shown in Figure 21 resembles a series reliability network diagram (Green n.d.).

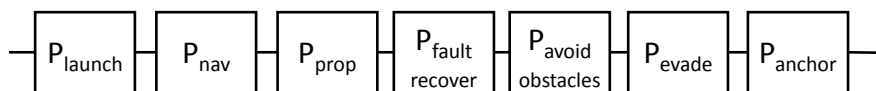


Figure 21. Deploy Chain.

Lusser's product law states “...if a system consists of a series of subsystems, each with no backup, or in reliability engineering terms, with no redundancy, then the

reliability of the system is the product of reliabilities of the subsystems” (Bradley 2016). Thus,  $P_{\text{deploy}}$ , the probability of success in completing the autonomous deployment, expresses the product of the probabilities of success for each activity included in deployment.

$$P_{\text{deploy}} = P_{\text{launch}} \times P_{\text{nav}} \times P_{\text{prop}} \times P_{\text{fault recover}} \times P_{\text{avoid obstacle}} \times P_{\text{evade}} \times P_{\text{anchor}}$$

where:

- $P_{\text{launch}}$  represents the probability that MADMAN successfully launches from its host vessel;
- $P_{\text{nav}}$  represents the probability that MADMAN successfully navigates to a point within the allowable range of the target destination;
- $P_{\text{prop}}$  represents the probability that MADMAN successfully propels itself from the launch location to the target deployment location;
- $P_{\text{fault recover}}$  represents the probability that MADMAN successfully recovers from any internal faults experienced during deployment;
- $P_{\text{avoid obstacle}}$  represents the probability that MADMAN successfully avoids obstacles in its path;
- $P_{\text{evade}}$  represents the probability that MADMAN successfully avoids any enemy attempts to destroy MADMAN or otherwise interfere with its deployment; and
- $P_{\text{anchor}}$  represents the probability of successful attachment (anchoring) at the target destination.

Each of these probabilities must be less than one; therefore, the overall probability of successful deployment will be less than the minimum value of any of these individual probabilities.

## **2. Design Influences on Probabilities of Success**

Characteristics of the selected MADMAN architecture influence the probability factors within the “deploy chain” above.

**a.      *Launch***

Launching requires MADMAN to complete pre-deployment checks and perform personal internal checks that releases it for transit. Effective mining requires the launch and placement of multiple mines to populate the designated minefield. Launch failures that result in fouling of the launch mechanism can prevent the launch of additional mines, thereby risking success in deploying sufficient mine quantities to establish the intended minefield. The risk of launch failures can reduce with the use of multiple launch mechanisms.

**b.      *Navigate within tolerance***

As MADMAN moves to its destination undetected to stay on course and know where it is, is the next challenge. Navigation plays a great part in the transiting of this mine. The mine requires the precision of its location as well as awareness throughout the complete transits. The first influence is establishing an onboard inertial measurement system that consists of an inertial measurement unit and a laser-based vision system. Using low frequency, the vision system creates a position vector of the mine. On the other end of the spectrum, the inertial measurement system uses high frequency to measure accelerations and angular velocities. The result from this multisensory Kalman filter gives the mine a smooth, close loop steering control system (Karras 2007). Similar to obstacle avoidance, the ability to add swarm capabilities for mines communicate greatly improves the probability of an efficient navigation tool.

A swarm can increase the chance of the MADMAN colliding with objects or even avoid obstacles by replicating path that other mines have taken. The last influence apart from these two features is GPS. Another attribute that can give higher probability is GPS, but it requires an outside source to assist in guiding. There are two types of GPS. Periodic GPS only captures MADMAN's position at certain times during the mission or for a certain envelope of time. The other is dedicated GPS, which is designed for a specific mission. Either of the two systems would benefit the MADMAN mission.

**c.      *Propel full distance***

The movement of MADMAN is crucial due to time and distance limits. The mine requires time limits based on the battery life of the system and energy required run of the motor to its destination. Self-propelled mines started production in Russia in the 1970s; they had a capability of speed up to 42 knots and a traveling distance of over 17,000 meters. This can be considered the standard measurements for a self-propelled mine with minor enhancement to the design. Today, the greatest creation is the use of bio mimicry propulsion. In propelling a system, friction absorbs the greatest portion of the energy. To eliminate most of the energy lost to friction, bio mimicry uses patterns and processes from the natural world. Bio mimicry provides advantages in terms of speed, maneuverability, efficiency, and stealth.

**d.      *Recover from faults***

A successful launch produces a better result if the internal system components are equipped to assure mission success. Implementing an increase of software-based fault management increases the probability of recovering from internal system faults. The use of redundant systems can also increase the probability of mission success. With continued technological improvement, smaller, more powerful components can enable redundancy within MADMAN's volume constraints.

**e.      *Avoid obstacles***

Software and addition of redundancy measures address fault issues and creates a greater chance of success. To increase the probability of avoiding obstacles, the following types of software and hardware, working individually or in series, helps reduce the risk of failure. First, the use of cooperative navigation for MADMAN allows a swarm of MADMAN units to more effectively identify obstacles and seek out routes that avoid those obstacles. Another advantage of a swarm system is the ability to offset mines at a certain span of each to cover more area. This offset limits the chance of collision, based on each mine collecting data in transit. This data results in limiting the possibility of encountering unavoidable obstacles.

MADMAN mines may use embedded mapping features to deliver a more accurate understanding of its surrounding during transit. The uploaded terrain map assures a successful transit and reduces encounters of obstacles. The next best tool for increasing the probability of transit incorporates active sonar. “Active sonar transducers emit an acoustic signal or pulse of sound into the water. If an object is in the path of the sound pulse, the sound bounces off the object and returns an ‘echo’ to the sonar transducer” (U.S. Department of Commerce 2013). If the transducer receives signals, it can measure the strength of the signal. These real-time signals are the most accurate images obtained by the MADMAN during its mission.

***f. Evade countermeasures***

As MADMAN transits to its location, engineering analysis revealed the need for avoiding detection. Avoiding detection is highly required but can be difficult to achieve. The use of decoys attempts to reduce detection. As explained in Chapter III, decoys or dummy mines give a better chance for real mines to execute the release of the warhead. Also, decoys give the active mines a better chance to transit and get to their destination in the littoral area. Other evasion countermeasures include the use of quiet propulsion to assist in stealth. As sonar technologies improve, the chances of avoiding detection decrease. The use of systems similar to the Seaglider or Wave Glider does provide improved covert capabilities. Gliders transit at lower speeds, making them harder to detect and allowing them to stay operational for longer periods. Another beneficial feature of glider designs is their tendency to mimic the form and motion of sea life. The movement of the gliders mimics fish and other animals of the sea, which makes it difficult to distinguish between sea life and machinery.

***g. Anchor***

Once the transit completes, and the MADMAN reaches the target location, the mine needs to establish a fixed position. The mine must descend to the seabed, wait for detection of an adversary, and then deploy the warhead. To improve chances of the system executing the mission, MADMAN requires anchoring to the seabed. The first influence for fine-tuning is the weighted base anchor, which once descended releases a

weighted chain tethered to the mine. The conventional weighted anchor does improve the chances of staying in the proper location, but sea currents influence its course. Based on waves and current, anchors with a hooking mechanism provide a better chance for remaining at its required location. A variety of hooks are available for retaining the mine's position.

### **3. Modeling**

The MADMAN performance model utilized various tools including Microsoft Excel and Real Options Valuation, Inc.'s Risk Simulator add-in to perform Monte Carlo analysis of the MADMAN deployment chain model. Using defined sets of deployment-chain probability values, the model performs Bernoulli trials to determine the simulated outcomes for each key activity in the deployment chains. While single events, launch, navigation, propulsion, countermeasure evasion, and anchoring, obstacle avoidance and fault recovery occur multiple times during the deployment phase. To assess these successes in these recurring events, the model calculates an approximate number of each, based on "density" values for faults and obstacles. The model then uses a binomial distribution to model the success or failure of avoiding the number of obstacles encountered and recovering from all faults.

The model repeats this simulation for each of 10 MADMAN units to determine the total number of successfully deployed MADMAN units per run. Given that MADMAN units share launch mechanisms (either one or two), the model requires the availability (not fouled) of at least a single launch mechanism to allow the launch of each MADMAN. Repeated Monte Carlo runs then establish the probability distribution and confidence interval for the number of successfully deployed units.

#### ***a. Probability of successful launch ( $P_{\text{launch}}$ )***

The application of redundant launch systems influence  $P_{\text{launch}}$  through modeling the use of one or two launchers (Figure 22 and Figure 23 respectively) to execute launch operations for the modeled set of mines. The model separately tracks the operational status (ready or fouled) for each launcher. When the model executes for a single launcher

scenario, launcher 1 status must be ready to allow the simulated mine to launch; a fouled indicator prevents the launch of the mine and any subsequently modeled mines.

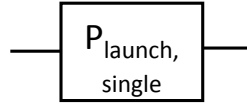


Figure 22. Single Launch Mechanism Model for  $P_{\text{launch}}$ .

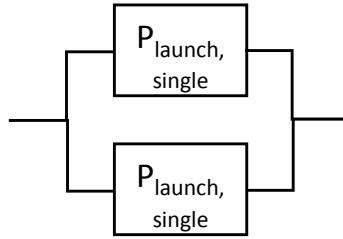


Figure 23. Dual Launch Mechanism Model for  $P_{\text{launch}}$ .

The model assumes that any MADMAN unit can launch from any non-fouled launch mechanism and that, once a launch mechanism is fouled, recovery will not be quick enough to support the launch of additional MADMAN units. Thus, when a two-launcher scenario runs, the model allows a mine launch as long as at least one of the launchers remains ready. When a single launcher scenario runs, the model ceases to launch 10 MADMAN units once a single launch fails and renders the launch mechanism fouled. Once confirming the availability of a launch mechanism, a single Bernoulli trial of probability  $P_{\text{launch}}$  executes to determine the outcome of the launch attempt. If the launch is successful, the model continues to the assessment of the next activity, navigation.

***b. Probability of successful navigation ( $P_{\text{nav}}$ )***

The probability of successful navigation, modeled as another Bernoulli trial of probability,  $P_{\text{nav}}$ , (Figure 24) where success defines the placement of the mine within the acceptable error distance of the desired anchoring location.

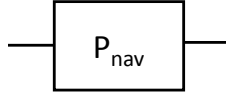


Figure 24. Probability of Successful Navigation ( $P_{nav}$ ).

Failure in this Bernoulli trial leads to a misplaced mine that cannot contribute to the minefield. It is important to consider that this strict assumption might not be correct; a misplaced mine could still contribute to the minefield but potentially not with the intended effectiveness. Large navigation errors could even place the mine in a location that hinders blue force access. If navigation within this range is successful, the model continues to the assessment of the next activity, propulsion.

**c. Probability of successful propulsion ( $P_{prop}$ )**

The probability of successful propulsion throughout the transit,  $P_{prop}$  (Figure 25), assesses MADMAN's ability maintain motion through the water for the full distance required to reach the designated target destination.

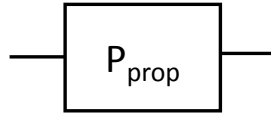


Figure 25. Probability of Successful Propulsion ( $P_{prop}$ ).

The model performs a Bernoulli trial of probability  $P_{prop}$  to determine the outcome of the MADMAN unit's propulsion. Failure in this Bernoulli trial leads to a lost mine that cannot contribute to the minefield. If navigation within this range is successful, the model continues to an assessment of the next activity, fault recovery.

**d. Probability of successful fault recovery ( $P_{fault\ recover}$ )**

As previously stated, the MADMAN unit may experience one or more internal system failures during the deployment. System failures include a broad range of possible problems such as computer failure or spontaneous reboot, other data system errors, and electrical system faults. Although some of these failures may also contribute to other

probability factors, such as  $P_{nav}$  and  $P_{prop}$ , this simple model does not include such coupling factors.

For each MADMAN unit, the model computes the time of the first fault using an exponential distribution function and an assumed MTBF. The model then compares the time of first fault to the deployment time to determine if the fault occurs during deployment. If so, the model performs a Bernoulli test to determine whether MADMAN successfully recovers from the fault as seen in Figure 26.

For each MADMAN unit, the model computes the time of the first fault using an exponential distribution function and an assumed MTBF. The model then compares the time of first fault to the deployment time to determine if the fault occurs during deployment. If so, the model performs a Bernoulli test to determine whether MADMAN successfully recovers from the fault.

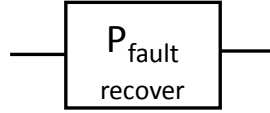


Figure 26. Probability of Fault Recovery during Deployment.

***e. Probability of successful obstacle avoidance ( $P_{avoid\ obstacle}$ )***

The model assesses MADMAN's ability to avoid obstacles using a technique similar to that described above for failure recovery. Given an input "obstacle density," a normal distribution defining the number of obstacles encountered per unit distance, the model predicts "n", the total number of obstacles that the MADMAN unit will encounter over the total distance traveled.

For each MADMAN unit, the model computes a random number of obstacles, "f", experienced across the deployment range "x" using an exponential distribution function. The model then uses a given probability of single obstacle avoidance,  $P_{avoid\ single}$ , computes  $n_{avoid}$ , the number of sequential obstacles that the MADMAN unit will successfully avoid before its first failed attempt as a random number of binomial distribution as seen in Figure 27.

A MADMAN unit must avoid all obstacles to complete deployment. Thus,  $n_{\text{avoid}}$  must be equal to or greater than  $n$  for a successful deployment. If this is the case, the model continues on to an assessment of the next activity, countermeasure avoidance. However, if  $n_{\text{avoid}}$  is less than  $n$ , the MADMAN unit fails and unable to contribute to the minefield.

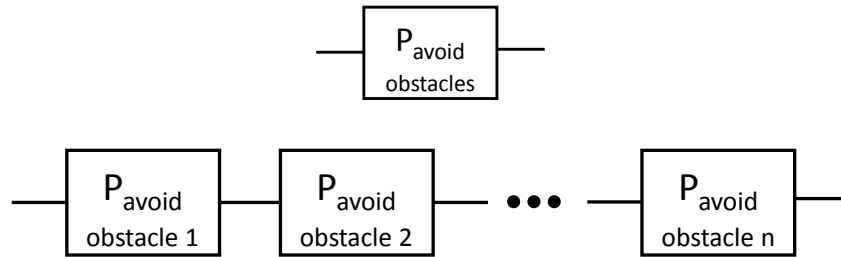


Figure 27. Probability Chain for Avoidance of Multiple Obstacle Avoidance.

***f. Probability of successful countermeasure evasion ( $P_{\text{evade countermeasures}}$ )***

The model decomposes evasion of countermeasures into two activities and corresponding probabilities—detection avoidance, represented by  $P$ , and kill avoidance, represented by  $P_{\text{kill}}$ . Given these probability parameters, the model performs one or two Bernoulli trials. The first Bernoulli trial assesses the MADMAN unit’s success in avoiding detection. If the MADMAN unit fails to avoid detection, the model performs a second Bernoulli trial to determine the ability of a countermeasure weapon to intercept and “kill” the MADMAN unit. If the MADMAN avoids detection, launching countermeasures is not necessary, and the model transitions to the assessment of the next activity, anchoring.

This “one-shot” approach constitutes a very simple countermeasure model. Using models that are more sophisticated could study an enemy’s use of continuous searching. Continuous searching techniques increase MADMAN’s probability of detection as it approaches and allows time for multiple countermeasures. More sophisticated models may support a better understanding and lead to improving the possibility of not destroying the MADMAN unit before it reaches its destination.

***g. Probability of successful anchoring ( $P_{\text{anchor}}$ )***

The model assumes that each MADMAN unit may make a single attempt to anchor at its target location. Given an input probability of success, the model performs a Bernoulli trial of probability  $P_{\text{anchor}}$  to determine success or failure to anchor. If the MADMAN unit is successful in this Bernoulli trial and all previous activities during deployment, the mine counts as a part of the minefield. If MADMAN anchors unsuccessfully, it is considered lost and therefore not a part of the minefield. Anchoring is critical to the successful execution of MADMAN. In an unanchored condition, the MADMAN unit may become a hazard to surface or underwater craft causing unanticipated harm.

Depending upon the system, there are multiple possibilities for probability results. The combination of these probabilities determines the overall probability of the deployment chain and overall effectiveness of the MADMAN. These probabilities potentially require individual increases to meet the overall system objective probability. An examination of the improvements needed allows the system to reach a goal probability, which addresses the aspects of system design that falls short and demands improvement.

**4. Simulation Results and Sensitivity Analysis**

Cost, complexity, and stakeholder desires affect the merit of increasing probability for a particular part of the deployment chain. The models presented in this paper represent a target endpoint of mission success probability. The individual probabilities that comprise the deployment chain represent segmented systems that need to perform at a certain level for MADMAN to reach an overall target probability. Developing an accurate account of the probabilities in these individual systems requires a sensitivity analysis. Each system requires a certain probability of success based upon the performance of other probabilities. Many of those systems carry different levels of importance or weights and as such, may mean more to a stakeholder.

Initial simulation efforts focused on the assessment of mine deployment success rates for each of the three architecture alternatives. Key output parameters related to the

number of delivered mines—the 95% confidence level, the median value, and the mean value—provided a basis for comparison. Table 5 summarizes the assumed simulation input parameters for each design alternative. Note that several of these inputs describe the mission and environment, rather than the attributes of the design itself. Subsequent sensitivity analysis varied these mission and environment inputs to assess design architecture robustness in varying conditions.

Table 5. Design Alternative Simulation Inputs.

| Characteristic                                                                | Variable                       | UUV   | Wave Glider | Aircraft |
|-------------------------------------------------------------------------------|--------------------------------|-------|-------------|----------|
| Probability of successful launch                                              | $P_{1 \text{ launch}}$         | 0.98  | 0.98        | 0.98     |
| Number of launch mechanisms                                                   | $n_{\text{launchers}}$         | 2     | 2           | 2        |
| Probability of navigating to target location within acceptable distance error | $P_{\text{nav}}$               | 0.995 | 0.999       | 0.98     |
| Deployment distance, nm                                                       | $x_{\text{transit}}$           | 12    | 25          | 3        |
| Probability of propulsion functions supporting deployment to full distance    | $P_{\text{prop}}$              | 0.99  | 0.999       | 0.99     |
| Cruise speed, knots                                                           | $v_{\text{cruise}}$            | 4     | 3           | 4        |
| Probability of successfully avoiding a single obstacle                        | $P_{\text{avoid 1 obstacle}}$  | 0.99  | 0.9         | 0.99     |
| Obstacle density, mean, nm                                                    | $\mu_{\text{obstacles/nm}}$    | 0.1   | 0.1         | 0.1      |
| Obstacle density, standard deviation                                          | $\sigma_{\text{obstacles/nm}}$ | 0.02  | 0.02        | 0.02     |
| Probability of successfully recovering from a single fault                    | $P_{1 \text{ fault recover}}$  | 0.99  | 0.98        | 0.99     |
| Mean time between failures (MTBF) hours                                       | MTBF                           | 100   | 100         | 100      |
| Probability of evading detection                                              | $P_{\text{evade detect}}$      | 0.95  | 0.9         | 0.5      |
| Probability of evading intercept                                              | $P_{\text{evade intercept}}$   | 0.9   | 0.7         | 0.9      |
| Probability of successful anchoring                                           | $P_{\text{anchor}}$            | 0.999 | 0.999       | 0.999    |

The initial goal for these simulations was to achieve high-reliability demonstrating 95% confidence in the deployment of 10 mines. Simulations involved the deployment of 10 MADMAN units from one; two, or three launch mechanisms using each of the deployment architecture options (UUV, Wave Glider, and Aircraft). Table 6 depicts the results from these simulations.

Table 6. Mines Delivered (out of 10) for Each Deployment Architecture Alternative.

| Category                           | UUV   | Wave Glider | Aircraft |
|------------------------------------|-------|-------------|----------|
| <b>95% Confidence (right tail)</b> | 8     | 5           | 7        |
| <b>Mean</b>                        | 9.440 | 7.228       | 8.992    |
| <b>Standard Deviation</b>          | 0.898 | 1.498       | 1.073    |
| <b>Median</b>                      | 10    | 7           | 9        |

Although the UUV alternative did exhibit a median of 10 mines deployed, the 95% confidence level for UUV mine deployment was only eight. In fact, none of the alternatives supported a high confidence delivery of 10 mines. Additional simulation scenarios using 12, rather than 10 MADMAN, launches successfully achieved the high confidence delivery goal. Table 7 displays the results from these simulations.

Table 7. Mines Delivered (out of 12) for Each Deployment Architecture Alternative.

|                                    | UUV    | Wave Glider | Aircraft |
|------------------------------------|--------|-------------|----------|
| <b>95% Confidence (right tail)</b> | 10     | 6           | 9        |
| <b>Mean</b>                        | 11.310 | 8.678       | 10.778   |
| <b>Standard Deviation</b>          | 1.110  | 1.674       | 1.258    |
| <b>Median</b>                      | 12     | 9           | 11       |

Figure 28 compares the histogram results for the 10 and 12 mine deployment simulations for each design alternative.

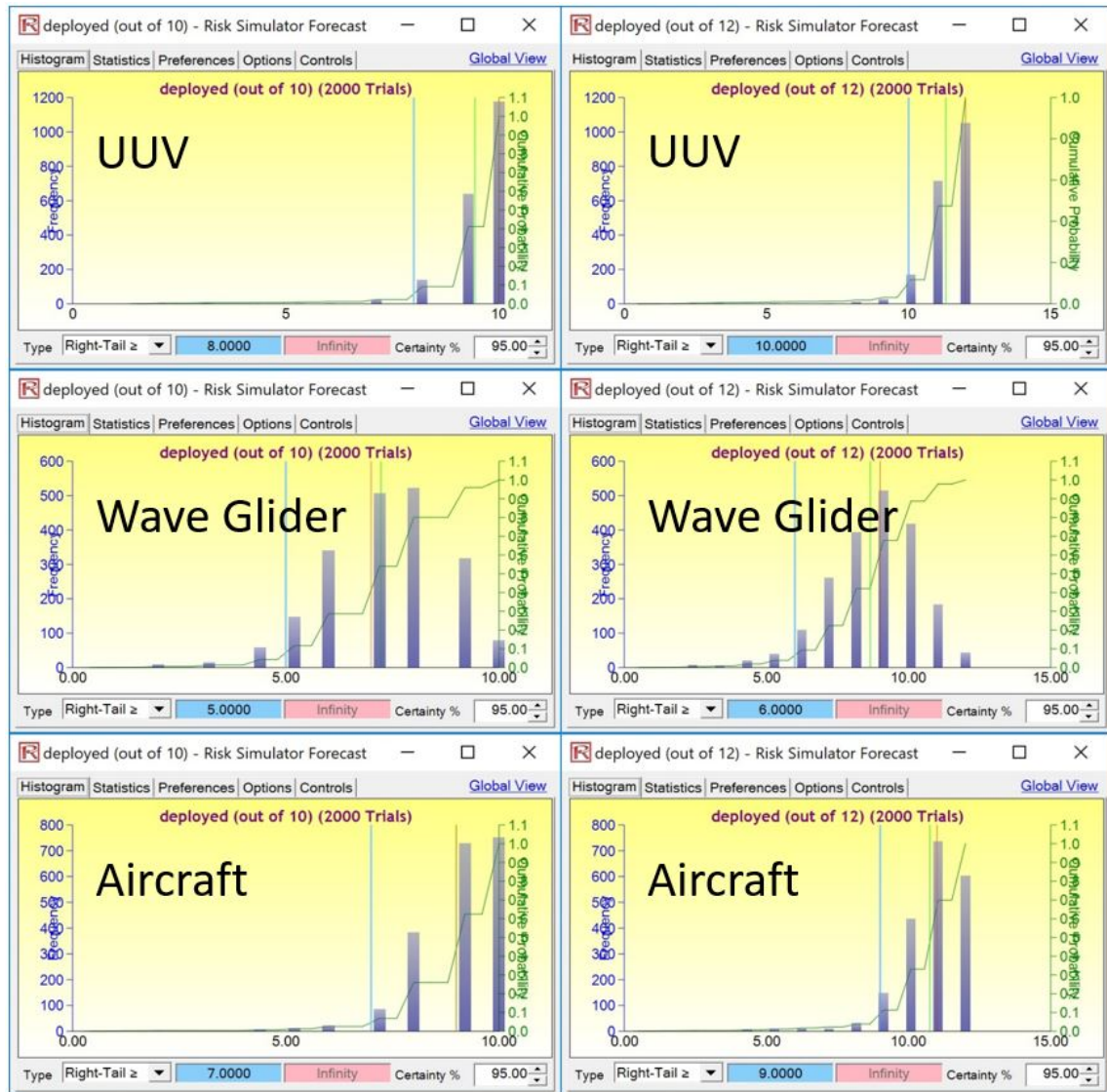


Figure 28. Comparison of Mine Deployment Results for Each Design Alternative.

The UUV option performed well across the board, and those results allow for a detailed sensitivity analysis. In the following sections, the examination of each probability and potential alternate scenario offers a perspective of how each probability affects the overall system. Performing the sensitivity analysis on the UUV data provides results that identify behaviors that other alternatives would exhibit.

**a. Launch**

The tornado analysis assists in the understanding of the effects of simulation output. Figure 29 presents the design performance factors and their influence on the overall success probability of the UUV-derived MADMAN design.

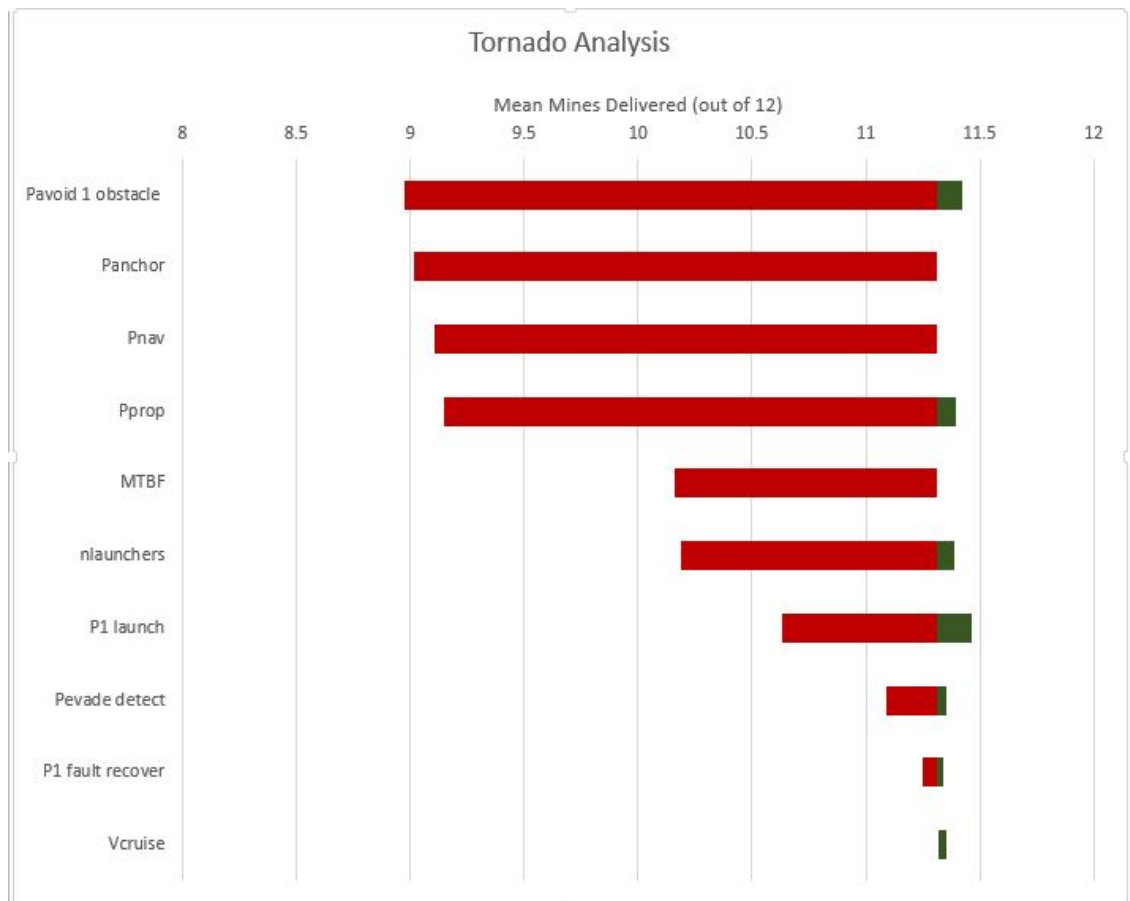


Figure 29. Tornado Analysis of System Probabilities and Elements.

The tornado analysis illustrates the relative impact of each design characteristic on overall system success probability through the size of corresponding bars. Red bars indicate the effect of design characteristic values less than those of the baseline case. Green bars indicate the effect of values greater than the baseline. Overall, the predominance of larger red bars over green bars indicates that most of the baseline design characteristic values are near the values that provide the highest probability of success. However, four characteristics— $P_{\text{avoid 1 obstacle}}$ ,  $P_{\text{prop}}$ ,  $n_{\text{launchers}}$ , and  $P_{\text{1 launch}}$ —show some

potential to yield an increased probability of success if their values increase beyond those in the baseline case. The tornado analysis also reveals the potential that some design characteristic values could lower without significant impact on overall system performance. Such decreases could reduce development constraints and costs. The limitation of this diagram is that only focuses on the raw simulation results and does not account for stakeholder preference. However, this tool presents elements that need to factor into the final decision-making due to the level of influence on the actual system design. With these raw metrics providing insight into how the system behaves from a baseline perspective, the focus shifts to potential improvements in the design.

**a. Launch**

The probability of launch success is the first step to building a minefield. Launch systems, proven in many cases of active warfare, suggests that the importance of improvement would be trivial. However, stakeholders would argue that without a successful launch, there is no minefield. Similar to the other subsystems, the launch system requires operational capability demonstration. Improving the launch system would likely not be realistic for the development of MADMAN and would require a separate endeavor. The simplest way to improve the probability to this system would be to add redundancy. Adding more than one redundant system would only increase the probability to a marginal degree Table 8 and add cost.

Table 8. Marginal Increase for Redundant Launch Systems.

| <b>2 Launchers at 0.98 Probability of Success</b> | <b>3 Launchers at 0.98 Probability of Success</b> |
|---------------------------------------------------|---------------------------------------------------|
| $(1-(1-0.98))^2=0.999600$                         | $(1-(1-0.98))^3=0.999992$                         |

Figure 30 provides a graphical view of the sensitivity analysis conducted on both the probability of successful single launch and the number of available launch mechanisms. Sensitivity analysis further demonstrates that increasing beyond a single redundancy is not necessary in the case of the UUV.

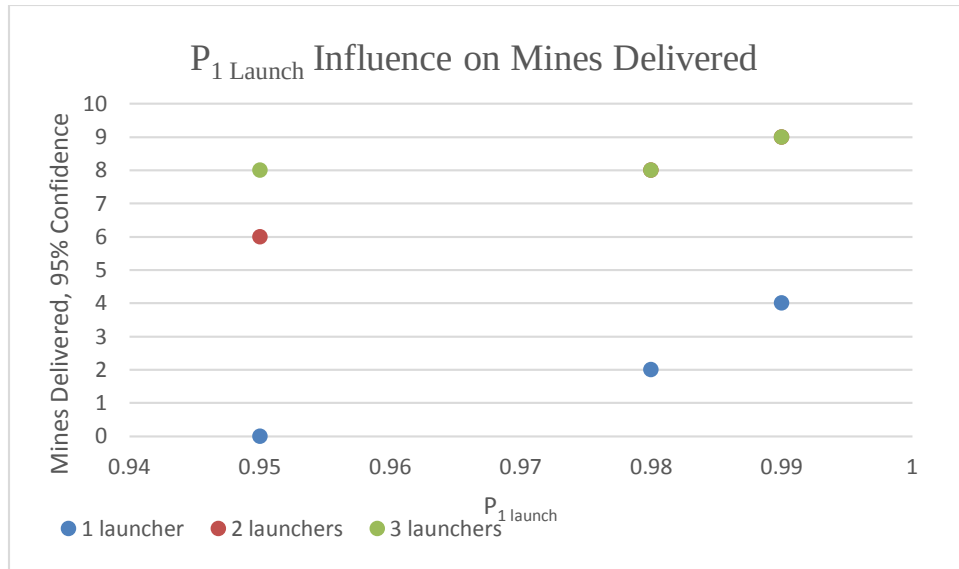


Figure 30. Launcher Redundancy Sensitivity Analysis Example for UUV Option.

#### ***b. Navigation***

The navigation system determines the success probability of MADMAN reaching the correct location. Various forms of automated navigation exist and operate properly. Unlike the launcher system, redundancy would not improve the probability of success for the navigation system. Improving the system may not be feasible from an effort perspective. With an allowable margin of error to reach a higher probability, the navigation system does not require perfection. The mines must still reach a general area for developing the minefield.

The probability of successful navigation to a target destination (within an acceptable error),  $P_{nav}$ , demonstrated expected linear effect on the overall probability of success. As illustrated in Figure 31, even the highest possible  $P_{nav}$  values yielded a maximum 95% confidence value of mines delivered was 10 out of 12.

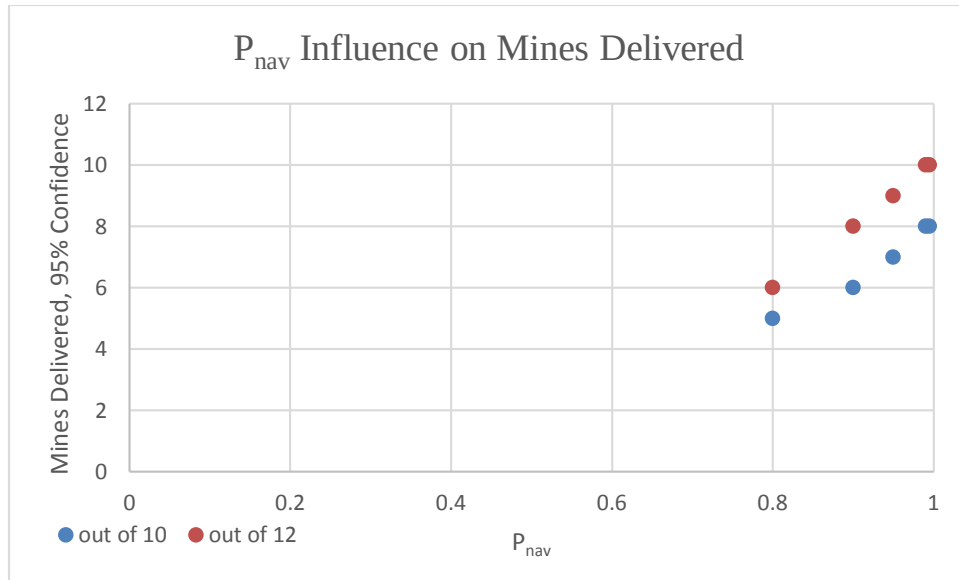


Figure 31.  $P_{nav}$  Influence on Mine Deployment Success.

The original UUV-based design alternative  $P_{nav}$  value of 0.995 then provided no clear advantage over a less challenging—and potentially costly—value of 0.99.

### c. **Propulsion**

The propulsion system is a critical part of the MADMAN deployment. This system moves the mines to a safe distance away from friendly forces and physically delivers them to the minefield. Multitudes of options for propulsion exist. Different levels of power and acoustic signature offer a range of potential components that system alternatives may or may not support. Improving the propulsion system may be feasible depending on the deployment system capability. Through engineering analysis, the propulsion system holds a heavy weight of importance because it combines reaching the target minefield and removing the mine from friendly proximity.

Even with a high stakeholder importance, the probability of successful propulsion across the full deployment distance,  $P_{prop}$ , also demonstrated the expected linear effect on the overall probability of success. As illustrated in Figure 32, even the highest possible  $P_{prop}$  values yielded a maximum 95% confidence value of mines delivered of 10 out of 12.

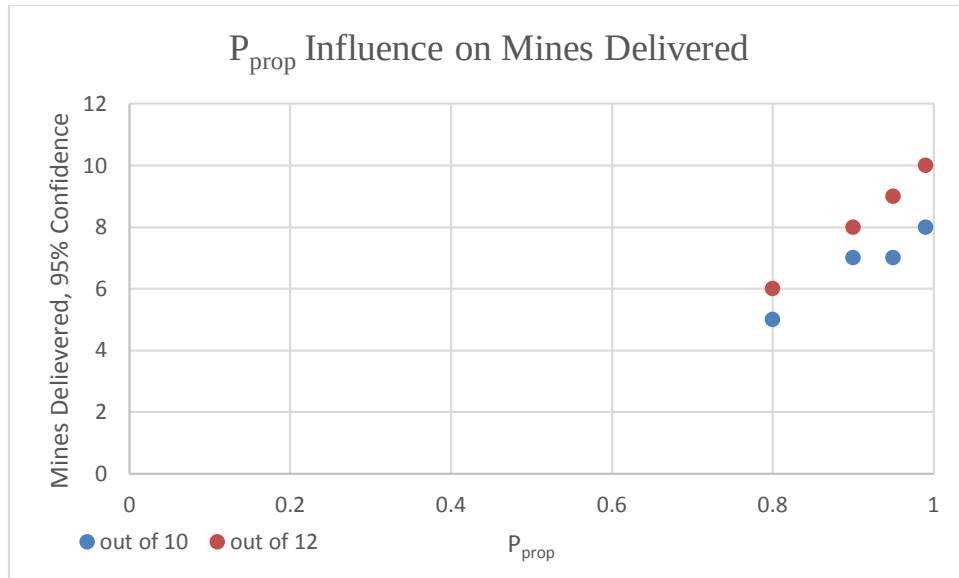


Figure 32.  $P_{prop}$  Influence on Mine Deployment Success.

The original UUV-derived design alternative  $P_{prop}$  value of 0.99 demonstrated sufficient performance to support mission objectives and satisfy stakeholder needs.

#### d. *Obstacle Avoidance*

The ability for MADMAN to avoid obstacles combines distance traveled and a normal distribution of obstacles encountered per unit of distance traveled. In a perfect scenario, MADMAN would reach a target destination without encountering anything in the path to the minefield. In littoral waters, especially in combat zones, obstacles are more common than in open water, and the mines must have the capability to identify and avoid anything preventing reaching the target minefield location. The mine must avoid obstacles, but from a stakeholder perspective, the likelihood of encountering obstacles before reaching the minefield is relatively low in most situations; however, modeling high traffic areas was still necessary.

The UUV design alternative required assessment for mine deployment capability across a range of obstacle densities. Modeling consisted of densities using a normal distribution with varying means and standard deviations. Results summarized in Figure 33 demonstrate the profound effect of increasing obstacle density on mine deployment success.

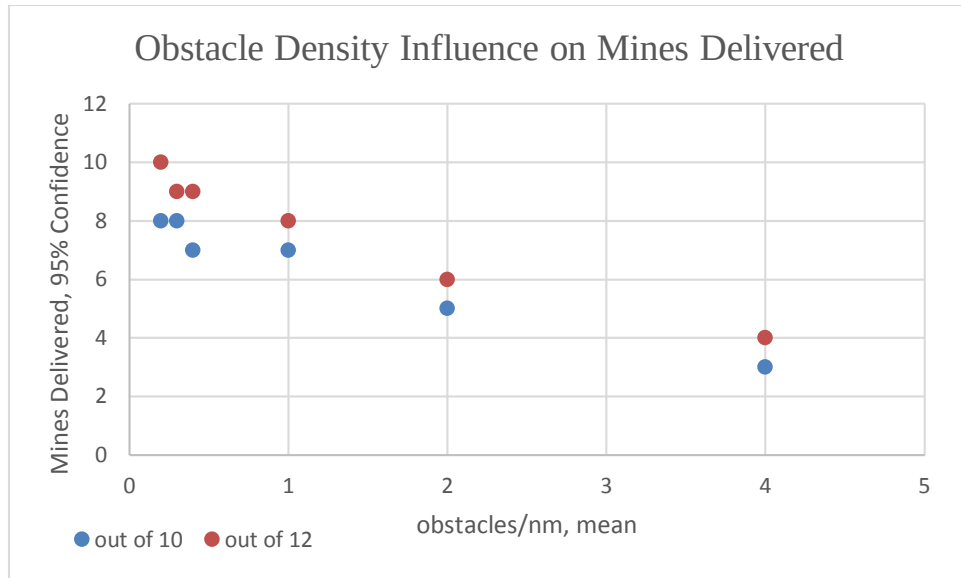


Figure 33. Obstacle Density Influence on Mine Deployment Success.

To address the reduced performance in these obstacle environments, additional simulations investigated the effects of increased  $P_{\text{avoid 1 obstacle}}$  (as high as 0.9999) on overall mission success. Simulations assumed an obstacle density function as a normal distribution of mean 0.4 objects/nm and standard deviation 0.08. Results from these assumptions appear in Figure 34.

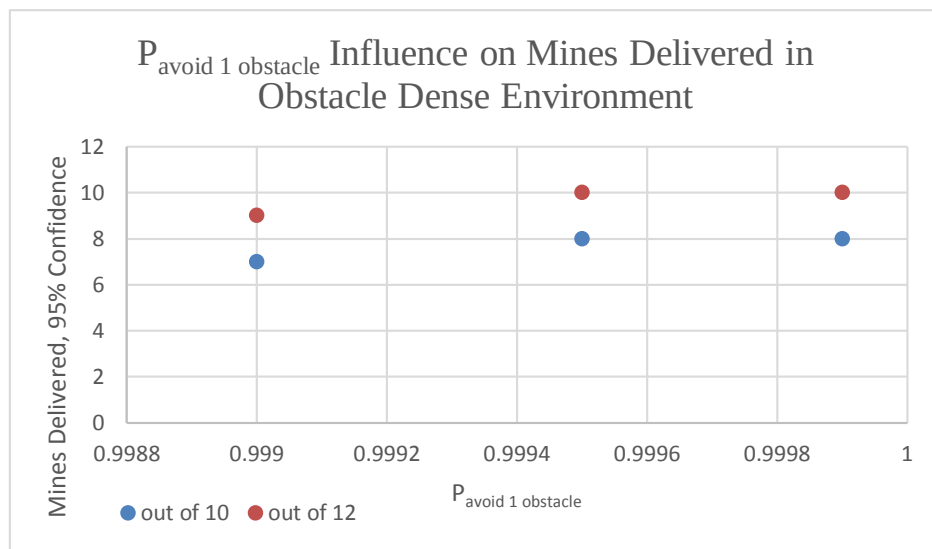


Figure 34. Obstacle Avoidance Probability Variation Impacts on Performance in Dense Obstacle Environments.

This study reveals that an increase of  $P_{\text{avoid } 1 \text{ obstacle}}$  to 0.9995 restored high confidence in successful delivery of 10 out of 12 mines in the dense obstacle environment. Although a low likelihood of obstacle density exists in most areas for developing a minefield, providing these numbers is important to understanding how the system would behave in a high-density environment. This behavior results in the actual mission environment density determining the importance of how well the system responds.

**a. *Fault Recovery***

An autonomous mine will naturally contain a greater amount of electronics than a standard mine. These additional electronics translate to the potential for failure and faults. The model provides a combined MTBF for these elements. The higher the MTBF, the longer a system is more likely to operate without any faults or failures. Since all systems eventually fail to some degree, the model builds in response to this failure and provides a probability of recovering from failure. Additionally, the model takes into account the transit distance traveled. The combination of single fault recoverability, MTBF, and transit distance results in a complete system recovery probability. Available systems have a wide range of MTBF values, suggesting that there are many options available for improvement. If the distance traveled decreases by some method, this would improve the probability of success by lowering the chance of faults occurring. Stakeholders would see fault recovery as necessary; however, the main candidate for improvement is MTBF. With such a broad range of options, improving the deployment fault recovery could involve selecting an alternate device, requiring minimal research.

Repeated simulation with varying probability of successful recovery from a single fault,  $P_{1 \text{ fault recover}}$ , indicated that with the default MTBF approximately two orders of magnitude greater than the mission duration, even significantly lowered probability values had no significant effect on mission outcomes as shown in Figure 35.

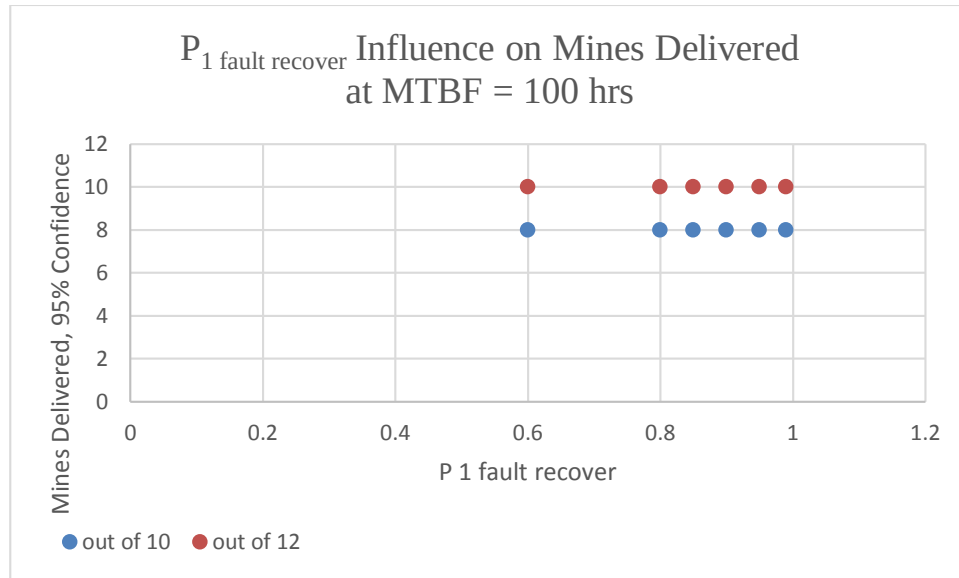


Figure 35. Influence of Reduced Probability of Fault Recovery at Baseline MTBF.

Additional simulations targeted the identification of the lowered MTBF value at which the probability of fault recovery would influence mission performance. As illustrated in Figure 36, this critical minimum MTBF value was less than 10 hours, less than three times the planned mission duration.

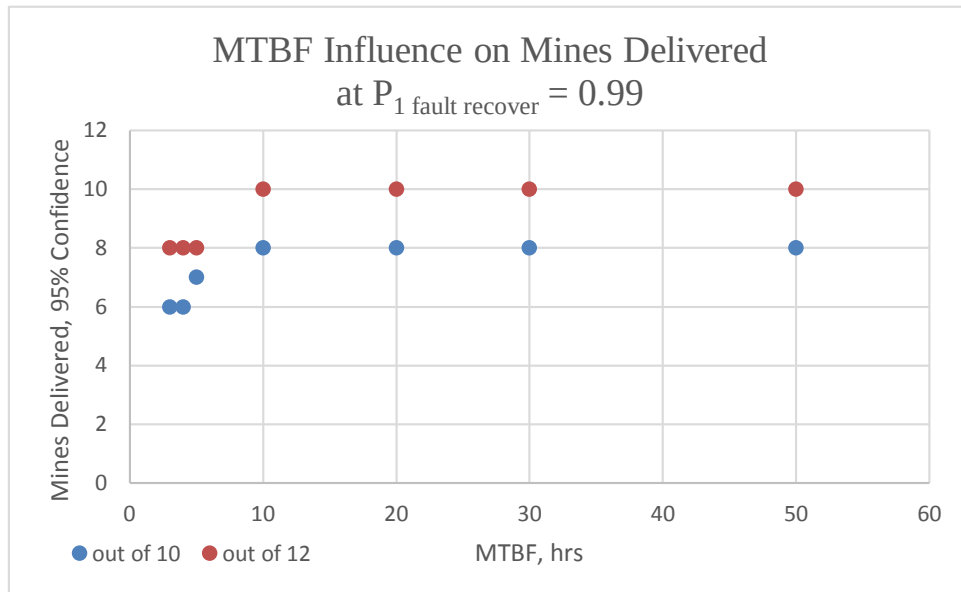


Figure 36. Critical Minimum MTBF.

From these results, a modest reduction in fault recovery probability while preserving overall mission performance, appeared possible. As illustrated in Figure 37, a reduction of  $P_{1 \text{ fault recover}}$  from 0.99 to 0.9 exhibited negligible impact on the number of delivered mines.

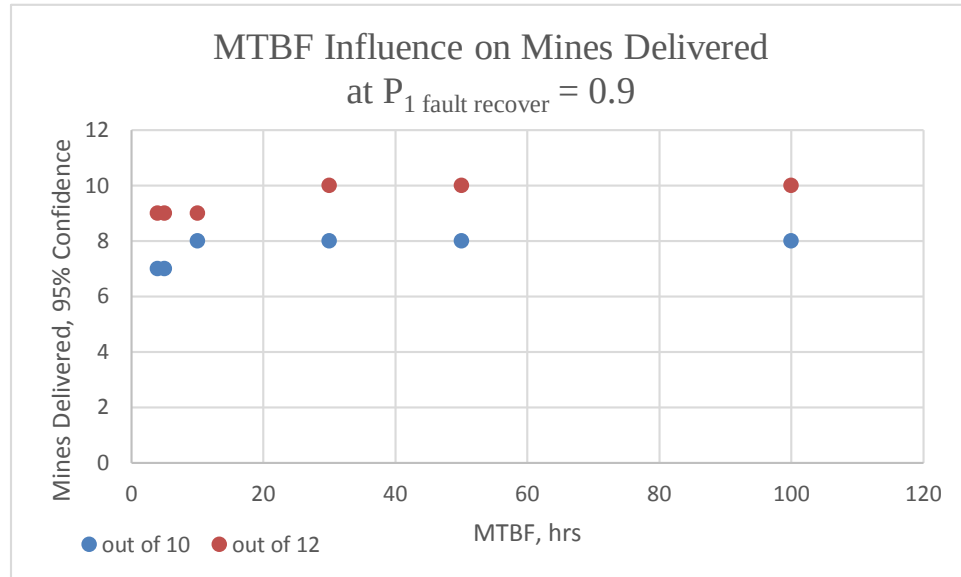


Figure 37. MTBF Sensitivity at Lowered Fault Recovery Probability.

This performance requirement change presented an opportunity to reduce system development cost. While the ability to recover from faults is important to stakeholders, increasing beyond the stated baseline probability for recovery has almost no effect.

#### ***b. Countermeasure Evasion***

Evading enemy forces is a key function for the MADMAN. This system probability incorporates the probability of detection and the probability of interception. This combination of probabilities is unique compared to other combinations because one is purely dependent on the other. If the mine avoids detection, interception cannot occur. Stakeholders are looking for a mine that has stealth capabilities. Decreasing the chance of interception may not be feasible. However, increasing stealth is possible through design choice.

Simulations investigated the effects of varying MADMAN's probability of evading detection. As illustrated in Figure 38, results suggested that decrease of  $P_{\text{evade detect}}$  to values as low as 0.85 had limited effect when MADMAN's ability to evade intercept remained constant at 0.9. This constant of 0.9 represents a relatively low-performance countermeasure (0.1 success rate). Under these conditions,  $P_{\text{evade detect}}$  values as low as 0.85 did not have a significant negative impact on the number of mines delivered.

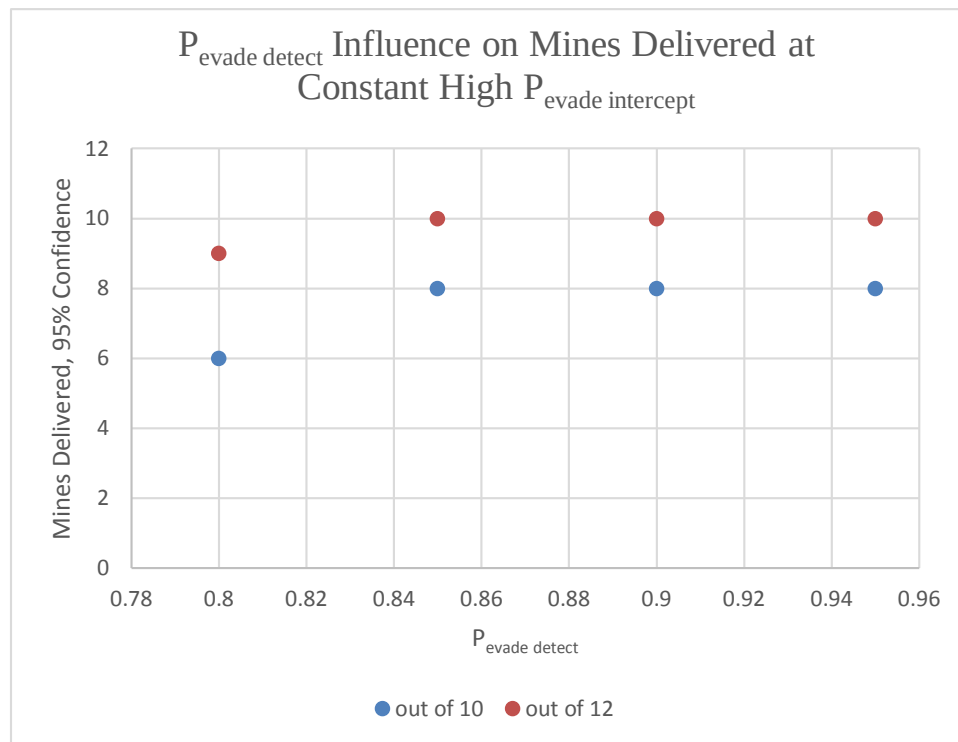


Figure 38. Influence of Varying Probability of Evading Detection on Mine Delivery.

Additional simulations investigated performance against a more advanced countermeasures system with increased ability to intercept MADMAN. This increase in countermeasure ability reflects as a decreased probability that MADMAN would avoid intercept (0.5). Figure 39 illustrates this.

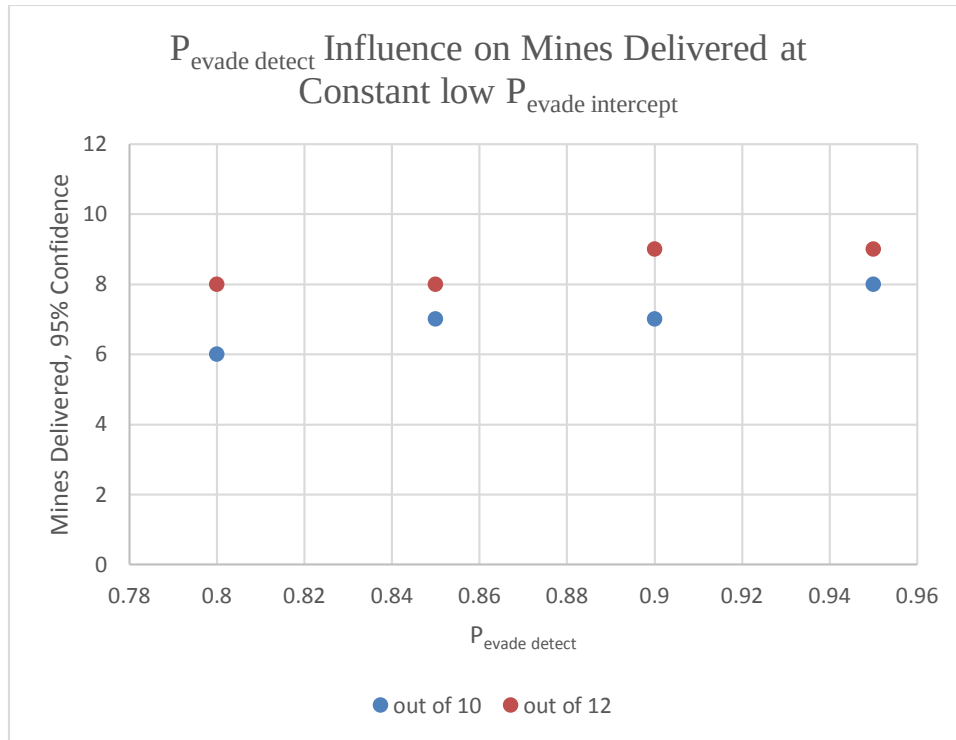


Figure 39. Influence of Varying Probability of Evading Detection against Advanced Intercept Systems.

The figure suggests that, although MADMAN will experience a lower success rate against such an improved countermeasure, the effects of  $P_{\text{evade}}$  detection had a relatively weak influence on the outcome. The lack of influence results in considering alternate areas to improve toward achieving an overall mission probability of success.

#### **a. Anchoring**

The anchor system is required to keep the mine in place when developing the minefield. Improvement of this system would require re-design of current designs. While potentially feasible, stakeholders would not wish to expend valuable resources in developing new anchor systems. In the current state, the anchor system performs as needed and improvement would provide a small success probability improvement.

Multiple simulations of UUV design alternative performance with varying  $P_{\text{anchor}}$  indicated the expected linear impact of this parameter on overall mission success.

However, is illustrated in Figure 40, overall success in deploying 10 mines did not increase substantially with  $P_{\text{anchor}}$  values greater than 0.99.

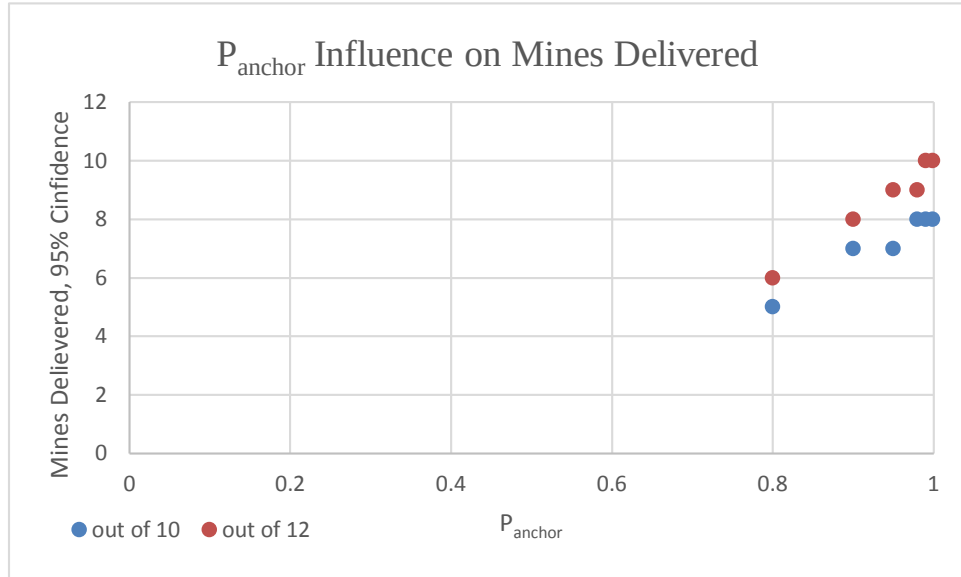


Figure 40.  $P_{\text{anchor}}$  Influence on Mine Deployment Success.

Thus, there is the possibility that the initial design value of 0.999 is overly constraining. A  $P_{\text{anchor}}$  value of 0.99 was determined to be sufficient to meet design goals, given an assumption that 10 of 12 mines deploy.

## 5. Design Alternative Improvement

Given the sensitivity analysis results described above, a new generated design alternative takes advantage of noted opportunities to improve mine delivery performance. This design alternative incorporated opportunities to reduce strict performance requirements in the original design option where those requirements provided little or no increase in the number of mines deployed. These adjustments may allow system developers to focus more resources on factors that provide the most benefit. Table 9 provides the characteristics of this updated design alternative below.

Table 9. Improved Design Alternative Characteristics.

| Characteristic                                                                | Variable                      | Modified Value |
|-------------------------------------------------------------------------------|-------------------------------|----------------|
| Probability of successful launch                                              | $P_{1 \text{ launch}}$        | 0.99           |
| Number of launch mechanisms                                                   | $n_{\text{launchers}}$        | 2              |
| Probability of navigating to target location within acceptable distance error | $P_{\text{nav}}$              | 0.99           |
| Deployment distance, nm                                                       | $x_{\text{transit}}$          | 12             |
| Probability of propulsion functions supporting deployment to full distance    | $P_{\text{prop}}$             | 0.99           |
| Cruise speed, knots                                                           | $V_{\text{cruise}}$           | 4              |
| Probability of successfully avoiding a single obstacle                        | $P_{\text{avoid 1 obstacle}}$ | 0.9995         |
| Probability of successfully recovering from a single fault                    | $P_{1 \text{ fault recover}}$ | 0.9            |
| Mean time between failures (MTBF), hours                                      | MTBF                          | 100            |
| Probability of evading detection                                              | $P_{\text{evade detect}}$     | 0.95           |
| Probability of successful anchoring                                           | $P_{\text{anchor}}$           | 0.99           |

This design alternative compared with the original UUV design in a series of simulations to demonstrate performance under three environments—the original design reference mission (low obstacle density and normal countermeasures capabilities), a denser obstacle environment, and pitted against more advanced countermeasures in Table 10.

Table 10. Original and Modified UUV-Based MADMAN Design Performance in Original Design Reference Mission Comparison.

| Performance (12 MADMAN Units) | Original | Modified |
|-------------------------------|----------|----------|
| 95% Confidence (right tail)   | 10       | 10       |
| Mean                          | 11.310   | 11.41    |
| Standard Deviation            | 1.110    | 0.7957   |
| Median                        | 12       | 12       |

Modeled obstacle density using a normal distribution with a mean of four obstacles/nm generates in the high obstacle density environment simulation. The results

presented in Table 11 reflect a significant advantage for the modified design alternative. Improved probability of obstacle avoidance restored MADMAN's ability to deploy 10 of 12 mines with high confidence, even in dense obstacle environments.

Table 11. Original and Modified UUV-Based MADMAN Design Performance in High Obstacle Density Environment Comparison.

| <b>Performance (12 MADMAN Units)</b> | <b>Original</b> | <b>Modified</b> |
|--------------------------------------|-----------------|-----------------|
| 95% Confidence (right tail)          | 4               | 10              |
| Mean                                 | 5.952           | 11.154          |
| Standard Deviation                   | 1.623           | 0.933           |
| Median                               | 6               | 11              |

Creating an improved countermeasure simulation revealed that both designs assess against interceptor weapons with a 0.5 probability of intercepting and disabling the MADMAN unit. As shown in Table 12, the modified design alternative provided similar performance as that of the original UUV design option.

Table 12. Original and Modified UUV-Based MADMAN Design Performance against Improved Countermeasures Comparison.

| <b>Performance (12 MADMAN Units)</b> | <b>Original</b> | <b>Modified</b> |
|--------------------------------------|-----------------|-----------------|
| 95% Confidence (right tail)          | 9               | 9               |
| Mean                                 | 11.089          | 11.156          |
| Standard Deviation                   | 1.191           | 0.925           |
| Median                               | 11              | 11              |

Thus, in all three environments, the performance of the modified alternative either met or exceeded that of the original UUV-based design. This modified version suggests that utilizing these probabilities serves to meet development costs, timelines, and feasibility targets. By analyzing the behaviors of these probabilities, a system with potential cost and resource savings emerged. By reaching these ideal probabilities, the alternative options compare their native probabilities to an ideal option. Ideal design

alternatives require measurement against satisfying overarching mission requirements and addressing stakeholder desires.

#### **C. CHAPTER IV SUMMARY**

A functional architecture emerges from the FFBD, detailing the behavior of the system. A functional architecture visually provides a logical decision process for the MADMAN that applies to the three alternatives. The method for determining the importance of each subsystem supports metric definition, which allows a direct comparison between alternatives. Following the basic determination of subsystem probabilities needed to provide a successful mission; a sensitivity analysis details the shortfalls. The sensitivity analysis provides insight into where probabilities could decrease to provide cost savings or increase when it would merit a significant improvement in mission success (more mines laid). Resulting new probabilities allow a cost savings while maintaining confidence in mission success. The modeling and simulation performed in this section leads into the strength and weakness discussion of the alternatives.

## V. ALTERNATIVES

Alternative selection can be critical to the development of a successful, efficient system. It may be the case that every alternative option is feasible and functional. The purpose for analyzing alternatives, especially when they are all similar or all attainable, is that it is in the best interest of the U.S. Navy to select the system that has the highest chance for success. Table 13 displays a summary of the requirements and objectives discussed in previous chapters with its corresponding value measure and category.

Table 13. Requirements, Objectives, and Value Measures Linkage.

| <b>MADMAN System Requirements</b>                                      | <b>Key Objectives</b>              | <b>Value Measures</b>          | <b>Category</b>        |
|------------------------------------------------------------------------|------------------------------------|--------------------------------|------------------------|
| The system shall be capable of entering shallow littoral areas         | Access littoral target area        | Transport of Mine              | Technical              |
| The system shall avoid detection while in the active mission area      | Avoid detection                    | Stealth and System Sensors     | Performance, Technical |
| The system shall be deployable                                         | Deployable                         | Operational Range              | Performance            |
| The system shall be able to accept engage and disengage commands       | Respond to mission start and abort | Communications                 | Performance            |
| The system shall autonomously navigate to a pre-defined destination    | Reduce or remove human risk        | Autonomy and Position Accuracy | Technical, Performance |
| The system shall use existing naval mine warhead and influence systems | Sustainable                        | Integration                    | Technical              |
| The system shall reduce risk of human casualty                         | Reduce or remove human risk        | Personnel Risk                 | Personnel Risk         |

Technical measures explore the transport of the mine, autonomy, system integration, and mine sensors. Performance measures include operational range, communication capability, position accuracy, and stealth factor. Cost assesses development, acquisition, and sustainment efforts. Risk is the last of the four categories and includes technical, performance, cost, and personnel risk. Combining these discussions with the modeling serves to provide a complete picture of expected alternative behavior. For evaluating alternatives consistently, the following definitions explain the ratings in each of the categories.

#### High

- Technical characteristics significantly achieve mission requirements.
- Performance characteristics significantly achieve mission requirements.
- Cost is significant requiring extensive modifications.
- Risk significantly impacts mission requirements.

#### Medium

- Technical characteristics moderately achieve mission requirements.
- Performance characteristics moderately achieve mission requirements.
- Cost is moderate requiring some modifications.
- Risk moderately impacts mission requirements.

#### Low

- Technical characteristics partially achieve mission requirements.
- Performance characteristics partially achieve mission requirements.
- Cost is low requiring no or minimal modifications.
- Risk partially impacts mission requirements.

## **A. ALTERNATIVE 1 – UUV DEPLOYMENT**

The unmanned underwater vehicle (UUV) deployment calls for either a ship or submarine to release a self-propelled device carrying a naval mine at a safe distance. The self-propelled device (MADMAN) autonomously navigates from the launch point until the entire device reaches the deployment location upon which it will sink to the bottom and activate the mine portion of the device.

### **1. Technical**

Utilizing a UUV for deployment provides inherited technical capabilities depending on the selected model. There is a broad spectrum of UUVs. Many of those UUV options natively provide features closely aligned with MADMAN objectives. UUVs used in mine countermeasure activities provide navigation, sensors, internal monitoring, and transiting systems. Additionally, they can carry many sizes of payloads internally or externally. The ability to carry different payloads translates to the ability to carry the MADMAN with minor modifications.

Autonomous UUVs that deliver mines and perform offensive mining tasks do not exist. Lacking that delivery is a limitation of the transport ability exhibited by currently fielded systems. The reserved payload space also accounts for the ability to upgrade the sensor suite of the UUV, allowing for proprietary additions and upgrades. Current sensor systems include three dimensional, sonar, magnetic, and electronic detection capabilities with high definition cameras. Preprogrammed sensors provide data to existing programmable software. Currently operating mine countermeasure UUVs are already capable of performing many identification and avoidance tasks required by the MADMAN. The software allows MADMAN to engage in completely autonomous, pre-programmed missions and includes internal system monitoring. The UUV provides nearly every system required to achieve the central goals of MADMAN. From this perspective, integration into an offensive mining capability requires low effort. An example system available for commercial use is the Remus 6000 with many available subsystems as shown in Figure 41.

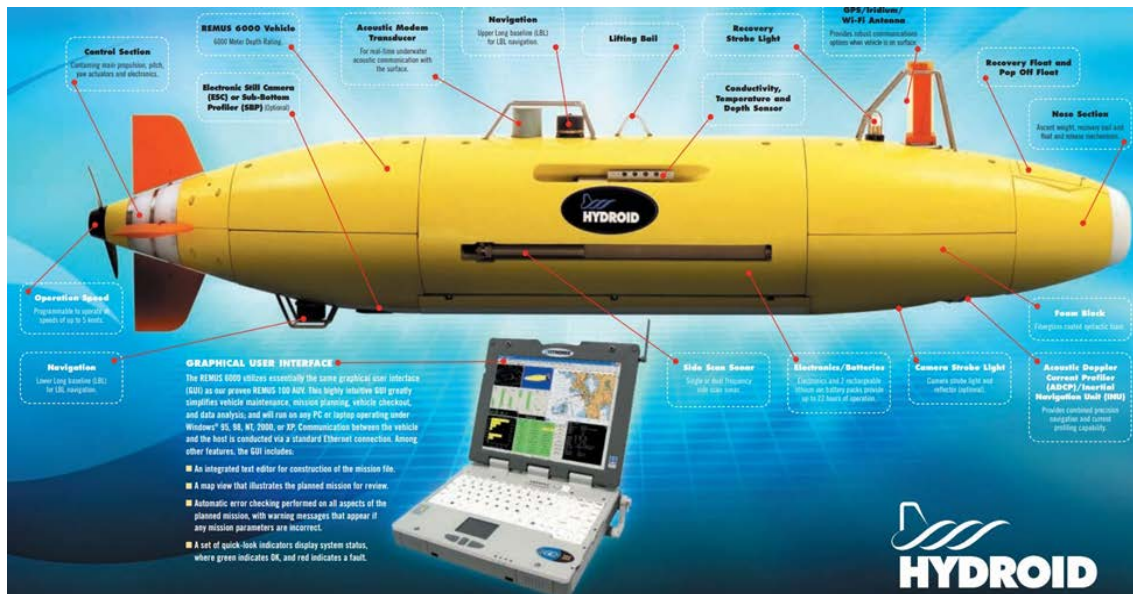


Figure 41. Hydroid Remus 6000 Multiple Features. Source: Hydroid (2015).

The Hydroid Remus 6000 operates at a relatively quick speed on average (about four knots, or two meters per second) and has no requirement to surface during mission operations. This alternative is very favorable from a technical perspective due to the availability of required capabilities and native functions in many UUVs. With an understanding of what the UUV is technically capable of, next is to examine how well those functions perform.

## 2. Performance

A UUV approach provides exceptional levels of demonstrated performance for many functions required of the MADMAN system. An exploration of the Autonomous Undersea Vehicle Applications Center (AUVAC), a publicly available database, revealed over one hundred applicable UUVs that contained many of the required capabilities. This availability results in a very high-performing alternative. Extensive research leads to the identification of a common configuration for matching speed and endurance requirements enabling the UUV to travel for about 24 hours at approximately four knots (Table 14).

Table 14. Selected UUV Operating Speed and Endurance Time Comparison. Adapted from: Autonomous Undersea Vehicle Applications Center (AUVEC) (2018).

| <b>UUV Model</b> | <b>Speed (Knots)</b> | <b>Endurance (Hours)</b> |
|------------------|----------------------|--------------------------|
| SeaWolf          | 8                    | 3                        |
| Bluefin-12       | 4                    | 26                       |
| Exoceterus       | 3                    | 70                       |
| Remus 6000       | 5                    | 22                       |
| Hugin 3000       | 3                    | 60                       |
| Alister REA      | 4                    | 12                       |
| SQX-500          | 4                    | 8                        |
| Seahorse         | 4                    | 72                       |
| Sparus II        | 11                   | 8                        |
| Comet            | 6                    | 12                       |

UUVs have a tradeoff between speed and endurance. The inverse relationship between speed and endurance means that final stakeholder opinion may consider this common configuration a performance hindrance depending upon on the timeframe required for minefield development. Communication elements installed on current UUV options are typically the most advanced forms of underwater communication available. From an underwater perspective, these devices communicate within their specified range very well. These are limiting factors, however, because the communication is within a certain range and only underwater. UUVs likely cannot communicate with satellites, preventing live updating accuracy.

Potential options for communications include floating buoy communications to satellites, or underwater network. UUV options currently available do not include these features. Navigation systems have matured greatly over the last few decades, and sophisticated sea maps exist for upload to UUVs. UUVs can use these maps to identify their target area for creating a minefield. Similar to the communication limitation, navigation is reliant on the accuracy of their onboard sensors and pre-loaded maps to guide them to their deployment areas. This limitation is minor and modern mapping, and navigation systems keep this performance aspect considered high. Finally, from a stealth

perspective, the UUV performs fairly well. While the device is not silent, due to the use of motors to propel it, there is no requirement to surface during mission activities, preventing the device from exposing itself visually on the water surface. From a performance perspective, the UUV option performs well with minor limitations.

### **3. Cost**

The cost of all the alternatives will pertain to the procurement and alteration required to the mine. The cost breaks down into particular life cycles: development, procurement, and sustainment. Development focuses on the alterations required for mostly autonomous performance. In the performance and technical portion of the UUV alteration, communications are a major concern and require additional funding for incorporation of this capability. New modifications to add autonomous capability into the mine and programming of the system requires further evaluation. For sustainment, the fiberglass and non-ferrous case suggest the maintenance cost as more economical and easily accessible to other components in the mine for alteration or repair.

Overall, the UUV alternative requires minimal change to carry the mine, has affordable pricing and its ability to be more readily available makes it a captivating low-cost option. The use of a standard mine, like the Mark 60 Captor is a low-cost option based on its time in service and competitive pricing. The current cost of Mark 60 is \$113,000 per mine (National Research Council 2000). MADMAN also requires software and hardware modifications to meet the required capabilities.

### **4. Risk**

Risk analysis for the UUV deployment alternative presents a summary of the risks identified and maps each on a three by three risk matrix. Risk matrices identify and quantify risks associated with jeopardizing mission success. Using the same three areas of development risk, technical risk and personnel risk allows for a consistent evaluation of the three alternatives. Figure 42 illustrates a risk assessment for each technical, performance, cost and an additional category of personnel risk. The UUV option presents a low-risk option for the development of MADMAN.

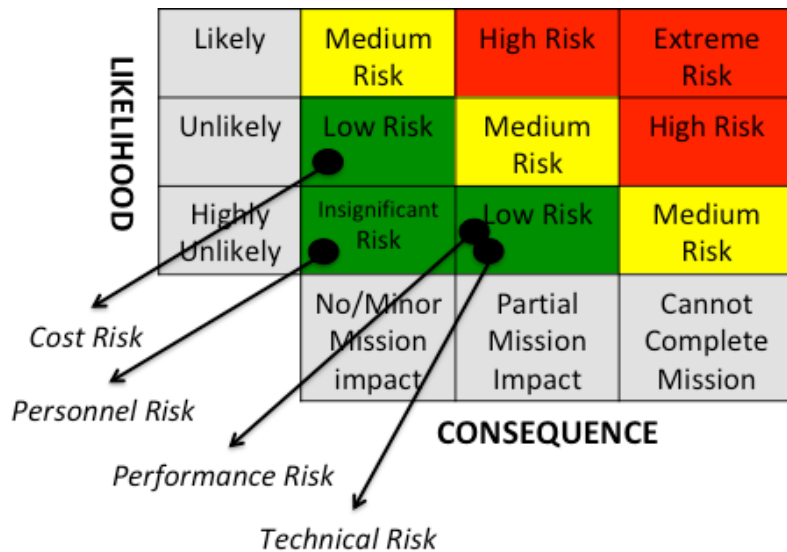


Figure 42. UUV Alternative Risk Summary.

**a. Technical Risk**

UUVs currently exist providing nearly every system required for achievement of MADMAN goals. Transitioning of current UUV systems to offensive mining requires minimal effort making the technical risk highly unlikely with partial mission impact.

**b. Performance Risk**

While the UUV alternative has improved control at slower speeds, technically, the tradeoff between the distance traveled, and speed means that expeditious deployment of a minefield is at risk. Although the risk of detection decreases at slower speeds, the UUVs inability to communicate with satellites introduces risk for mission redirection or termination. These factors make this risk highly unlikely but with a partial mission impact.

**c. Cost Risk**

Some minor modifications are required for this alternative but are not significant in the scheme of things. The low development, maintenance, and sustainment cost make the cost risk unlikely with no/minor mission impact.

**d. Personnel Risk**

Once deployed and transits begin out of the explosive damage range, the risk to personnel dissolves with completely unmanned UUVs. The UUV option operates fully autonomously dissolving all risk to friendly forces. Due to the autonomous nature of this alternative, personnel risk is highly unlikely with no/minor mission impact.

**5. Alternative 1 Summary**

Use of a UUV device to move the mine from a launch ship presents many benefits over other possibilities. Historically, although not considered a UUV at the time, the SLMM operated with many similarities to a UUV. A UUV approach allows for accomplishing multiple mission areas encompassing multiple types of launch platforms facilitate using a UUV approach. If one were to consider the mine as simply a payload, the UUV quickly jumps to the forefront as the easiest, quickest, and least costly alternative to pursue when developing an autonomous underwater device.

However, if we place more emphasis on minimizing the risk to human life, a UUV approach presents limitations for full consideration by stakeholders. The UUV approach has a limited standoff range. A launch vehicle must transport the UUV near the littoral areas. Depending on the timeline, this might become prohibitive to deployment based on combat operations. Stakeholders must understand this limitation should a UUV approach be selected.

Table 15. Alternative 1: UUV Assessment Summary.

|                    | <b>Technical<br/>(Max)</b> | <b>Performance<br/>(Max)</b> | <b>Cost (Min)</b> | <b>Risk<br/>(Min)</b> |
|--------------------|----------------------------|------------------------------|-------------------|-----------------------|
| Alternative 1: UUV | High                       | Medium                       | Low               | Low                   |

**B. ALTERNATIVE 2 – WAVE GLIDER DEPLOYMENT**

In 2007, Liquid Robotics, an American marine robotics corporation now owned by Boeing, introduced the first Wave Glider. When assessing Wave Glider as an

alternative, it is clear that the system travels long distances and has little to no need for external sources once programmed for its mission. The wave glider approach calls for a ship or submarine to launch a Wave Glider that also carries a mine device. Sea currents propel the overall device into contested littoral waters. Wave Glider lacks conventional motorized propulsion, which quickly makes them the covert option between the alternatives from an acoustic signature perspective. Once the Wave Glider reaches a target location, it releases the mines for autonomous transit to reach its destination and set an active minefield.

### 1. Technical

Using sea currents and tides, the Wave Glider travels underneath the water in a saw-tooth pattern to generate propulsion. The Wave Glider is a good candidate for mine transport because; it is equipped to tow payloads (Figure 43) using the force of the ocean. The saw-tooth travel pattern, however, causes the Wave Glider to travel around half a knot. Half a knot is eight times slower than the UUV option, which is a potential drawback depending on final stakeholder opinion.



Figure 43. Wave Glider Towing Additional Payload with Sensor Release. Source: (A Boeing Company 2018)

The towing capability of the Wave Glider offers the possibility to carry additional sensors. Wave Glider could release sensors along the journey to increase the range of detection for deployed mines. In place of deploying multiple sensors in transit, deploying multiple Wave Glider allows for a wide range of detection of enemy vehicles and underwater obstacles (Figure 44). While these primary Wave Glider tasks meet some of the needs of MADMAN, their main functions align more closely with mine countermeasure devices and tend toward surveillance. System adjustments would be required to address an offensive purpose.



Figure 44. Wave Glider Multiple Deployment Communications Grid. Source: A Boeing Company (2018).

Similar to the UUV, the Wave Glider is an unmanned vehicle. There is no need for human involvement once the Wave Glider deploys and it can carry out autonomous missions. The system as it stands however is not as MADMAN-ready as the UUV and integration into an offensive mining device requires a reasonable amount of effort.

## 2. Performance

Without the need for a thrust-based propulsion design, there is lower system power consumption. This translates to extended travel range for the Wave Glider and ultimately the MADMAN. Using sea power instead of engine thrust means that the

device is low power. This could provide power to different systems, allowing for capabilities that are more robust. Natively, the Wave Glider system has a permanently surfaced element that communication with satellites and remote command systems. This allows live location and mission updating. This feature means that the Wave Glider's exceptional potential to meet communication requirements makes it a viable alternative. The Wave Glider also surpasses the UUV in navigational performance. While it uses the same navigational tools, the Wave Glider can regularly update location information, allowing redirection or affirmation of staying on target. While performing silently in the water, the tradeoff exists due to the communications system. The surface portion of the Wave Glider is visible and detectable to a degree. While long-range sensors may not pick up the device, they may be visible to aircraft or enemy vessels on approach to their target location. Ultimately, the Wave Glider performs very well, has most systems required for a successful mission, but is slow and visible from the surface.

### **3. Cost**

The Wave Glider has gone through several iterations since 2007, and Wave Glider SV3 is currently in development with an expected cost \$300,000 a unit (Takahashi 2013). In the development of this alternative, the need to modify the system is vastly more extensive. Development requires external programs' involvement while the UUV and aircraft alternatives offer the capability for in-house enhancement. Also, tethering mines or sensors to a float requires additional propulsion, power capabilities, an anchor mechanism, and hardware and software modifications to the float and submerged carriage. The time required to develop these features are very extensive and can promote many hours of testing.

Considering sustainment, the Wave Glider has simple components and a very high MTBF that give it lesser chance of failure and less spare parts needed during sustainment. The procurement cost for the Wave Glider costs more for each unit compared to the other alternatives, and that is not including labor-hours to test and field. In addition, once the Wave Glider is ready to submerge, the additional equipment required releasing it from its float and anchoring to the seabed would require additional

design efforts to complete the mission. If failures do occur, the time needed to report repairs is significant. Wave Glider offers system independence and does not require assistance from external entities to perform its mission. While Wave Glider offers the ability to deploy without an external vehicle, its development and procurement costs are higher than the UUV and aircraft alternatives.

#### 4. Risk

While Wave Glider offers many benefits with built-in fleet connectivity producing a large communications grid and a greater MTBF, risk is inherent for newly developed/modified systems as seen in Figure 45.

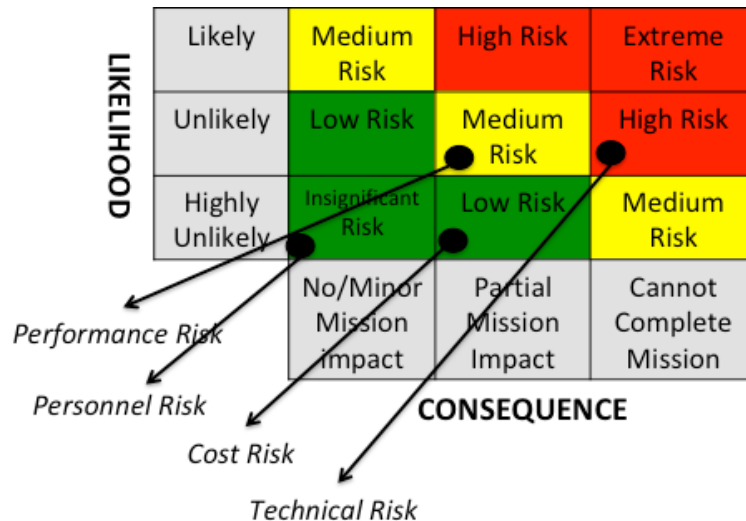


Figure 45. Wave Glider Alternative Summary.

##### a. Technical Risk

The Wave Glider alternative requires significant changes to release itself from its float and requires additional development for anchoring to the seabed increasing the development risk. Development risk becomes likely with partial mission impact.

##### b. Performance Risk

Wave Glider's visibility from the surface and slow speed increase the possibility for detection by enemy forces. Once detected, chances increase for enemy forces to

prevent the MADMAN from accomplishing its mission. Technical risk becomes unlikely and partially influences the mission.

**c. Cost Risk**

Cost risk increases for the Wave Glider alternative due to the requirement and development of additional propulsion, power, anchoring, hardware, and software modifications. However, additional development cost assesses cost risk as highly unlikely with partial mission impact.

**d. Personnel Risk**

Similar to the UUV alternative, the Wave Glider provides safety to personnel after its deployed. The removal of risk to personnel makes this highly unlikely with no/minor mission impact.

**5. Alternative 2 Summary**

Use of a Wave Glider presents new opportunities to the warfighter. Wave Glider has a potentially unlimited range that allows mines to penetrate into the deepest areas of enemy controlled territories. Wave Glider presents other technological opportunities to increase the effectiveness of a mine device. Wave Glider as it transits into the desired area could lay a sensor system capable of communicating with the mine a variety of data to include target location from further standoff ranges.

For all of the standout areas that Wave Glider could further develop, active mining capabilities lack reliably proven methods by existing systems. The potential to realize all of the potential areas for development exposes stakeholders to not only increased costs but also increased risk summarized in Table 16.

Table 16. Alternative 2: Wave Glider Assessment Summary.

|                               | <b>Technical<br/>(Max)</b> | <b>Performance<br/>(Max)</b> | <b>Cost (Min)</b> | <b>Risk<br/>(Min)</b> |
|-------------------------------|----------------------------|------------------------------|-------------------|-----------------------|
| Alternative 2:<br>Wave Glider | Medium                     | High                         | Medium-High       | Medium                |

### **C. ALTERNATIVE 3 – AIRCRAFT DEPLOYMENT**

Although current mining technologies involve the use of air-dropped naval mines, development of an air-dropped version of MADMAN requires exploration. Current naval mines free fall from the delivery vehicle to the seabed, adding an autonomous navigation capability to these device aids in preventing MCM efforts by enemy forces. An air dropped version of MADMAN would closely resemble the UUV-based alternative but would likely result in a shorter underwater deployment range based on weight requirements. The airdropped variant would also require hardening of technologies used in development due to impact with the water following launch from the aircraft. This option is the fastest to deploy and most familiar to current operations between the alternatives. However, this is the most dangerous to the mine structure and the personnel delivering the MADMAN.

#### **1. Technical**

This proven method is today's method used for building minefields. Flying mines into the littoral region is the fastest delivery method. One main performance area that aircraft option exceeds at is speed for deployment of a minefield. Using a P-3 Orion as an example aircraft, it has a cruising speed of 328 knots, meaning that it would only take one hour to travel 610 kilometers. Additionally, the airdrop method is not limited to oversea delivery. An aircraft can fly over landmass to shortcut travel time to littoral waters. Using an aircraft supports desires for a quick development of a minefield. Sensor suites on aircraft are typically the latest available and are likely beyond the classification of this project. With that in mind, it is safe to assume that the sensor systems would perform exceptionally well. The aircraft that drop mines are currently manned aircraft, so there is not a high degree of autonomy when using this method. Integration of the MADMAN would be relatively easy provided the system could fit into a standard mine enclosure as seen in Figure 46 of a MK 62 Quick Strike mine is being released.

Aircraft deploy multiple types of weapons in a naval battle. Multiple types of torpedoes, CAPTOR or Quick Strike mines and missiles all deploy from aircraft currently used by U.S. naval forces. Availability of launching platforms is not a limiting factor.

Torpedoes present many similarities to a UUV system. The most restrictive areas regarding integration are likely the systems required for long-term autonomous navigation and weight of fuel required allowing for longer transits.



Figure 46. MK 62 Quick Strike Mine Deploying from Aircraft. Source: Pietrucha (2016).

## **2. Performance**

An aircraft is fast, allowing the mine to get to a target location quickly. The operational range is far greater than the other two alternatives. Human alertness and fuel restrictions limit an aircraft's flight time. From a purely operational range perspective, an aircraft performs better with the target drop site identified. The communications system performs exceptionally well because an aircraft utilizes the same instruments as the other alternatives and adds the human element. The command center receives a visual identification of obstacles and mission situations reports quickly. Computers built into the aircraft allow relatively precise location determination, but the ultimate accuracy would depend on the airdrop itself.

Aircraft have fine-tuned instruments detailing a precise target location and dropping mines at high speed only lowers that precision to a negligible degree. From a stealth perspective, the aircraft alternative does not perform well. This large aircraft will immediately appear on radar and be visible to enemy forces. Adversary detection of the aircraft does not guarantee mine detection. However, it places a large beacon on where minefield deployment may occur. Overall, the aircraft is a familiar system that performs relatively well with minimal automation and stealth.

### **3. Cost**

The aircraft alternative cost is similar to the UUV with a procurement cost of \$113,000 for each unit and similar spare parts requirements. The difference between UUV and aircraft alternatives is the weight constraints, equipment hardening, battery life, and more software modifications. Although the mark 60 Captor supports air and sea deployment, releasing multiple units from the air has limitations in item weight. Removing weight results in removal of items like batteries that adds substantial weight to the mine. Removal of batteries means reduction to speed of MADMAN is required to transit to the deployment point with enough remaining power after anchoring. These factors create an increase in cost in development to modify the mine with smaller parts to address weight and additional time to develop software to assure the mine still meets the previous requirements as well as the autonomous aspect of the mission.

The sustainment of the system as mentioned should be the same as the UUV based on accessibility to parts within the mine that require repair. Overall, the aircraft alternative has historical data giving it confidence for success. Requiring modifications based on weight restrictions will reduce some performance parameters like propulsion and introduces additional cost to the development and procuring of this alternative. The procurement of the items also increases based on altering the standard mine due to weight.

### **4. Risk**

Aircraft is the current delivery method making this a proven method but with some risks as seen in Figure 47.

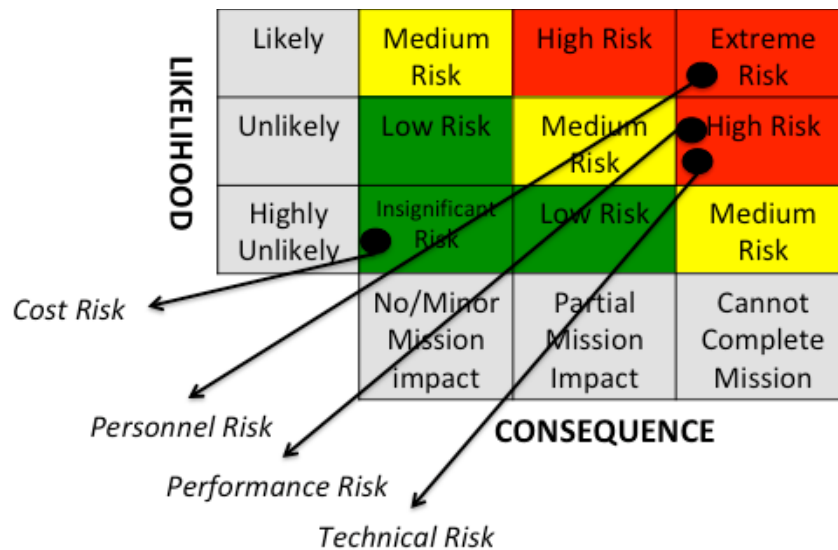


Figure 47. Aircraft Alternative Risk Summary.

**a. Technical Risk**

Development risk is highly unlikely with no/minor mission impact since this is the current method of delivery and development is minimal. Technically, the aircraft transports the mine with available system sensors, and system integration is easily accomplished. The technical risk increased in the autonomous aspect making technical risk unlikely and an inability to complete the mission.

**b. Performance Risk**

The aircraft deployment alternative increases accuracy issues. Even with fine-tuned instruments detailing a precise target location, deploying mines at high speed lowers precision jeopardizing successful completion of the mission. The stealth aspects of this deployment method are also low making the performance risk unlikely with the inability to complete the mission.

**c. Cost Risk**

The aircraft alternative requires some minor modifications to support MADMAN's mission. While some modifications are required to increase performance, cost assessment becomes highly unlikely and minor mission impact.

**d. Personnel Risk**

Large piloted aircraft immediately appear on radar making it detectable by enemy forces. This alternative limits the ability for a covert delivery placing human pilots at risk of counter air strikes. There is an increased risk to personnel during operations because enemy forces can counter-attack preventing mission completion. Personnel risk becomes likely and cannot complete the mission.

**5. Alternative 3 Summary**

While deployment of the system from an aircraft significantly lowers the time to establish a minefield, the main risk that MADMAN is attempting to remove the risk to human life, remains. Aircraft delivery requires a pilot flying into the littoral areas to place MADMAN close to its desired location. The range that MADMAN can travel following drop into the area is likely to be less than other deployed options based on weight. The reduction in range that MADMAN can traverse following launch only serves to increase the risk to human life when establishing a minefield.

Familiarity of using the airdrop method and knowledge of the associated timeline provide known benefits. Cost for an airdropped version of MADMAN is similar to those of a UUV and in actuality could be higher for the airdropped version to allow for the shocks experienced with an aircraft deployment. Table 17 summarizes the results of the aircraft deployment alternative against technical, performance, cost, and risk categories.

Table 17. Alternative 3: Aircraft Deployment Assessment Summary.

|                            | <b>Technical<br/>(Max)</b> | <b>Performance<br/>(Max)</b> | <b>Cost (Min)</b> | <b>Risk<br/>(Min)</b> |
|----------------------------|----------------------------|------------------------------|-------------------|-----------------------|
| Alternative 3:<br>Aircraft | High                       | Medium                       | Medium            | High                  |

**D. SUMMARY OF ALTERNATIVES**

After the value measures map against requirements, the importance of each value measure receives a weight in numerical form. The four value weight categories:

technical, performance, cost, and risk helps to distinguish the importance of each value measure (Table 18).

Table 18. Value Measures Weights.

|                                       | <b>Importance of Value Measure</b> |                            |                  |            |
|---------------------------------------|------------------------------------|----------------------------|------------------|------------|
| <b>Variation in Measure<br/>Range</b> |                                    | <b>High</b>                | <b>Medium</b>    | <b>Low</b> |
|                                       | <b>High</b>                        | Technical<br>85 (MAX)      |                  |            |
|                                       | <b>Medium</b>                      | Performance<br>75 (MAX)    |                  |            |
|                                       | <b>Low</b>                         | Personnel Risk<br>70 (MIN) | Cost<br>65 (MIN) |            |

Each value measure aligns with a measure of importance used for comparing alternatives. The value measures sum, individually divide, then provide a percentage of importance to the overall system. Those value measures decompose into subcategories, which calculate in the same way, and then provide their percentage importance within their value measure. These final decimal numbers are the swing weights that highlight importance to the system. The resulting numbers appear in Figure 48.

| Value Measure | Value | Swing Weight |
|---------------|-------|--------------|
| TECHNICAL     | 85    | .29          |
| PERFORMANCE   | 75    | .25          |
| COST          | 65    | .22          |
| RISK          | 70    | .24          |
| TOTAL         | 295   | 1.00         |

| Technical Sub-Measure | Value | Contribution to Measure Swing Weight |
|-----------------------|-------|--------------------------------------|
| Transport of Mine     | 25    | 0.29                                 |
| System Sensors        | 15    | 0.18                                 |
| Autonomy              | 30    | 0.35                                 |
| Integration           | 15    | 0.18                                 |
| Total                 | 85    | 1.00                                 |

| Performance Sub-Measure | Value | Contribution to Measure Swing Weight |
|-------------------------|-------|--------------------------------------|
| Operational Range       | 20    | 0.27                                 |
| Communications          | 10    | 0.13                                 |
| Position Accuracy       | 20    | 0.27                                 |
| Stealth                 | 25    | 0.33                                 |
| Total                   | 75    | 1.00                                 |

| Cost Sub-Measure | Value | Contribution to Measure Swing Weight |
|------------------|-------|--------------------------------------|
| Development      | 25    | 0.38                                 |
| Procurement      | 25    | 0.38                                 |
| Sustainment      | 15    | 0.23                                 |
| Total            | 65    | 1.00                                 |

| Risk Sub-Measure | Value | Contribution to Measure Swing Weight |
|------------------|-------|--------------------------------------|
| Technical Risk   | 15    | 0.21                                 |
| Performance Risk | 15    | 0.21                                 |
| Cost Risk        | 10    | 0.14                                 |
| Personnel Risk   | 30    | 0.43                                 |
| Total            | 70    | 1.00                                 |

Figure 48. Value Measure, Value, and Swing Weights.

The swing weights provide a comparable metric for importance of individual elements to the overall system. The next step is detailing raw scores of each analysis section to demonstrate preference between alternatives. These raw scores map to the previous detailed analysis of each alternative. A score of 5 results for an assessment of “High” in the technical and performance categories as well as a score of “Low” in the cost and risk categories, which means:

- Technical characteristics significantly achieve mission requirements.
- Performance characteristics significantly achieve mission requirements.
- Cost is low requiring no or minimal modifications.
- Risk partially affects mission requirements.

A score of 3 results for an assessment of “Med”, which means:

- Technical characteristics moderately achieve mission requirements.
- Performance characteristics moderately achieve mission requirements.
- Cost is moderate requiring some modifications.
- Risk moderately affects mission requirements.

A score of 1 results for an assessment of “Low” in technical and performance and a score of “High” in cost and risk categories, which means:

- Technical characteristics partially achieve mission requirements.
- Performance characteristics partially achieve mission requirements.
- Cost is significant requiring extensive modifications.
- Risk significantly affects mission requirements.

Raw scores used in conjunction with the swing weights produces weighted scores. Table 19 captures the summary of scores for each of the alternatives.

Table 19. Alternatives Summary of Scores.

| Value Weight             | Alt 1:<br>UUV | Raw<br>Score | Alt 2:<br>Wave<br>Glider | Raw<br>Score | Alt 3<br>Aircraft | Raw<br>Score |
|--------------------------|---------------|--------------|--------------------------|--------------|-------------------|--------------|
| <b>TECHNICAL SCORE</b>   | <b>High</b>   | <b>18</b>    | <b>Med</b>               | <b>10</b>    | <b>High</b>       | <b>16</b>    |
| Transport of Mine        | Med           | 3            | Low                      | 1            | High              | 5            |
| System Sensors           | High          | 5            | Med                      | 3            | Low               | 1            |
| Autonomy                 | High          | 5            | Med                      | 3            | High              | 5            |
| System Integration       | High          | 5            | Med                      | 3            | High              | 5            |
| <b>PERFORMANCE SCORE</b> | <b>Med</b>    | <b>14</b>    | <b>High</b>              | <b>16</b>    | <b>Med</b>        | <b>14</b>    |
| Operational Range        | Med           | 3            | High                     | 5            | High              | 5            |
| Communication            | Med           | 3            | High                     | 5            | High              | 5            |
| Position Accuracy        | High          | 5            | High                     | 5            | Med               | 3            |
| Stealth                  | Med           | 3            | Low                      | 1            | Low               | 1            |
| <b>COST SCORE</b>        | <b>Low</b>    | <b>15</b>    | <b>Med-High</b>          | <b>7</b>     | <b>Med</b>        | <b>9</b>     |
| Development              | Low           | 5            | High                     | 1            | High              | 1            |
| Procurement              | Low           | 5            | High                     | 1            | Med               | 3            |
| Sustainment              | Low           | 5            | Low                      | 5            | Low               | 5            |
| <b>RISK SCORE</b>        | <b>Low</b>    | <b>20</b>    | <b>Low-Med</b>           | <b>14</b>    | <b>Med-High</b>   | <b>8</b>     |
| Technical Risk           | Low           | 5            | High                     | 1            | High              | 1            |
| Performance Risk         | Low           | 5            | Med                      | 3            | High              | 1            |
| Cost Risk                | Low           | 5            | Low                      | 5            | Low               | 5            |
| Personnel Risk           | Low           | 5            | Low                      | 5            | High              | 1            |

Table 20 summarizes the swing weights for each alternative providing easily comparable scores in each category. Values for technical, performance, cost, and risk measures provide a baseline for comparison. This baseline is a combination of normalized swing weights that provide a value to system effectiveness and the raw scores that indicate alternative proficiency in each category. The product of swing weights and raw scores result in a final value measure for the alternatives.

Table 20. Alternatives Scoring.

| Value Measure      | Value      | Swing Weight | Alternative 1 UUV Value | Alternative 2 Wave Glider Value | Alternative 3 Aircraft Value |
|--------------------|------------|--------------|-------------------------|---------------------------------|------------------------------|
| <b>Technical</b>   | <b>85</b>  | <b>.29</b>   | <b>4.41</b>             | <b>2.41</b>                     | <b>3.59</b>                  |
| Transport of Mine  | 25         | 0.29         | 0.88                    | 0.29                            | 1.47                         |
| System Sensors     | 15         | 0.18         | 0.88                    | 0.53                            | 0.88                         |
| Autonomy           | 30         | 0.35         | 1.76                    | 1.06                            | 0.35                         |
| Integration        | 15         | 0.18         | 0.88                    | 0.53                            | 0.88                         |
| <b>Performance</b> | <b>75</b>  | <b>.25</b>   | <b>3.53</b>             | <b>3.67</b>                     | <b>3.13</b>                  |
| Operational Range  | 20         | 0.27         | 0.80                    | 1.33                            | 1.33                         |
| Communications     | 10         | 0.13         | 0.40                    | 0.67                            | 0.67                         |
| Position Accuracy  | 20         | 0.27         | 1.33                    | 1.33                            | 0.80                         |
| Stealth            | 25         | 0.33         | 1.00                    | 0.33                            | 0.33                         |
| <b>Cost</b>        | <b>65</b>  | <b>.22</b>   | <b>5.00</b>             | <b>1.92</b>                     | <b>2.69</b>                  |
| Development        | 25         | 0.38         | 1.92                    | 0.38                            | 0.38                         |
| Procurement        | 25         | 0.38         | 1.92                    | 0.38                            | 1.15                         |
| Sustainment        | 15         | 0.23         | 1.15                    | 1.15                            | 1.15                         |
| <b>Risk</b>        | <b>70</b>  | <b>.24</b>   | <b>5.00</b>             | <b>3.71</b>                     | <b>1.57</b>                  |
| Technical Risk     | 15         | 0.21         | 1.07                    | 0.21                            | 0.21                         |
| Performance Risk   | 15         | 0.21         | 1.07                    | 0.64                            | 0.21                         |
| Cost Risk          | 10         | 0.14         | 0.71                    | 0.71                            | 0.71                         |
| Personnel Risk     | 30         | 0.43         | 2.14                    | 2.14                            | 0.43                         |
| <b>TOTAL SCORE</b> | <b>295</b> | <b>1.00</b>  | <b>17.95</b>            | <b>11.72</b>                    | <b>10.99</b>                 |

Green shaded boxes denote the best score in each overall value measure

The UUV alternative receives the highest score in technical, cost, and risk while the Wave Glider alternative receives the highest score in performance. The UUV alternative is most likely to address all of MADMAN's key objectives with the lowest cost and lowest risk.

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## **VI. SUMMARY AND CONCLUSIONS**

The MADMAN study offers a path forward in future offensive mining endeavors. While there is no single answer, the research provided in this paper designates what improvements would be required to meet mission needs and satisfy stakeholder requirements. At the close of this project, there is no result because the intention was not to design a solution; rather, the purpose was to collect all of the elements necessary to develop the plan for creating a successful system. This final section highlights the lessons learned, future recommendations, and conclusions for the MADMAN.

### **A. RECOMMENDATIONS**

Current industry trends point toward efficiency and rapid turnaround of system development. In some instances, this is not possible and time is an unfortunate side effect of taking new technology into an operational state. The MADMAN project thrives on the concept of reuse. Weapons, navigational, monitoring, propulsion, anchoring, communication, and autonomous systems all currently exist. Incorporating all of these systems provides the potential for more sophisticated mission operations. The key concept of the MADMAN project is this integration of already existing systems into a functional system of systems.

Development of this project led to the realization that while many alternatives performed well in some areas, they lacked in others. Examining technical capability, performance, cost, and risk provided clarity on each alternative. Running simulations over multiple iterations provided success metrics for each portion of the deployment chain for each alternative, resulting in a final success likelihood of mine deployment. The initial results of simulation demonstrated that the UUV outperformed the Wave Glider and aircraft options. From a basic modeling perspective, this means that the UUV successfully placed more mines, more frequently, with fewer failures than that of other options.

Once identified as the better option, sensitivity analysis revealed potential probability leniency for the individual systems in the deployment chain. This leniency

translates to cost savings, allowing for less restrictive system requirements on certain systems. With lowered stringent probability requirements, systems do not need to attain unreasonable probabilities to reach a final goal. Without the sensitivity analysis, this would not be easy to identify because the degree to which probabilities affect the system success is not clear from a cursory glance at simulation results. The redesign of the probability needs additionally resulted in the UUV performing better in simulations when faced with high-density obstacle environments.

From the resulting research performed and simulation results, the team recommends developing the MADMAN using the UUV deployment option. The updated probabilities provide easier development and better performance. There will be effort involved in the integration of existing systems with the offensive mining aspect. The team additionally recommends enlisting support from the designers or engineers from the company of the selected UUV model. Additional involvement of designers and engineers ensures first-hand support and experience with any integration issues encountered throughout the lifecycle of the system.

## **B. CONCLUSIONS**

Naval mining as a system exists in maritime warfare and is a powerful tool for offense and even results in psychological defense against adversaries. Aircraft drop mines that lie in wait for their targets, but the system has room for improvement. Stakeholder analysis placed the two central goals of autonomy and safety at the top of the needs list. Current mining is minimal at best in both of these categories. This antiquated system requires intelligence and redesign in the fight for naval mining superiority. The most alluring aspect of this project is the ability to use existing autonomous systems. Where possible, improvements in launch success probability and automated obstacle avoidance capabilities can yield greater MADMAN mission success. Once integrated, this provides autonomy for the overall system and in turn creates a safer system by removing the human element in the deployment, delivery, and placement of the mine.

In the modern world, funding is a constant concern. Projects greatly exceeding their budgets are creating vacuums for funds that would otherwise be available in other

areas. With the growing need for frugality, the MADMAN is an ideal candidate to minimize funding while maximizing operational effectiveness. Reuse affords minimal need for new design or system development. Many systems available are plug and play especially when it comes to UUV technology and capabilities. There are many in existence performing mine countermeasure activities, and it would require low effort to repurpose them into mining devices. They currently have obstacle detection, navigation, propulsion, payload transiting, and communication functions, which accounts for nearly all of the MADMAN requirements.

Through a collaborative effort between government off-the-shelf or commercial off the shelf provided UUV prototypes, a fully integrated product is feasible. The UUV demonstrated a high rate of mission success when deploying mines and from a purely simulation perspective, was the clear leader. From a technical perspective, the UUV contains the necessary systems for mission success and requires minimal effort to rework into an offensive capability. The performance of the UUV from a transit and mission perspective requires minimal testing because the systems operate successfully in mission scenarios that are similar to the needs of MADMAN. Additionally, this known functionality, minimal need for testing, evaluation, and integration lowers the cost significantly. With the main effort as integration and adding features, there is no need for ground-up development. Finally, from a risk perspective, these mines can perform for long periods allowing them to travel far beyond dangerous proximity to personnel. Keeping our personnel free from harm is paramount in warfare, and this alternative ensures that safety.

Dependence on the novel integration of these technologies presents a risk. Unfortunately, throughout all military history, project development does not have a perfect success rate. This risk forces leadership and stakeholders to be more discerning in their procurement and project decisions. However, other than integration of systems, relief appears in the form of low development and cost risk. The MADMAN pieces all exist and the completion of this puzzle will ensure that the Navy leads the way into the future of maritime warfare.

### **C. RECOMMENDED TECHNOLOGY INVESTMENT AREAS**

The recommended configuration of MADMAN expands the integration of existing technologies ultimately yielding a material solution that minimizes risk to human life while actively placing mines covertly in littoral areas. Future efforts should continue this effort, incorporating existing technologies to further not only the abilities of MADMAN but other warfare areas as well.

Wave Glider is an area where future expansions of effort should yield viable solutions to existing problems. The Navy uses Wave Glider for surveillance of assets, search of areas, and scientific experiments. Wave Glider shows promise due to not only their autonomous nature of operations but also their low energy requirements. Further exploration of their potential to become active weapons vice only mobile sensors is required.

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