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DESIGN, ENGINEERING, AND ASSESSMENT OF MOBILE MINEFIELDS

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NAVAL POSTGRADUATE SCHOOL

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SYSTEMS ENGINEERING ANALYSIS CAPSTONE REPORT

DESIGN, ENGINEERING, AND ASSESSMENT OF MOBILE MINEFIELDS

by

Hui Yang Chew, Chi-hsuan Chu, Willie Clark II, Jun Jie Khng, Erik C. Kowalski, Fabio D. Matias de Souza, Brendan J. Metcalf, Zhi Hao Ong, and He Jiang Tan

September 2024

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Naval mine warfare typically supports a sea denial strategy through the denial and/or delay of the enemy's use of the water space or by controlling sea traffic in a designated area. Sea mines have been effective for decades. However, with technological progress, mine countermeasure (MCM) efforts have reduced the risks of a minefield by detecting and/or neutralizing mines to establish and maintain a Q-route for safe passage. The concept of a mobile minefield is proposed to increase the difficulty of the enemy's MCM and improve the survivability of the minefield by adding mobility. This research explores both the physical design concepts and the operational effectiveness of mobile mines based on simulations and models. The simulation results show that, compared to static mines, mobile mines improved the number of enemy ships destroyed by at least 200% and increased the time it took the enemy to transition through the minefield by 50%. The results suggest that the mobile minefield would be operationally useful for the Department of the Navy and this technology is worth pursing and exploring.

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ABSTRACT

Naval mine warfare typically supports a sea denial strategy through the denial and/or delay of the enemy's use of the water space or by controlling sea traffic in a designated area. Sea mines have been effective for decades. However, with technological progress, mine countermeasure (MCM) efforts have reduced the risks of a minefield by detecting and/or neutralizing mines to establish and maintain a Q-route for safe passage. The concept of a mobile minefield is proposed to increase the difficulty of the enemy's MCM and improve the survivability of the minefield by adding mobility. This research explores both the physical design concepts and the operational effectiveness of mobile mines based on simulations and models. The simulation results show that, compared to static mines, mobile mines improved the number of enemy ships destroyed by at least 200% and increased the time it took the enemy to transition through the minefield by 50%. The results suggest that the mobile minefield would be operationally useful for the Department of the Navy and this technology is worth pursing and exploring.

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LIST OF ACRONYMS AND ABBREVIATIONS

AMP	Analytic Master Plan
AMCM	Advanced Missions Cost Model
ASUW	Anti-Surface Warfare
ASW	Anti-Submarine Warfare
BDA	Battle Damage Assessment
C2	Command and Control
CAPTOR	Encapsulated Torpedo Mine
CNO	Chief of Naval Operations
COCOMO II	Constructive Cost Model
COMOMAG	Commander, Mobile Mine Assembly Group
CONOPS	Concepts of Operations
COSYSMO	Constructive Systems Engineering Cost Model
CPU	Central Processing Unit
DMZ	Demilitarized Zone
DOD	Department of Defense
DOE	Design of Experiment
DOF	Degrees of Freedom
ELF	Extremely Low Frequency
ELFE	Extremely Low Frequency Electric
EOD	Explosive Ordinance Disposal
ESLOC	Equivalent Source Lines of Code
EW	Electronic Warfare
FEBA	Forward Edge of the Battle Area
FHSS	Frequency Hopping Spread Spectrum
FMECA	Failure Modes, Effects, and Criticality Analysis
GAO	Government Accountability Office
GPS	Global Positioning System

GUI	Graphical User Interface
HSI	Human-System Integration
IFF	Identification of Friend or Foe
IMU	Inertial Measurement Unit
INS	Inertial Measurement Unit
IOC	Initial Operating Capability
ISR	Intelligence, Surveillance, and Reconnaissance
JDAM	Joint Direct-Attack Munition
MAST	Modeling and Simulation Toolkit
MCM	Mine Countermeasures
MDSU	Mobile Diving and Salvage Unit
MEDUSA	Mining Expendable Delivery Unmanned Submarine Asset
MHS	Mine Hunting Ship
MIW	Mine Warfare
MOE	Measure of Effectiveness
MOMAG	Maintenance and Operational Management Assembly Group
MOP	Measure of Performance
NATO	North Atlantic Treaty Organization
NAVPLAN	Navigation Plan
NAVSEA	Naval Sea Systems Command
NIF	NAVPLAN Implementation Framework
NOLH	Nearly-Orthogonal Latin Hypercube
NPS	Naval Postgraduate School
NSWC	Naval Surface Warfare Center
OEM	Original Equipment Manufacturer
OMER	Operator-Maintainers
OSM	Orchestrated Simulation through Modeling
PADAL	Passive Acoustic Detection and Localization
PEO	Program Executive Office

PLAN	People’s Liberation Army Navy
POM	Program Objective Memorandum
RF	Radio Frequency
ROV	Remotely-Operated Vehicle
SEA	System Engineering Analysis
SIT	Simple Initial Threat
SLF	Super Low Frequency
SLMM	Submarine Launched Mobile Mine
SMWDC	Surface and Mine Warfighting Development Center
SONAR	Sound Navigation and Ranging
SSN	Nuclear-powered Submarines
STANAG	Standardization Agreement
SWaP	Size, Weight and Power
TRL	Technology Readiness Level
TTP	Tactics, Techniques, and Procedures
UAV	Unmanned Aerial Vehicle
UEP	Underwater Electric Potential
USAF	United States Air Force
USC	Unmanned and Small Combatants
USN	United States Navy
UUV	Unmanned Underwater Vehicle
VLF	Very Low Frequency
WEZ	Weapon Engagement Zone
WGS-84	World Geodetic System 1984
XLUUV	Extra Large Unmanned Underwater Vehicle

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EXECUTIVE SUMMARY

Naval mine warfare (MIW) has historically been a cost-effective means to delay or deny the use of water space to an enemy. Technological advancements in mine countermeasures (MCM) have gradually made traditional sea mines less effective and easier to counter. When the existence of a minefield is known, the enemy will traditionally conduct MCM to create a Q-route (a safe path through the minefield where the mines have been cleared to an acceptable risk level). Once this Q-route is created, ships can transit relatively safely, with the only way for the adversary to close this Q-route being to reseed the minefield with additional mines. Reseeding can be difficult if the minefield is in enemy waters, as the Q-route will likely be defended. The U.S. Navy has prioritized the protentional benefits of MIW and is looking into how modern technologies such as unmanned underwater vehicles (UUVs) and autonomous systems could be incorporated into MIW to make more effective sea mines that could resist MCM and produce a minefield that creates a persistent threat to enemy transiters.

This project sought to understand the design and implementation of mobile mines, which after they are deployed could reposition in the minefield to counter enemy MCM efforts and adjust to enemy transit patterns. The project included developing the operational concept for how mobile mines could be employed. Additionally, the research team created a functional and physical architecture for a mobile mine as well as an assessment of the cost and feasibility of such a design. Finally, the team conducted an operational analysis of the performance of the mobile mines in an environment contested by enemy MCM compared to the performance of legacy static mines.

The design effort was conducted utilizing agile systems engineering methods, first assessing the current state of practice in mine, torpedo, and UUV systems. This assessment was used to create requirements that the mobile mine system would need to both achieve acceptable mine effects and sufficient mobility to meet the system objectives. In particular, the team was concerned about delivering sufficient energy density and efficient mobility to achieve acceptable endurance of the system in the minefield. The team also focused on maintaining a platform agnostic design to provide the maximum operational flexibility of

the system by not constraining the system by existing U.S. Navy mining capabilities. The team developed the mobility logic assuming a worst-case scenario with no communication between mines or to any control platform. The mines would use onboard sensors to detect explosions or vessel transit paths, onto which they would converge using incremental movements.

The operational assessment was conducted using the Naval Surface Warfare Center, Dahlgren Division Modeling and Simulation Toolkit (MAST). The assessment involved an offensive mining scenario with a 5 nm x 2 nm minefield to delay/deny an enemy's departure from port. The enemy would attempt to transit 10 ships through the minefield conducting breakthrough MCM to clear a 1,000-yard-wide Q-route whenever a transiter struck a mine. The assessment looked at the number of ships that successfully transited the minefield (deny) and the time it took for the ships to attempt to leave the port, including MCM efforts (delay) for a varying number of mines. Additionally, the density of active mines that remained in the cleared Q-route was assessed to demonstrate the sustained threat that the mobile mines achieved.

The final mobile mine design was a torpedo profile, 86 inches in length with a 21-inch diameter. The mine utilized a 330-lb propelled warhead with an overall system weight of 1075 lbs. The target detection device included magnetic, acoustic, and electric field sensors. Navigation used a combination of global positioning system and inertial navigation system. Mobility was achieved with a combination of a buoyancy control system and electric propulsion capable of a 3-knot transit speed. Utilizing a 143-lb lithium/water battery, an endurance of 90 days was estimated with a 50 nm delivery range (100 nm maximum range).

The torpedo profile facilitated submarine delivery, while still allowing possible surface and air delivery with minimal modifications. The speed and range allowed delivery platforms to maintain significant standoff for safe covert mine delivery while the endurance provided sufficient operational life in the minefield. All the mobile mine subsystems utilized mature technology with assessed technology readiness levels (TRL) of at least 8. Therefore, the design was assessed to be technologically feasible; however, because these systems are integrated in a unique, untested manner, the overall TRL of the mobile mine design was assessed at a 2. The estimated acquisition cost of the system for the first 100 units is $468.3 million.

The MAST simulation showed a significant increase in both lethality and delay enemy movement when mobile mines were utilized in comparison to static mines. The static mines averaged one to three ships killed and an induced delay of 2.6–6.7 hours, depending on number of mines laid. The mobile mines averaged four to ten ships killed and an induced delay of 3.6–9.6 hours. This is an increase of an average of 270% transiters killed and 50% induced delay. This result also showed that mobile mines could provide an equal amount of induced delay with half of the required number of static mines or equal number of transiters killed with a quarter of the required number of static mines.

The design demonstrated a feasible means to implement mobile mines and the model showed a clear operational advantage that could be achieved. The limitations of MAST however prevented optimization of the mine mobility logic. Future work could develop a purpose-built model that could better simulate the mobile mine behavior and allow for a more complete assessment. A prototype mobile mine could be built to assess the integration and performance challenges that may exist in this system and ultimately improve the TRL of the full mobile mine. Additionally, expansion of the MAST software to include MIW specific assets classes could allow for more robust modeling of the mission set.

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I. INTRODUCTION

Sea mines have been an effective asset in naval warfare. They are stealthy, destructive, and low-cost. Aside from the physical damages they cause, sea mines can bring other critical advantages such as the risk imposed upon the enemy, often exaggerated, which leads to delaying the enemy's actions and decision process. However, technology development in mine countermeasures has gradually decreased the effectiveness of mines. According to an analysis done by the Australian Defence Science and Technology Organization, quoted in an article in *Proceedings*, "This combination (mine hunting and minesweeping) results in an overall probability of clearance, in all minehunting conditions, approaching 100%" (Donohue 1998, para. 8). Therefore, the importance of the research is to provide an integrated solution that applies emerging technology to increase the effectiveness of sea mines.

This chapter provides readers an overall understanding of the challenges presented by mine warfare and how the project team analyzed it from different approaches. The chapter begins with an overview of mine warfare, including the problem statement describing the current issues, followed by how the team defines mobile mine system and the proposed concept of operations (CONOPS). This chapter also includes the system engineering process the team implemented to manage the research and development life cycle.

A. BACKGROUND

Naval mine warfare is typically used to protect strategic locations, deny and/or delay the enemy's use of water space, or control sea traffic in a designated area. Naval mines can be deployed by aircraft, surface vessels, or subsurface platforms. Once the mines are deployed, they sit and wait for the targets to come to their vicinity. Depending on the detonating mechanism (contact or influence), the mines will be detonated and inflict damage to the targets. Mines have been effective in sea denial operation due to their elusive yet destructive characteristics for decades. However, technical and operational progress in mine countermeasures (MCM) efforts make it easier for adversaries to detect and/or neutralize mines and establish a Q-route for safe passage, which reduces the effectiveness of a minefield. The concept of a mobile minefield is proposed to increase the difficulty of the enemy’s MCM and improve the longevity of the minefield.

1. Problem Statement

To accomplish the task assigned by the Memorandum for Systems Engineering Analysis (SEA) Cohort 33, which was to provide a “Design, Engineering, and Assessment of Mobile Mine Fields,” (Kline 2023) the project team generated the following problem statement: *Design, engineer, and analyze a mobile minefield to delay or deny the transit of surface and underwater vehicles in a water space for a period by establishing a dynamic threat resilient to enemy’s mine countermeasures using mobile mines.*

2. Tasking Orders

The specific tasking given to the project team are:

1. Define the function and performance of the mobile minefield;
2. Develop a proposal for an operational concept for the system;
3. Develop physical architectures of the system;
4. Conduct operational analysis for specified scenarios in offensive, defensive, and protective roles; and
5. Conduct cost analysis.

3. Definition of Mobile Mine System

The project team defined a mobile mine system as a persistent undersea device that can self-deploy from a certain distance to the desired deployment location and have the ability to move around in the minefield for a certain range and direction through some integrated logic or command to deliver an effect on surface and subsurface vehicles. The specified range and period of time was based on technological limits of energy storage.

4. Concept of Operations

According to Joint Publication 3-15 (Joint Chiefs of Staff 2018), static minefields can be used in offensive, defensive, and protective roles. The mobile minefield CONOPS draws from this concept. Offensively, it can be deployed in water space such as a narrow channel in enemy's port to deny enemy's use of water. Defensively, it can be deployed in an area to destroy enemy's ships in transit and destroy a surface formation. In a protective role, it can be deployed offshore of a friendly beach to delay enemy's landing force from accessing it. Among all three roles, employing mobile mines in offensive mining brings the most benefits compared to static mines since the difficulties presented in reseeding a minefield in a hostile environment is the most challenging. To provide flexibility in support of various mission objectives, mobile mines are designed to be delivered covertly and/or overtly by aircraft, surface ship, and underwater vehicles, as shown in Figure 1. The mobile mines can be deployed at a certain distance from the desired location and can travel autonomously to their designated location.

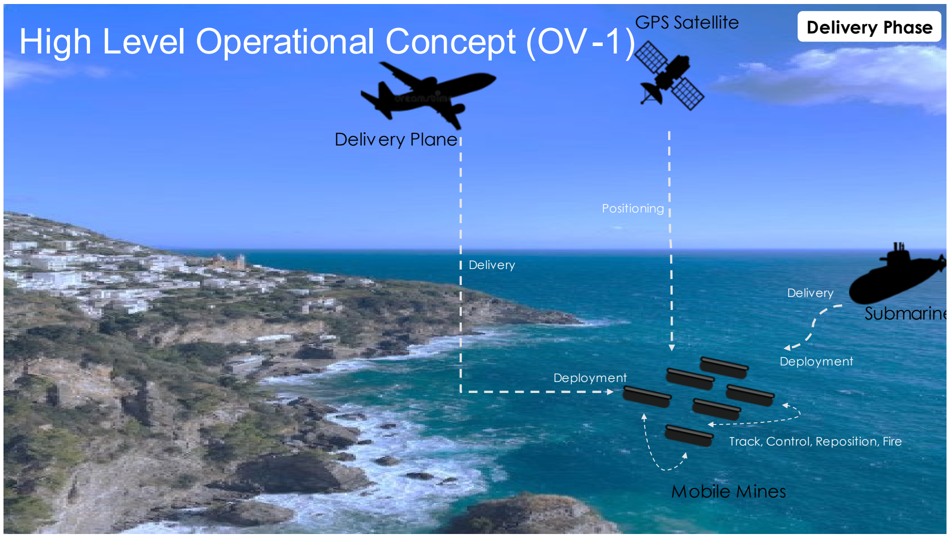

Figure 1. Mobile Minefield Delivery Concept Diagram

To increase the effectiveness of the minefield, the team introduced the concept of mobile mines where mobility can increase the mine's threat. Mobile mines can provide persistence in the presence of enemy MCM by moving into Q-route and allowing the minefield to be tuned to enemy transit patterns, as shown in Figure 2. The red crosses represent the mines that are cleared by the enemy's MCM efforts and a Q-route has been established. Nearby active mobile mines then move into the Q-route, which would obviously confound and confuse enemy MCM actions.

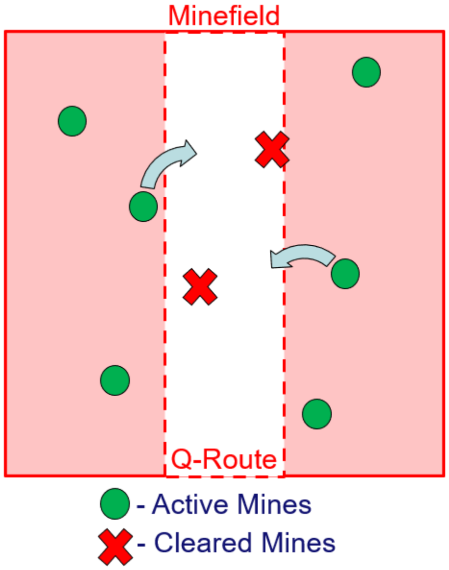

Figure 2. Mobile Mine Field Concept

B. PROJECT OBJECTIVES

The project team developed a proposal for an operational concept, operational analysis, technical feasibility assessment, and design architecture and conducted modeling and simulation to analyze the performance of the mobile minefield for specified scenarios.

The project team also delivered a briefing and a report to the Office of the Chief of Naval Operations (OPNAV) N9I with considerations on performance, costs, and design alternatives to inform the Department of Defense's (DOD's) Program Objectives Memorandum (POM) process, with explicit ties to the analytic master plan (AMP) and frame analysis and results in terms of elements of the NavPlan implementation framework (NIF).

C. SYSTEMS ENGINEERING PROCESS

The project team adopted a Scrum-Agile framework (Berman 2022), with a two-week sprint cycle, to manage project deliverables. This framework is an iterative and collaborative approach designed to enhance adaptability and responsiveness to new insights as the team delved deeper into research. During the sprint cycles, each team worked on various aspects of the project and at the culmination of each two-week sprint, a Scrum meeting was conducted. This meeting served as a pivotal event for the team to review the progress of the sprints; each team received feedback on the completed work and planned for the subsequent sprints. This project management framework facilitated timely delivery of work and ensured that the project remained flexible and responsive throughout its development life cycle.

The project team augmented the Scrum-Agile framework with an adjusted V-model (INCOSE 2015) to determine the focus areas for each Scrum meeting. As this project did not go into the physical production of the mobile mines, the system development process can be summarized in three broad stages: (1) System requirements analysis and CONOPS development on the left of the V; (2) System design, delivery, and sustainment on the right of the V; and (3) Verification and Validation through simulation and modeling as the linkage between the two. The V-model ensured that the project deliverables were consistently aligned to the system requirements at each stage of its design, while the Scrum framework enabled the project team to adjust quickly.

D. TEAM ORGANIZATION

The project team was divided into several sub-teams according to each team member's strength, professional knowledge, and academic background to achieve the best quality and result for the study.

1. Requirement and Analysis: Responsible for mobile mine's capabilities, delivery, functional, and non-functional requirement analysis.
2. System Design: Responsible for the high-level physical design of the mobile mines and ensuring the required functions can be traced to the physical components.

3. <u>Delivery and Support</u>: Responsible for system delivery methods and delivery compatibility analysis.

4. <u>CONOPS</u>: Responsible for developing the CONOPS, designing scenarios and defining the measures of effectiveness (MOEs) and measures of performance (MOPs) for operational analysis.

5. <u>Modeling and Simulation</u>: Responsible for simulation development and mathematical modeling.

6. <u>Cost Analysis</u>: Responsible for the system cost analysis.

E. STAKEHOLDERS

Based on the concept of a mobile minefield, our team identified the following core stakeholders. These pertinent stakeholders were identified based on having common interests such as maintaining maritime dominance and ensuring national security. They also shared similar concerns of geopolitical international relations.

1. OPNAV N9/N9I/N94/N72: Responsible for various aspects of naval operations, technology, and resources. They are interested in comprehensive naval mine strategy and maintaining maritime dominance using mobile mines as one of the assets.

2. Resource Sponsors—OPNAV N95/N96/N97/N98: Oversee resource allocation and management within the Navy. They are interested in budget allocations and mobile mines life cycle sustainment.

3. Surface and Mine Warfighting Development Center (SMWDC): Develops tactics and concepts for surface warfare and mine warfare. They are interested in aligning mobile mines with operational objectives and establishing training and doctrine.

4. Program Executive Office (PEO) Unmanned and Small Combatants (USC): Responsible for procuring and keeping up the Navy's small combatants, mine warfare assets, and unmanned vehicles for maritime operations. They are interested in designing, developing, building, and modernizing naval mines.

5. PMS 495 Mine Warfare: Oversees the development and sustainment of mine warfare related programs. They are interested in designing, developing, building, and modernizing naval mines.
6. Commander, Mobile Mine Assembly Group (COMOMAG): Responsible for maintenance, upkeep, and assembly of mines. They are interested in mobile mines physical specifications, delivery methods, and preparation process.
7. Naval Surface Warfare Center, Panama City Division: Conducts research, development, testing, and evaluation of naval surface warfare systems. They are interested in researching and testing advanced mobile mines technology.
8. Naval Undersea Warfare Center: Conducts research, development, testing, and evaluation focused on undersea warfare. They are interested in researching and developing advanced mobile mines technology.

F. ORGANIZATION OF THE CAPSTONE REPORT

This section offers an overview of the subsequent chapters. Chapter II, Literature Review, focuses on the history and development of mine warfare and technical developments associated with sea mines. Next, Chapter III, Modeling Methodology/ Approach, elaborates on the CONOPS modeled in the modeling software, Modeling and Simulation Toolkit (MAST), for the project's analysis and validation. Chapter IV, System Requirements and Design Architecture, describes the high-level design of the mobile minefield system, its delivery methods, and the mine device. Chapter V, Experiments and Analysis, provides the results of the model and life cycle cost analysis. Last but not least, Chapter VI, Conclusion and Recommendations, addresses the hypothesis on static versus mobile minefields, system design, feasibility, and future research.

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II. LITERATURE REVIEW

This chapter examines the history of U.S. mine warfare beginning with the American Revolutionary War and continuing to an assessment of current U.S. mine capabilities compared to known data from other countries. Next, the chapter covers a few relevant legal considerations of mine warfare, including conclusions from the Hague convention and the San Remo Manual. Then the chapter covers the types of sea mines currently developed and the most recent technological advancements such as modifications to the QuickStrike and the emergence of unmanned systems and smart mines. Lastly, this chapter summarizes the chief of naval operations' statements regarding guidance from the 2022 Navigation Plan (NAVPLAN) and some of the resultant implications.

A. MINE WARFARE

This section delves into the history of mine warfare, explores the legal considerations in mining, and elaborates on the current trend of offensive mining.

1. History of Mine Warfare

The continental army allowed inventor David Bushnell to attempt attaching a mine to a British ship moored in New York Harbor in 1776 during the American Revolution. David Bushnell is credited with inventing the first sea mine by filling wooden kegs with gunpowder and fitting them with a contact fuse (aka, Submarine Turtle; Hoffmann 1977, National Research Council 2000a). Other forms of more sophisticated sea mines appeared for sea control such as channeling, blocking, deflecting, disrupting, and delaying opposing forces (including surface and sub-surface vessels). The advantages of sea mining include denial of access to a maritime area, delay of pace of hostile maritime operations, reduction in number of enemy surface ships and submarines over time, and restricting activities of enemies (Hurley 1997).

Since the conclusion of World War II in 1945, damage from sea mines has been blamed for 15 of the 19 U.S. Navy (USN) ships (78.9%) that have been sunk or severely damaged (Lagrone 2014). Most of those losses of destroyers and minesweepers were incurred during the Korean War. During the battle of Wonsan, the amphibious landing operation was delayed for more than 10 days due to the mining risk. The coast was saturated with pre–World War I moored contact mines interspersed with magnetic influence mines. Two minesweeping ships were sunk by mines while clearing the minefield (Cagle 1957).

Uncharted mines from previous conflicts pose a serious danger to marine vessels, so the area of mine countermeasures began to see technological advancements (Griner 1997). It was estimated in the mid-2020s that countries such as Russia, China, Iran, and North Korea had a combined advanced mine inventory that was more than 20 times larger than the U.S. mine inventory (Truver 2021). In December 2020, sea mines were employed by Yemen's Houthi rebels in the Red Sea to strike commercial maritime traffic; 171 sea mines were detected and destroyed by the Saudi-led coalition (AP News 2020). In the Russo-Ukraine War, sea mines have also been deployed in the Black Sea which is used by the Ukrainians in their export of grains to Europe and Africa (Rothchild and Jessup 2023).

2. Legal Considerations in Mining

The use of sea mines is governed by the Hague Convention (VIII) of 1907 Relative to the Laying of Automatic Submarine Contact Mines (Second International Peace Conference 1907). The Hague Convention is the only treaty governing naval mines and is only legally binding to the signatory states (in accordance with Article 6), including the United States and China but not Russia (International Committee of the Red Cross n.d.-b). The treaty was enacted to address the growing concern over the use of contact mines, which had posed a significant threat and resulted in damage to neutral commercial maritime traffic during the Russo-Japanese War (1904–1905; Second International Peace Conference 1907). Mining has political and economic implications due to the increased risk and disruption mining imposes on commercial maritime traffic (Richer 2023), and mining continues to be an issue despite the stipulations in Article 4 to give official notice on mine locations to governments through diplomatic channels.

In addition to the Hague Convention (VIII) of 1907, the San Remo Manual on International Law Applicable to Armed Conflicts at Sea was created by a self-organized group of experts in the legal and maritime domain who are concerned with military activities at sea and was adopted by the International Institute of Humanitarian Law (1995). While this document is not a binding set of guidelines to any states, its wide acceptance made it influential in laying out the standard for responsible conduct during armed conflicts at sea. According to the International Institute of Humanitarian Law (1995) the document contained the following:

- legal aspects in different maritime zones or operational regions
- the basic rules and elaboration on target discrimination
- the acceptable methods and means of warfare at sea
- gray-zone measures that are provocative
- protection for people, medical transports, and aircraft

Specifically for sea mines, provisions in Part IV Section I (Mines) guide the usage of mines for military purposes (International Institute of Humanitarian Law 1995). Per the regulations, the design of future mobile mines should consider incorporating safeguards when they malfunction including a means for remote deactivation and ensuring that the mines are able to maintain position or at least be contained within the stipulated minefield boundaries.

3. Offensive Mining

In addition to conventional sea mining for defensive and protective purposes, sea mines are also employed for offensive purposes in contested maritime territories (Joint Chiefs of Staff 2018). Offensive mines can be especially effective in susceptible waters such as restricted channels and shallow waters close to ports and harbors (Hoffmann 1977; Kerg 2020). Because sea mines are typically considered weapons that do not promote escalation, they are seen as a weapon of deterrence in the susceptible areas (Howard 2020) that can wait for the right target before striking.

In 2020, the Chief of Naval Operations (CNO) issued the project Overmatch challenge to “support the operational . . . environment that will enable our sustained maritime dominance” by “projecting synchronized lethal and non-lethal effects” (CNO

2020, 8). The Naval Postgraduate School (NPS) SEA 32 Capstone Project (Deken et al. 2021) researched the USN's offensive denial mining as a possible solution to the CNO's challenge. The project team described the traditional sea mining operational concept for offensive mining as comprised of varied deployment vehicles, each with its own unique advantages and disadvantages; including friendly surface vehicles, submarines, unmanned underwater vehicles (UUVs), and aircraft. The different types of sea mines considered for offensive mining were also listed, including moving mines (i.e., drifting and oscillating mines), moored mines, and bottom mines (Deken et al. 2021; Joint Chiefs of Staff 2018). The project team also defined the offensive denial mining problem space into its mission objectives (i.e., turn, block, fix, and disrupt), deployment mode, enemy behavior, and operating environment (Deken et al. 2021). The project team reported that offensive denial mining can actively participate in "integrated any-sensor/any-shooter kill chain" (Deken et al. 2021, 1). The NPS team conducted an analysis of offensive sea mines in a Nearly-Orthogonal Latin Hypercube Design of Experiment (NOLH DOE) in the Modeling and Simulation Toolkit (MAST) software (Naval Surface Warfare Center Dahlgren Division 2021). The team's analysis found that a mine's impact was specifically driven by the target's tendency to change its course or not move from their own position (i.e., operational risk acceptance/aversion) and the vessel's mine detection and identification capabilities (Deken et al. 2021).

B. DEVELOPMENT OF SEA MINES

After understanding more about the history and developments in mine warfare, this section examines the latest methods of delivery and deployment and how they have become smarter. Lastly, the section will provide a sneak peek into the future of the USN's mining capabilities through interpretation of prevalent strategic plans and trends of development of sea mines.

1. Types of Sea Mines

Sea mine technology has advanced quickly to suit different operating environments and requirements and to reduce mine detectability. Some advanced capabilities are already in development including stealth technology and specialized SONAR-absorbing coatings;

non-metallic casing such as fiberglass have been applied to mines to make them even more difficult to detect (Rios 2005). This section addresses the major classes of sea mines that are being used globally today.

Moored mines are used for very deep waters where an anchor can be released. The mine is moored via a chain to an anchor while floating above the seafloor. One of the cons of such a design is that it needs to be buoyant enough to support a considerable weight of cable. Consequently, the moored mine must be large, which would limit its laying rate (Slade 2000). An identified moored minefield can also be easily cleared by mechanically sweeping the minefield using a long wire cable tethered between two boats or on a single boat (e.g., Oropesa Sweep or RAN wire sweeping) snapping the mooring chains (Turner 2019). The USN moored mine inventory includes the enCAPsulated TORpedo (CAPTOR) mine (out of production since 1986), which is an anti-submarine mine delivered by surface and submarine (Weapon Systems n.d.). The CAPTOR's replacement, the Hammerhead mine, will be delivered by submarines and UUVs, will support the Marine Corps' anti-submarine warfare efforts as part of its expeditionary advance base operations (Hambling 2020; Truver 2021), and is dual-use in nature, as an intelligence, surveillance, and reconnaissance (ISR) and communications node that is fitted with communications and processing capability (Deken et al. 2021).

Bottom mines are used for deep waters in areas that cannot be mined, or where the seabed is soft, viscous, and "sticky." Some bottom mines have self-burying capabilities to blend themselves into the seabed to reduce detectability (a.k.a. buried mines; Kallenborn 2017). Another variant of bottom mines is called rising mines which are mines that will rise to the surface through activated propulsion system (e.g., jettisons ballast and rocket propulsion) to get closer to the target. Having a large target acquisition area relative to moored mines translates to greater effectiveness against conventional anti-mine tactics of clearing narrow safe passages, i.e., a Q-route (Slade 2000). However, bottom mines are hard to dispose of (Tranchemontagne and Price 2022). The USN bottom mine inventory includes QuickStrike mobile mines (i.e., MK-62, MK-63, and MK-65; Trevithick 2021) and the MK67 Submarine Launched Mobile Mine (SLMM) consisting of modified homing MK37 torpedo (Tingley 2021).

Drifting mines are another type of mine that floats at or just below the surface but is susceptible to movement due to water currents and waves. These sea mines are easy to deploy and difficult to detect by modern mine countermeasure sensors (Savitz 2022). Due to the restrictions imposed by the Hague Convention (VIII) and risk imposed on commercial maritime traffic, drifting mines are not being developed but were still deployed by countries who are not signatories of the treaty. Due to the lack of Identification of Friend or Foe (IFF) capability, such drifting mines can be indiscriminate in their damage to surface ships around them (Rothchild and Jessup 2023).

2. Advancement in Sea Mine Delivery and Deployment

The delivery and deployment methods of sea mines have also transformed to support different concepts of operation (e.g., aerial and clandestine delivered sea mines used for offensive mining). In September 2014, the USN and United States Air Force (USAF) demonstrated the delivery of a Quickstrike-ER (extended-range) from a B-52H. It was modified from the 500-lb winged Joint Direct-Attack Munition (JDAM)-ER equipped with a JDAM-ER guidance kit that includes a pair of foldable fins (Pietrucha 2016).

A parallel effort successfully deployed a 2,000-lb MK-64 Quickstrike-J (equipped with the JDAM guidance kit) from another B-52H (Truver, O'Rourke, and Millard 2020). The testing demonstrated that the Quickstrike-J can be released at altitudes above 40,000 feet and a deployment range beyond 40 nautical-miles. With global positioning system (GPS) guidance, the aircraft can lay an entire minefield in a single sortie at a standoff distance away from the designated mining zone (Truver, O'Rourke, and Millard 2020). The Quickstrike mines are being aerial-delivered by USAF B-52s and USN F/A-18s, however the B-52s are also required to fly at very low altitudes and speed to be able to deliver them, and as a result exposing themselves to a high risk of being targeted (Truver, O'Rourke, and Millard 2020). Moreover, it is unlikely that commanders will release their B-52s or F/A-18s for mining missions due to competition for these air assets for other tasks (Truver, O'Rourke, and Millard 2020).

Submarines and extra-large UUV (XLUUV) are being developed to deliver sea mines in a stealthy manner (Alkonis 2020; Wester and Mancini 2023). The ORCA XLUUV that is being developed is a modular and autonomous vessel that can assist in anti-submarine warfare (ASW), mine countermeasures (MCM), anti-surface warfare (ASUW), ISR, electronic warfare (EW), and even strike capabilities (Vavasseur 2022). The USN is keen to use the ORCA XLUUV for anti-submarine warfare—specifically to deploy the Hammerhead moored sea mine in a clandestine manner (O'Rourke 2023).

3. Advancement in Smart Mines

Understanding the limitations of single sensor systems for target detection, many countries that have capabilities to produce their own sea mines have looked into coupling multiple sensor systems to improve the sensitivity of the sea mine's target detection and classification (Cancian 2022). The effort of designing mines with multiple sensors gave rise to "multiple-influence" mines. The MANTA was the first of such mines and is triggered based on both acoustic and magnetic influences (CAT-UXO n.d.). The bomb-converted QuickStrike bottom mines are also equipped with a MK-71 target-detection-device firing mechanism that uses acoustic, magnetic field, seismic, and pressure sensors. The QuickStrike bottom mines can also be programmed with algorithms for both target-processing and counter-countermeasures (Truver 2021). Multi-influence mines are more difficult to sweep through traditional MCM of emulating a ship's signals.

The Australian Defence Force has announced recently that they will purchase new smart sea mines (Naval News 2023) including the MN-102 MUNERA and ASTERIA multi-influence bottom mines. The MUNERA can be laid by surface vessels, aircraft, and submarines; its sensors are based on acoustic, magnetic and pressure sensors. The ASTERIA on the other hand can only be laid by surface vessels and submarines. Its multi-sensor architecture (including acoustic, seismic, magnetic, pressure, underwater electric potential/extremely low frequency electric fields [UEP/ELFE] and optical sensors) coupled with its smart logic, makes it selective and effective against a wide range of targets and resistant against the modern countermeasure techniques. These MCM techniques include mine jamming, which involves the use of advanced signature compensation systems to manipulate their magnetic field's characteristics and generate signals that could jam the sea mine (Holmes 2008). The ASTERIA is also designed to facilitate remote command and control and gathering of data out in the sea (Rheinmetall Defence Australia 2023). These sea mines, like many other smart mines, also have IFF capabilities programmed to enhance targeting against specific types of targets instead of allies and neutral commercial maritime traffic (Reuters 2023).

The equipping of multiple sensors and communication nodes to communicate with different classes of vessels (e.g., surface ships, submarines, other sea mines), also contribute to the naval intelligence, surveillance, and reconnaissance effort and linkage of joint/naval communication networks (Edwards 2019) in a mission. As sea mines become smarter, they also have the potential to become mini-UUVs of their own. These smart sea mines can work together as a swarm of interconnected sensor drones that can communicate among themselves to coordinate each of their actions, searching for incoming target over a larger area of coverage, and engage adversaries or stand-down against a vessel that is considered “friendly” (Kallenborn 2017). Such systems can strike various locations of a hull simultaneously, which is critical when targeting larger ships that have higher survivability (Kallenborn 2017). The success of autonomy augmentation in UUVs can be translated to an autonomous, swarming capability among multiple smart sea mines. Autonomous sea mines may also decide based on the multiple influences to engage pre-programmed types of hostile targets when there is a high level of confidence (Borchert 2019).

In addition to traditional sea mine engagement, swarms of unmanned assets can also be used for jamming and deception to hide a friendly platform by generating clutter signals to confuse adversaries (Popa et al. 2018). Such capabilities of superior decision-making and coordination can support the objectives of the current project, which is the design, engineering, and assessment of mobile minefields, particularly in a key objective of reseeding minefields to sustain the sea control capabilities of the minefield.

4. Future of U.S. Naval Mining Capabilities

During a discussion between the CNO and the commander of the Naval Mine and Anti-Submarine Warfare Command in 2011, it was proposed that “the USN should consider the development of advanced underwater weapon systems rather than maintaining obsolescent capability of current mine inventories and the warfare capability historically provided by static minefields” (Emmersen et al. 2011, 199). The discussion also described that “the emerging technologies in underwater sensors, networks, and unmanned vehicles can build enhanced capability for undersea warfare dominance” (Emmersen et al. 2011, 199). The discussion signals that the new capabilities in mobile minefields possess great potential as an advanced weapon—one that can embrace advanced sensors, networks, and the notion of unmanned vehicles to augment naval warfare capabilities.

While the 2017 and 2022 *National Security Strategy* and the 2018 and 2022 *National Defense Strategy* did not directly reference mines (Biden 2022; Kerg 2020; Office of the Secretary of Defense 2022), it is still important for mine warfare (MIW) capabilities to continue to develop in anticipation of future threats, due to the low cost and high effectiveness. The 2022 NAVPLAN explained that “modern naval warfare requires integrated systems to manage the information necessary to generate decision advantage, close complex kill chains, and logistically sustain a distributed, forward-deployed force. We must design every platform, weapon system, and support facility with this in mind” (Chief of Naval Operations [CNO] 2022, 18).

Mines can also be used as important communication and ISR nodes that will help the USN extend the sensor coverage area to have a better battlespace situational awareness. The 2022 NAVPLAN further explains that as new platforms/forces are being developed, capabilities can be grouped into six Force Design Imperatives of “Expand Distance, Leverage Deception, Harden Defense, Increase Distribution, Ensure Delivery, and Generate Decision Advantage” (CNO 2022, 8). The dual role as an ISR and communication node can support both the minefield in its objectives and support other friendly platforms and weapon systems in extending their range, which can achieve both “Expand Distance” and “Generate Decision Advantage.” In order to address “Increasing Distribution,” a mobile minefield can employ smaller, more lethal, and less costly platforms that disrupt sea control and impose dilemmas for the adversaries as the minefield continues to replenish itself through local mobility (CNO 2022, 8–9). The CNO also stated in the 2022 NAVPLAN that “we will build future platforms with modernization in mind—hardware upgradeable and software updateable at the speed of innovation” (CNO 2022, 11). He also added that large long-life capital investments should also support evolving sensors and weapons systems by providing adequate space, weight, and power (CNO 2022, 11).

Based on the technological and operational developments in sea mines, a mobile minefield that can be deployed covertly at a large scale will be beneficial to the sustainment of sea control by allowing safe passage by neutral and friendly ships and denying access to hostile targets. The mobile minefield would also fill a second role as a communication and ISR node to a larger intelligence network for superior battlespace situational awareness. The system design can embrace the adoption of technologies in autonomy, swarming control, and multiple sensor-influence for a target-detection-device firing mechanism that can improve the robustness and sensitivity/performance of the mobile minefield. The project team drew from the NOLH DOE model developed in the MAST software by SEA 32 Capstone Project Team (Deken et al. 2021) to use the enemy behaviors developed to test against the proposed behavior algorithm of mobile mines which are deployed in a defined location and operational environment.

III. MODELING METHODOLOGY/APPROACH

This chapter offers a comprehensive overview of mobile mines, their deployment strategies, and the tactical benefits of using these mines. The focus is on the advantages of using mobile mines alone or in conjunction with static mines, compared to only traditional static mines. It introduces simulations that detail the operational dynamics and strategic benefits of mobile and static mines, setting the stage for further detailed analysis. Ultimately, this discussion aims to foster further research and engineering efforts to integrate mobile mines into modern naval weaponry.

A. MODELING AND SIMULATION APPROACH

The Modeling and Simulation Toolkit (MAST), developed by the Naval Surface Warfare Center (NSWC) Dahlgren Division, has emerged as a pivotal technology for contemporary naval warfare simulations. Initially conceived to enhance missile defense strategies, MAST expanded its utility to encompass a broad range of military operations across various domains, demonstrating its versatility and effectiveness. Enhancements to MAST, including the addition of a graphical user interface (GUI), military-specific plugins for the U.S. Navy, and an upgraded software framework, have enabled it to meet complex simulation needs crucial in both educational and operational contexts. These developments reflect MAST's capacity for rapid configuration and scenario testing, qualities that stem from its design as a versatile, domain-agnostic platform. Collaborative efforts with academic institutions like the Naval Postgraduate School have refined MAST's functionality, integrating user feedback and advancing simulation technologies. This partnership has extended MAST's application spectrum to include orchestrated simulation through modeling (OSM), a pivotal concept in modern military simulations. As MAST continues to evolve, it is integrating advancements such as artificial intelligence and machine learning to enhance predictive accuracy and operational efficiency, pushing the boundaries of what is possible in military simulation technology (Deken et al. 2021).

B. MAST SOFTWARE

The following subsections detail the Modeling and Simulation Team's approach to selecting the MAST. We compared MAST with other available simulation software programs, highlighting its operational advantages, developmental history, and proven effectiveness in past projects with military applications.

1. Comparison Analysis with Other Software

In our evaluation, we considered MAST alongside two other major simulation tools: AnyLogic and Extendsim, to determine the best fit for our defense-oriented applications.

- **AnyLogic**

Pros: Supports diverse modeling methods including system dynamics, discrete event, and agent-based modeling; highly customizable and integrates well with various programming languages and databases.

Cons: Features a steep learning curve; its commercial nature requires extensive system requirements that exceed our current capabilities.

- **Extendsim**

Pros: Notable for robust statistical and data analysis capabilities.

Cons: Offers limited 3D visualization capabilities and is primarily tailored for industrial rather than military applications.

- **MAST**

Pros: Specifically developed for military applications, which facilitates easier adaptation to defense-related modeling; efficient in quick scenario testing and supporting effective human-in-the-loop simulations.

Cons: Limited developer support and lack of open-source access may restrict extensive customization.

Our analysis highlighted MAST's specialized features for defense applications and its proven effectiveness in similar projects, confirming it as the optimal choice for meeting our project requirements.

2. Reasons for Selection

The Modeling and Simulation team selected MAST for this project after a thorough analysis of alternatives. The team's decision was influenced by several key factors that set MAST apart from other available modeling tools.

- **Ease of Use:** MAST's user interface is intuitively designed, enabling quick setup and execution of complex simulations—critical elements for meeting our project timelines. This intuitive design is evidenced by MAST's customizable interface and its comprehensive support for surface and air warfare concepts, which allow for detailed definitions and manipulations as required for diverse simulation scenarios. Specifically, the "agents window" allows users to seamlessly add agents, geometries, or builders, streamlining the setup process for both static and dynamic naval defense scenarios (Deken et al. 2021).

- **Proven Track Record:** MAST has been successfully utilized in numerous projects by notable entities such as the NSWC and the Naval Postgraduate School, providing a solid history of effective use in contexts similar to ours.

- **Flexibility and Customization:** MAST supports multiple programming languages, which offers extensive flexibility in customizing simulations to meet specific project needs, as shown by its ability to define and interact with geographic agents (Deken et al. 2021).

These attributes collectively emphasize MAST's alignment with our strategic goals and operational demands, particularly our requirement for a simulation tool that is intuitive, capable of detailed asset analysis, and instrumental in influencing naval mobile mine development, acquisitions, and tactics. This alignment confirms MAST as our preferred modeling toolkit for this project.

3. Previous Relevant Work on MAST

The effectiveness of the MAST is well-documented through its extensive use in previous Naval Postgraduate School projects. These projects have typically focused on areas such as minefield simulation and warfare strategies, where MAST's capabilities in detailed scenario modeling and simulation have been critical. Specifically, MAST enabled effective multi-agent simulations that supported complex strategic analyses, pivotal in projects like *Modeling and Simulation to Identify Offensive Denial Mining Key Performance Drivers and Behavioral Responses,* conducted by Naval Postgraduate School SEA cohort 32. This extensive simulation capability allowed for an in-depth exploration of operational effectiveness and the impact of various deployment strategies, influencing naval tactics and strategies. The insights gained from these simulations, such as the nuanced perception of mine deployment effectiveness under varied conditions and strategic decision impacts, have informed current methodologies. These realizations particularly enhanced the comprehension of operational dynamics and decision-making processes in mine warfare. These prior projects have established a foundation of heuristic data that enhances current simulation accuracy and reliability. The historical application of MAST in educational and operational settings not only validates its effectiveness but also yields a rich data set that enhances the precision and relevance of current simulations (Deken et al. 2021).

C. CONOPS

The following section provides the mission objective and the two scenarios the team develops for modeling and simulation purpose. It describes what goals the team expects the mobile mine system to achieve and the specific scenarios to simulate for further analysis on the effectiveness of the system.

1. Mission Objective

A mission objective, also known as the system goal statement in the systems engineering field, is a brief but precise definition of a system's main purpose or aim. It acts as a guiding principle that helps to design, implement, and evaluate the system's capabilities and functionalities.

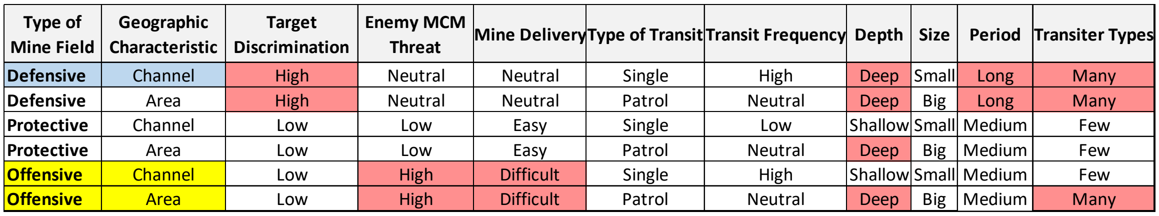
For years, the traditional minefield has fulfilled its purpose of disrupting enemy maritime activities and enhancing sea denial capabilities. However, the evolution of mine countermeasure (MCM) sensors, tactics, techniques, and procedures (TTP) has decreased the effectiveness of this weapon. Therefore, the USN called for a system that impedes or restricts adversary transit routes and complicates MCM efforts, frustrating enemy attempts to neutralize or bypass a minefield (Kline 2023). In this context, the mission objective of the mobile minefield system is **to delay or deny the transit of surface and underwater vehicles in a water space for a period of time by establishing a dynamic threat resilient to the enemy's MCM efforts**.

2. Scenarios

Scenarios are an important part of the mobile minefield project, as they provide a means to validate the system's effectiveness. These scenarios illustrate scenes in which the mission occurs, providing a better visualization of the system's restrictions, resources, and objectives. These scenarios comprise military situations, operational flow, equipment, opposing and friendly forces, and environmental conditions.

To create the scenarios, we analyzed the different types of minefields and the factors related to them, as shown in Table 1.

Table 1. Relevant Factors Analysis to the Scenarios' Generation



Type of Mine Field	Geographic Characteristic	Target Discrimination	Enemy MCM Threat	Mine Delivery	Type of Transit	Transit Frequency	Depth	Size	Period	Transiter Types
Defensive	Channel	High	Neutral	Neutral	Single	High	Deep	Small	Long	Many
Defensive	Area	High	Neutral	Neutral	Patrol	Neutral	Deep	Big	Long	Many
Protective	Channel	Low	Low	Easy	Single	Low	Shallow	Small	Medium	Few
Protective	Area	Low	Low	Easy	Patrol	Neutral	Deep	Big	Medium	Few
Offensive	Channel	Low	High	Difficult	Single	High	Shallow	Small	Medium	Few
Offensive	Area	Low	High	Difficult	Patrol	Neutral	Deep	Big	Medium	Many

The factors are described as follows:

Type of Minefield: The minefields were classified as defensive, protective, and offensive. Defensive mining is characterized by fields laid within friendly territorial waters, while protective mining is off the coast, and offensive mining is fields laid within hostile territorial waters.

Geographic Characteristics: The geographic characteristics were classified into channel or area. Channel relates to close-bounded water spaces, like bays, while area minefields are located in open sea zones.

Target Discrimination: Target discrimination is the complexity of identifying the transiters as friend or foe. High indicates a scenario where both friendly and enemy transiters are likely, while low indicates only enemy transiters likely.

Enemy MCM Threat: This is the level of the enemy's effort to clear the passage for its forces.

Mine Delivery: Delivery concerns the ease of laying the mines in the desired zone.

Type of Transit: Type of transit is linked to the behavior of the transiters' vehicles. It can be a single passage through the field or a patrol pattern within the field.

Transit Frequency: Frequency relates to the number of transiters over time.

Depth: Depth relates to the distance between the bottom and the surface of the zone of interest.

Size: Size is the product of the height and width of the minefield's rectangular shape. The channel minefield was designated 1 nm x 1 nm, while the area minefield was designated 5 nm x 2 nm.

Period: Period concerns the expected time that the minefield must remain active to comply with its desired result.

Transiters Types: Transiters types relates to the number of different types of vehicles that are expected to navigate the minefield.

After establishing these relevant factors, we assessed them for each of the minefield types, assigning them a relative level of easy/neutral/difficult based on military experience. We then highlighted the most difficult factors for each possible scenario to group the scenarios by similarity. We narrowed the possible scenarios down to the two offensive scenarios due to the highest threat from enemy MCM and the most difficult mine delivery posed by the enemy that does not apply in other scenarios. As such, we kept both offensive scenarios due to the difference in enemy behavior between the two scenarios including both enemy MCM objective and enemy transiter behavior.

a. Scenario 1—Offensive Channel Minefield

Strategic Objective: Disrupt enemy naval transit in the contested waters of the Indo-Pacific region. This operation aims to impede adversary movements in and out of harbors, denying access to vital sea lanes and logistic hubs.

Tactical Objective: Deploy a 1 nm x 1 nm channel-type minefield across a designated maritime channel to obstruct, delay, or deter enemy vehicles' transit through the controlled waterway. The objective is to create a barrier to prevent the enemy from accessing a harbor or other point of interest at one side of a channel, forcing them to navigate through alternative routes and complicating their operational planning by establishing a dynamic threat resilient to enemy MCM efforts.

Enemy Forces: The scenario involves potential encounters with adversary naval forces, including but not limited to surface vessels, submarines, and maritime patrol aircraft. Enemy forces may employ specialized MCM assets, like the Wozang-class mine hunting ships (MHS); which are equipped with remotely operated vehicles (ROVs) to neutralize mines.

Enemy MCM Objective: The adversary's primary objective is to execute a breakout operation through the channel minefield, bypassing or neutralizing the deployed mines to regain access to critical maritime passages.

Location and Terrain: The operational theater encompasses a strategic maritime channel connecting major shipping lanes and maritime chokepoints in the Indo-Pacific region. The sea depth within the channel averages 200 meters, providing sufficient clearance for mine deployment and vessel transit. The terrain features underwater ridges, seafloor contours, and navigational hazards, influencing minefield placement and tactical considerations.

Timeframe: The scenario unfolds in the near future, amid escalating tensions and geopolitical rivalries in the Indo-Pacific. Although the operational timeframe spans several weeks to months, the minefield endurance is expected to be 30 days without reseeding needs.

Friendly Forces: Friendly forces comprise a coalition of naval assets drawn from allied nations, supported by dedicated mine warfare platforms, maritime patrol aircraft, and surveillance assets. The mobile minefield is integrated into existing naval platforms, enabling rapid deployment and adaptive response to emerging threats in the operational environment.

b. Scenario 2—Offensive Area Minefield

Strategic Objective: Disrupt enemy naval operations in a contested theater of operations. This operation aims to impede adversary movements and deny access to critical maritime regions.

Tactical Objective: Deploy a 5 nm x 2 nm area-type minefield across a designated maritime zone to create a hazardous environment for enemy vessels, impeding their transit, reconnaissance, and operational flexibility within the controlled area. The objective is to establish a robust offensive perimeter that forces adversaries to avoid mined waters, impeding or restricting their usage by establishing a dynamic threat resilient to enemy MCM efforts.

Enemy Forces: The scenario involves potential encounters with adversary naval forces, including but not limited to surface vessels, submarines, and maritime patrol aircraft. Enemy forces may employ specialized MCM assets, like MHS, equipped with ROVs to neutralize mines.

Enemy MCM Objective: The adversary's primary objective is to execute a clearance operation within the offensive area minefield, neutralizing or bypassing the deployed mines to regain access to critical maritime regions and operational freedom.

Location and Terrain: The operational theater encompasses a strategic maritime area located in a contested region of interest, characterized by varying sea depths, underwater topography, and navigational challenges. The sea depth within the designated area averages 1000 meters, providing ample clearance for mine deployment and vessel transit. The terrain features underwater ridges, seamounts, and deep-sea trenches, influencing minefield placement and tactical considerations.

Timeframe: The scenario unfolds in the near future, amid escalating tensions and geopolitical rivalries in the Indo-Pacific. Although the operational timeframe spans several weeks to months, the minefield endurance is expected to be 30 days without reseeding needs.

Friendly Forces: Friendly forces comprise a coalition of naval assets drawn from allied nations, supported by dedicated mine warfare platforms, maritime patrol aircraft, and surveillance assets. The mobile minefield is integrated into existing naval platforms, enabling rapid deployment and adaptive response to emerging threats in the operational environment.

3. Enemy MCM Capability

The lack of public available information on People's Liberation Army Navy (PLAN) mine hunting and sweeping vessels poses a significant challenge for the team to determine the data used for the simulation. PLAN has about 60 mine warfare ships and crafts including minesweepers, mine hunters and remotely operated unmanned mine countermeasures vessels (Waidelich and Pollitt 2023). The team chose Wozang-class MHS for its ability to operate ROVs to neutralize mines (Waidelich and Pollitt 2023). The enemy's mine hunting tactic used in the simulation is "neutralize in stride," meaning the mine hunter detects, identifies, and neutralizes the mine in sequence. As mentioned in the beginning, due to lack of publicly available information, the team leveraged our military background and previous operational experience to determine that the sensor range of the mine hunter is 1000 yards and the total processing time is 45 minutes per mine.

4. Enemy Behavior

To account for the enemy's movement in the simulation, the team designed a total of 10 enemy surface ships transiting through the area. The enemy transiter maneuvered in single file through the minefield. If a transiter detonated a mine, the transitioning mission paused, and the mine hunter started the mine hunting process to clear a Q-route. Once a Q-route was established, transiters continued moving until another mine is detonated. The process repeats until all transiters are either safely past the minefield or sunk.

5. Mobile Mine Behavior

The goal of adding mobility to the mine is to provide more flexibility for the miners and to make the minefield more resistant to enemy MCM. The movement logic of the mine is designed to prevent the enemy MCM from detecting any mine movement and keep enemy transiters from passing safely through the minefield. To prevent the mine movement from being detected, the mines are programmed to remain stationary when observed by MCM SONAR. To increase the difficulties for enemy transiters from safely passing through the minefield, the mines are designed to mobilize and then fill gaps in the minefield that are identified through either the detonation of one of the mines or the passage of multiple enemy ships.

Figure 3 represents the logic tree of how an individual mine reacts in three different situations. The following paragraphs provide more details of each situation and the mine movement logic.

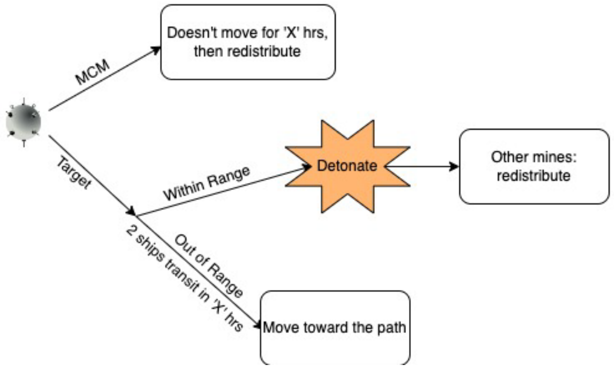


Figure 3. Mine Behavior Logic

Case 1: When the mine senses an MCM SONAR signal, the following actions will be taken:

- **Action 1.1: The mine remains stationary for "X" hours.**
- **Action 1.2: The mine moves 50–100 yards in a random direction.**

By remaining stationary for a preprogrammed amount of time, the mobility of the mines can likely be concealed from the enemy for some time. Upon detecting a mine with MCM SONAR, the enemy will either prosecute the mine (identify and neutralize in stride) or mark the mine for follow-on identification and neutralization by another platform. In the case that the enemy prosecutes the mine, the MCM ship would continue to observe the mine throughout the process, during which we do not want the mine to move. If the mine is marked by the MCM ship for follow on action (typically neutralization), the next platform would likely not be tasked for that mission for at least 6–12 hours based on deconfliction considerations and the enemy staff's battle rhythm. The follow-on platform will need to reacquire the mine; by moving 50–100 yards the mine has moved far enough to reduce the probability of reacquisition and consequently prevent neutralization, particularly in a high clutter environment. This movement is also short enough that it will not have a significant impact on the overall minefield layout.

Case 2: When the mine senses a target vessel passing within the effective range of the mine, the following actions will be taken:

- **Action 2.1: The mine that senses the target vessel detonates.**
- **Action 2.2: The other mines sense the detonation and move in that direction.**

The movement distance is based on the other mines' range from the detonation (Table 2).

Table 2. Mine Movement Distance by Range

Distance from detonation (yards)	Distance to move (yards)
1000	1000
2000	900
3000	800
4000	700
5000	600
6000	500
7000	400
8000	300
9000	200
10,000	100

This behavior allows the mines to fill in gaps created by mine detonations. In a static minefield, as mines are detonated either by enemy MCM or enemy transiters, the minefield will pose less of a threat in that location as the density of mines has decreased. By the mobile mines moving in response to another's detonation, the mines fill gaps in the minefield created by both enemy MCM neutralizations and enemy transiter mine strikes. The goal of having the mines move a greater distance the closer they are to the detonation is to maintain as much distribution throughout the minefield as possible while having the close mines fill the path of travel where the mine was removed.

Case 3: When the mine senses a target vessel pass by outside of the effective range of the mine, the following actions will be taken:

- **Action 3.1: The mine waits for another vessel to pass from the same direction within “X” hours.**
    - **Action 3.2.1: If a second vessel passage is not detected, the mine returns to normal operation.**
    - **Action 3.2.2: If a second vessel passage is detected, the mine moves in the direction of the vessel’s path. The movement distance is based on their range from the vessel detected, shown in Table 2.**

This behavior allows the mines to react to successful enemy passage through the minefield by closing gaps that have been exploited by the enemy. The requirement for two vessels to pass within a preprogrammed number of hours provides hysteresis to prevent unnecessary hunting behavior by the mines. The mines movement distance is based on Table 2 as for detonations to achieve the same effect of maintaining distribution throughout the minefield while still converging on the enemy path of travel.

The direction of movement for Case 2 and Case 3 is either lateral or longitudinal in the minefield based on the quadrant from which the trigger signal was detected as seen in Figure 4. This type of movement allows the mines to move to close travel lanes through the minefield, while maintaining dispersion and preventing the mines from all converging on a single point, which could eventually be recognized by the enemy.

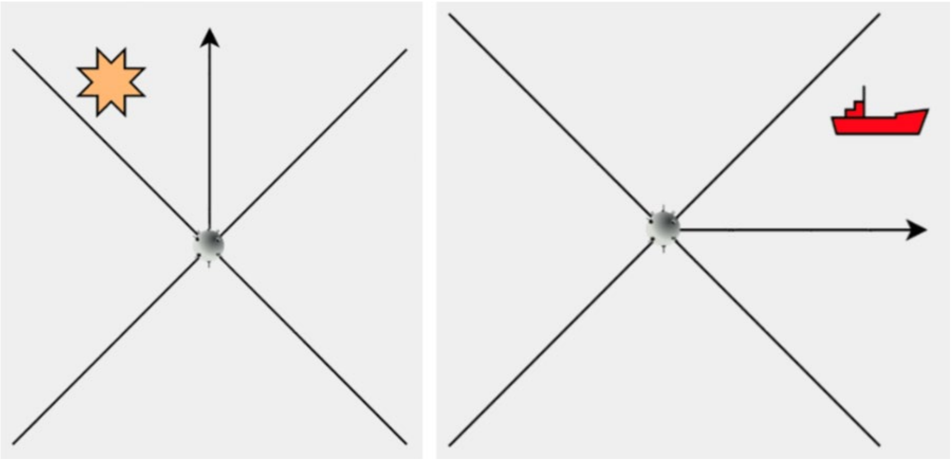


Figure 4. Mine Movement Direction Determination

6. System Assessment

The system assessment objective provides quantitative data about the system's performance, suitability, and affordability across its life cycle, considering the proposed operational environment. It uses technical measurements to evaluate to what extent the developing system meets the mission objective and the technical requirements. Furthermore, these indicators are crucial when establishing trade-off studies and comparing different alternatives in a system development or between systems, such as mobile minefields and static minefields.

MOEs are defined as "the 'operational' measures of success that are closely related to the achievement of the mission or operational objective being evaluated, in the intended operational environment under a specified set of conditions; i.e., how well the solution achieves the intended purpose" (Roedler and Jones 2005, 9). These measures are a key acceptance criterion regarding the degree and quality of the stakeholders' needs fulfilment. MOEs are directly connected to the system's mission statement. Before going into the details of the MOEs that are generated by the project team, the following paragraphs explain why, the Simple Initial Threat (SIT) and Risk, the two common MOEs employed in mine warfare, are not used to assess this system.

First, the SIT is the "probability that the first vessel to attempt transiting through the minefield will become a casualty" (Edwards 2019, 51). This MOE is derived by:

$$SIT = 1 - (1 - wl/A)^m,$$

where w is the mine's sweep width, l is the ship's length of track within the minefield, A is the minefield area, and m is the number of mines. The wl/A portion of the formula is the mine actuation probability, given $wl << A$.

One critical assumption applied in this formula is that after a mine detonates, the location of the remaining mines would change to keep the mines uniformly distributed in the minefield. In the case of a mobile minefield, when the mines move they will tend to converge on the channelization, making the uniform distribution assumption overly pessimistic. Even though it is a valid MOE for initial threat assessment, it cannot be used to compare a static and a mobile minefield's effectiveness over time because the static minefield cannot redistribute itself after seeding, and the mobile minefield does not use a uniform distribution as its logic.

Another common MOE used to assess static minefields is risk, which is defined as "the threat level of the minefield to enemy transiters and the risk to friendly transiters (active mines that lack remote command and control are a risk to both enemy and friendly forces)" (Edwards 2019, 51). It is important to note that transiters, in the scope of this project, are the surface and underwater vehicles that move from one point to another, navigating through a path within the established minefield. Although it is considered a good measure, it is provided through complex computer calculations made by classified software unavailable to us. Therefore, it is not available to use in this unclassified work.

As discussed before, the MOEs must be related to the system goal. Considering this, it is important to analyze the mission objective of the mobile minefield. The team identified some key factors to establish measures that would indicate the extent to which the system meets its goals. Figure 5 was created to show a breakdown of the MOEs.

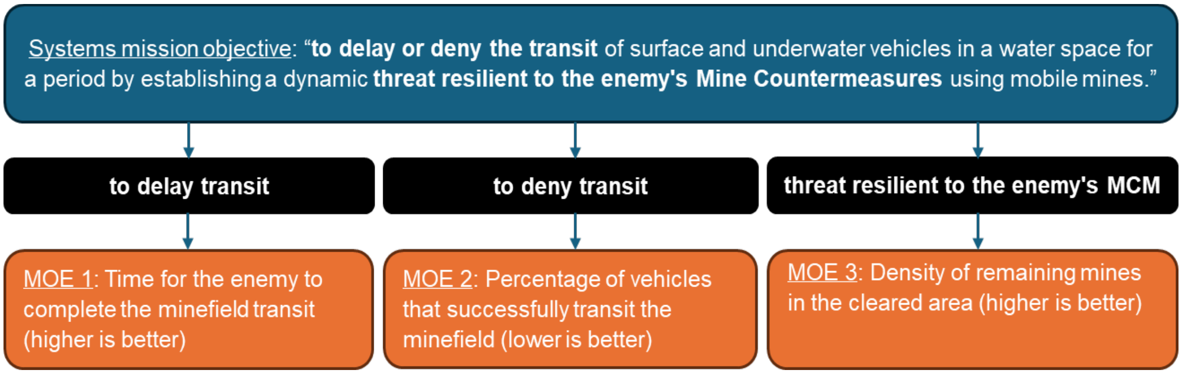


Figure 5. Mission Objective Analysis and MOEs Identification

The analysis of the mission objective exposed three capabilities of the system: to delay, to deny, and to be a threat that is resilient to the enemy's MCM.

To evaluate the system delaying capability, MOE 1 is intended to measure the time that the enemy completes the minefield transit. It is comprised of the time spent to conduct *j* number of required adequate MCM and the time for *n* number of transiters (*N*) to pass through the area of interest. It is given by

$$MOE\ 1 = t_{MCM1} + t_{MCM2} + \cdots + t_{MCMj} + t_{N1} + t_{N2} + \cdots + t_{Nn} \therefore \sum_{i=1}^{j} t_{MCMi} + \sum_{k=1}^{n} t_{Tk},$$

where t_{MCMi} denotes the MCM operation time for the *i*th MCM ship, which comprises the requesting order; the displacement to the MCM initial point; the search, identification, and neutralization/flagging of mines within a Q-route; and the clearance order dissemination. The t_{Tk} denotes the time each transiter *k* takes to complete the passage through the designated area.

The MOE 2 assesses the capability of denying a path based on the percentage of vehicles that successfully transit the minefield. This measure uses the number of successful transiters (N_s) over the total number of vehicles that attempted the transit (N_T):

$$MOE\ 2 = {}^{N_S}/_{N_T}.$$

Finally, the capability of being a threat resilient to the enemy's MCM was rated using MOE 3. This measure takes into account the number of active laid mines (*M*), neutralized mines (M_N), and detonated mines (M_D) within the cleared area (Q) to define the density (ρ_M) of remaining active mines in that area. It is calculated by

$$MOE\ 3 = \rho_M = \frac{M - (M_N + M_D)}{Q}.$$

These technical measurements allowed an objective assessment of the system's effectiveness. Furthermore, they provide data to compare the simulation results and permit an efficiency evaluation of the static minefield and the mobile minefield.

D. MAST MODEL

1. Environment Modeled

The simulation environment models a rectangular area of 5 nautical miles (nm) by 2 nm at the entrance to a harbor, systematically divided into 10 sectors. Each sector measures 0.5 nm in width and 2 nm in length, allowing for precise tactical simulations and scenario analyses. This setup is designed to align with strategic operational plans as outlined in Section C CONOPS, reflecting MAST's capability to configure detailed and complex battlefield scenarios. Additionally, it enables the simulation of varied tactical approaches within a controlled and segmented operational area. A visualization of this environment is depicted in Figure 6.

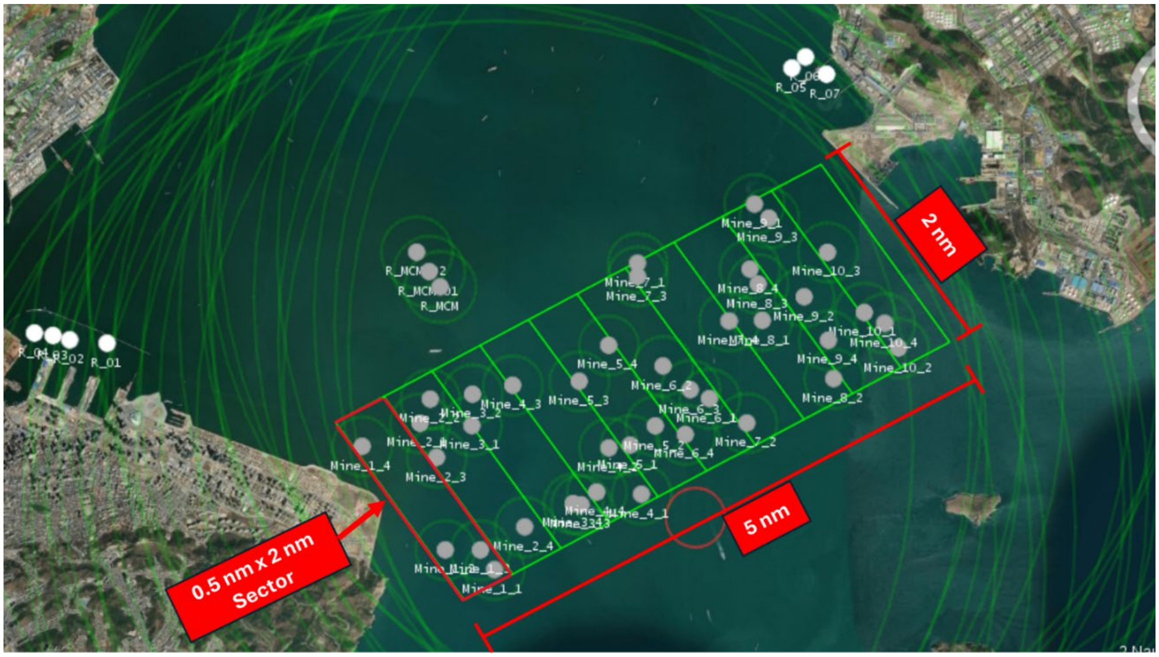


Figure 6. CONOPS Notional Harbor Entrance Protected by 5 nm X 2 nm Rectangular Mine Area

2. Entities Modeled

The simulation incorporates three types of entities.

Red Transiting Platforms: These platforms remain the same across all experimental scenarios, from static to dynamic because we want to eliminate the ship platform type as a variable affecting the minefield's performance.

Red MCM Platforms: These platforms specialize in locating and neutralizing mobile mines, avoiding engagement with these mines to ensure their operational longevity in the field.

Mobile Mines: As unmanned underwater vehicles (UUVs) equipped with advanced stealth capabilities, mobile mines are designed to remain undetected by Red transiting platforms, thus enhancing their effectiveness in operational stealth scenarios. The mines are programmed with advanced detection avoidance settings that safeguard them from Red platform sensors. In dynamic scenarios, these mines demonstrate increased interactive capabilities by adjusting their positions in response to environmental triggers such as nearby sweeping activities, thereby testing their operational effectiveness under different strategic conditions.

3. Scenarios Description

a. Static Scenario

The static scenario simulates the operations of ten Red transiting platforms, labeled R_01 through R_10. These platforms are grouped into three clusters within the simulated harbor environment: R_01 to R_04, R_05 to R_07, and R_08 to R_10. Each group is paired with one of three dedicated MCM platforms, identified as R_MCM 01, R_MCM 02, and R_MCM 03. These MCM platforms are tasked with clearing potential threats along a 1000-yard path, designated as the Q route, to facilitate safe passage for the transiting platforms. The scenario unfolds with R_01 initiating the movement toward a predetermined endpoint. Following the successful completion of R_01's route, R_02 begins its transit, and this sequential movement continues through R_10. Each MCM platform executes a single sweep operation to ensure a clear route for its corresponding group, emphasizing the simulation's ability to model precise operational logistics and mine countermeasure tactics. This scenario is depicted in Figures 7 through 10.

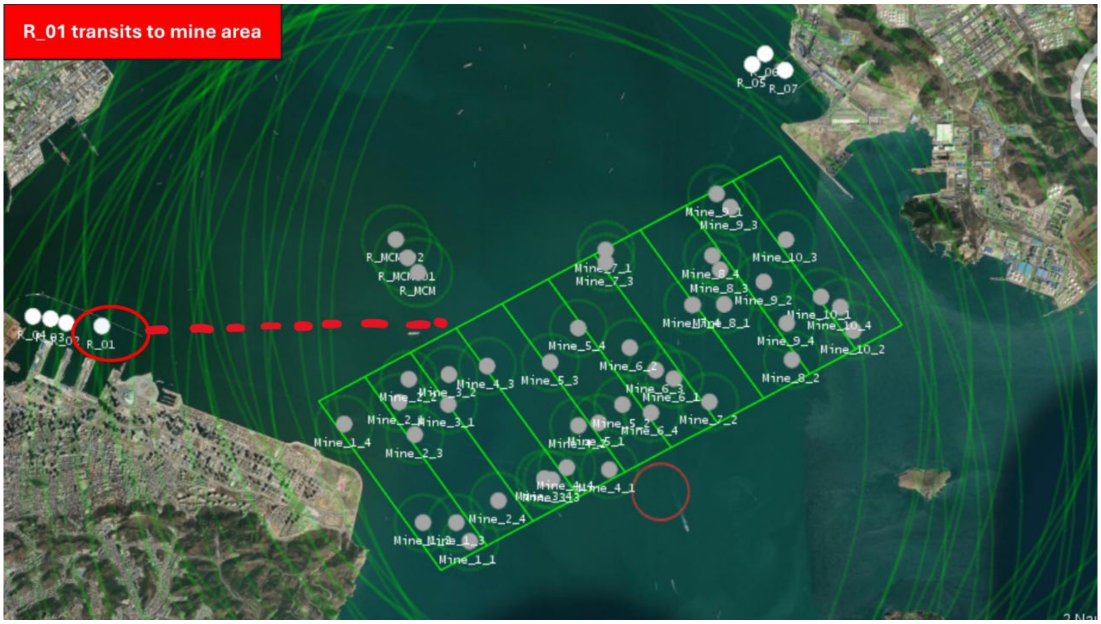


Figure 7. Red Transiting Platform Begins Movement to Predetermined Route

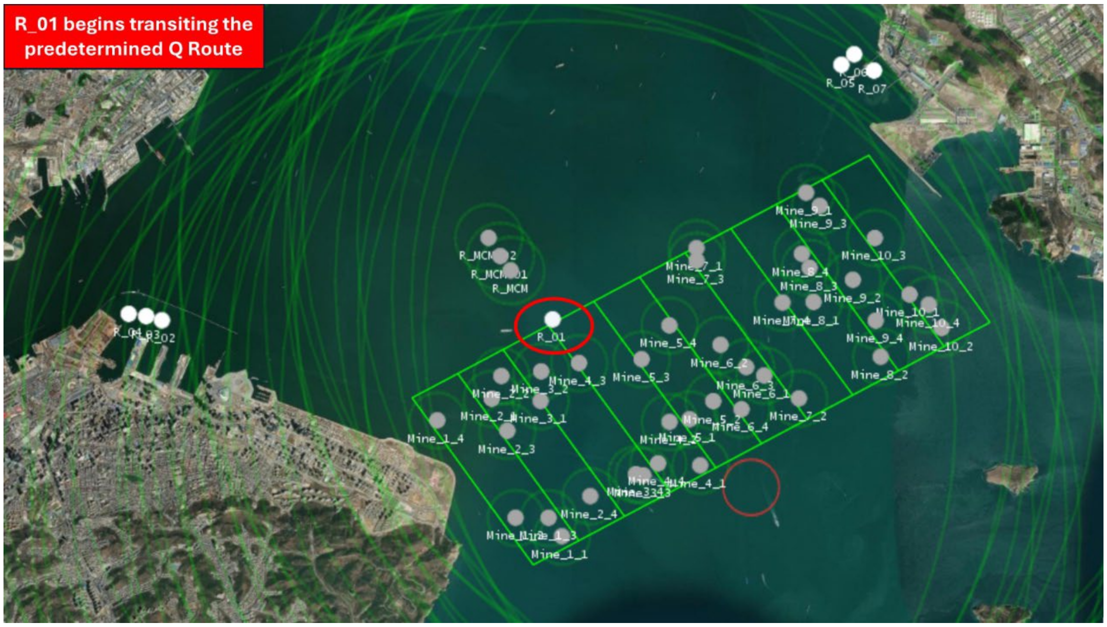


Figure 8. Red Transiting Platform Begins Movement in Predetermined Q Route

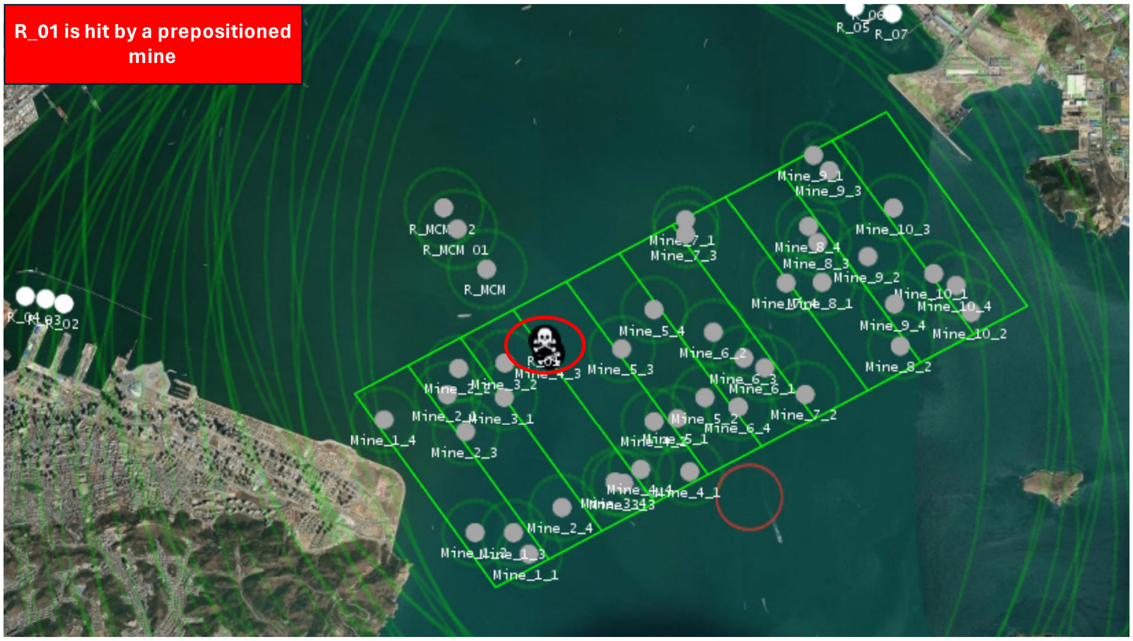

R_01 is hit by a prepositioned mine

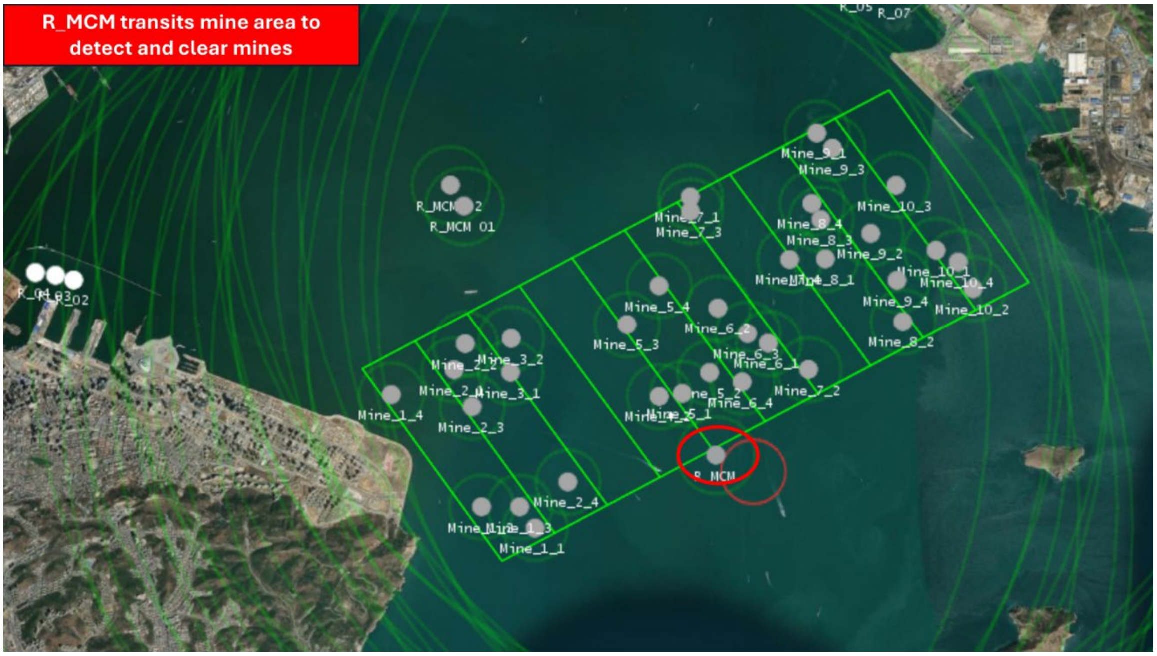
Figure 9. Red Transiting Platform Is Hit by a Mine


R_MCM transits mine area to detect and clear mines

Figure 10. MCM Transits Mine Area to Clear Route for Its Assigned Group

b. *Mobile Scenario*

In the mobile scenario, the dynamics of mine behavior introduce a layer of complexity that enhances the simulation’s fidelity and strategic depth. Unlike the static scenario, mobile mines are programmed to dynamically adjust their positions in response to triggers. These adjustments are specifically initiated by the completion of mine sweeping operations by the MCM platforms. For example, when R_MCM 01 completes a sweep of a harbor segment, the nearby mines receive a signal to move toward the cleared area. The logic governing their movement involves calculating the optimal path to close the opened route, thereby effectively re-establishing a barrier. This behavior not only tests the operational effectiveness of the mines under different strategic conditions but also showcases the simulation’s capability to mimic real-world tactical maneuvers realistically. Figures 11 and 12 illustrate the mines’ formations before and after the sweeping operation, clearly depicting how the simulation executes these complex dynamics to maintain an effective defense posture in a changing battlefield environment.



R_MCM transits mine area to detect and clear mines

Figure 11. MCM Transits Mine Area to Clear Route for Its Assigned Group

Figure 12. Mines Adjust Positioning to Re-Establish the Barrier

c. *Comparison and Contrast to Historical Model*

Unlike the broader, environmentally sensitive scenarios modeled by SEA cohort 32, our MAST simulations employ controlled settings that isolate specific variables such as interactions between mines and vessels. In these settings, environmental elements like weather and bathymetry are excluded, ensuring that a mine's effectiveness is not altered by underwater terrain or weather conditions, which provides consistent results across simulations. Additionally, we simplify agent dynamics; for example, aircraft within the simulation will not crash due to mechanical failure or topographical obstacles unless explicitly programmed for specific scenario testing. This allows for precise control over direct agent-to-agent interactions—such as a ship detecting a mine through SONAR—crucial for training exercises where predictable outcomes are essential. This focused approach contrasts with SEA cohort 32's broader research into the impact of environmental factors on strategic decisions (Deken et al. 2021).

E. SUMMARY

The team chose the modeling approaches to verify and validate the operational effectiveness of the mobile mine system and further evaluate the movement logic of the mines. The comparison of the modeling results is analyzed in Chapter V.

IV. SYSTEM REQUIREMENTS AND DESIGN ARCHITECTURE

This chapter delves into the intricate details of the mobile minefield system relating to its requirements and design. Section A outlines its capabilities and operational requirements while Section B scrutinizes the capability concept through a “5D” framework and derives relevant function requirements for the system. Section C continues to explore non-functional requirements associated with the system to meet the capabilities and operational requirements. Considering that the mobile minefield system is not totally human-out-of-loop during its operational life cycle (i.e., Human-Optionally On-the-Loop) despite the automation/autonomy that will be imbued into the system, Section D details the Human-System Integration Analysis done for the system. Sections E, F, and G detail the overall system design in aspects such as communication and autonomy, design of delivery scheme for the mobile mine to bring it to its area of operation, and its physical architecture, respectively. Lastly, Section H addresses the design considerations in relation to its operational environment.

A. CAPABILITIES AND OPERATIONAL REQUIREMENTS

In the development of the mobile minefield system capability, the team conducted a comprehensive capability and requirements analysis that aligns with the stakeholders’ key objectives and needs. This section outlines how each requirement contributes to the overall analysis and development of this capability.

The analysis was driven by a thorough understanding of the stakeholder requirements, which include the following:

Reconfigurable Deployment. The system design shall incorporate mobility elements in the sea mines to enable independent maneuvers for repositioning to overcome shortcomings of static mines, such as gaps within the minefield once a Q-route is opened.

Offensive Covert Operation. The system shall be able to operate in hostile enemy waters, where covert placement and communication of sea mines are necessary, to enable offensive naval strategies while maintaining operational secrecy.

Deep Sea Operation. The system design shall be able to operate in deep sea conditions to withstand high water pressure and corrosion and provide reliable deep-water communication capabilities.

Mission Sustainment and Recovery. The system shall feature autonomous capabilities and efficient power management systems, for extended missions and incorporate recovery mechanisms to retrieve or deactivate deployed sea mines as needed.

Reduce Collateral Damage. The system shall incorporate advanced targeting algorithms, discrimination technologies, and fail-safe mechanisms to minimize the risk of unintended impacts on civilians or friendly vessels, improving operational safety and compliance.

System Maintainability. The system shall be made of standardized components, where repair procedures and protocols of the Maintenance and Operational Management Assembly Group (MOMAG) are able to ensure rapid turnaround times for maintenance and upgrades, minimizing downtime and life cycle costs.

Surpass Static Mine Performance. The system shall provide superior operational value and strategic advantage in operations by providing better hit and kill rate, and greater time delay to enemy forces.

Agnostic Platform Delivery. The system design shall enable seamless integration with diverse existing delivery platforms allowing for interoperability and compatibility across various naval and air assets, including submarines, surface vessels, airplanes, and unmanned platforms.

This comprehensive capability analysis highlighted critical stakeholder requirements. To operationalize these requirements effectively, the team developed an overarching 5D capability concept encompassing design, delivery, durability, doctrine, and disposal, as shown in Figure 13. This overarching concept scoped and guided the development process, ensuring that the mobile minefield system is not only technologically advanced but also strategically aligned with naval operational objectives.

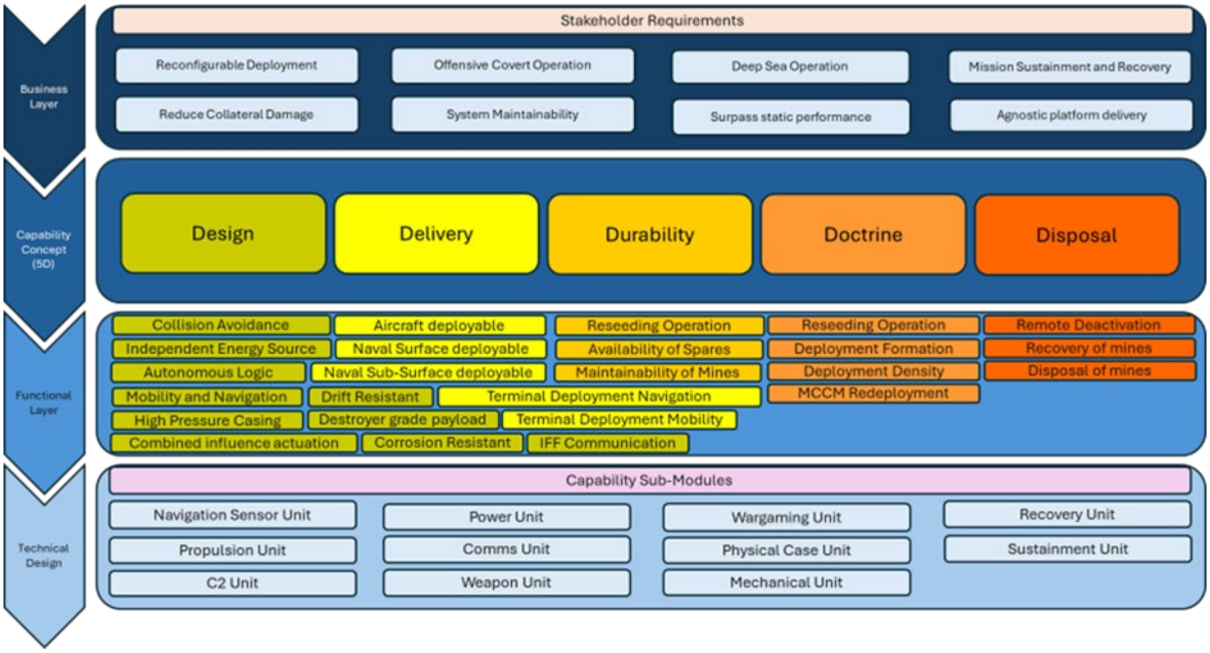


Figure 13. Capability Architecture of the Mobile Minefield System

Design. The design aspect focuses on the architecture and engineering of the mobile mine system. This includes the development of advanced sensors, propulsion, energy, and autonomous technology to ensure operational effectiveness and flexibility.

Delivery. Delivery pertains to the methods and platforms used to deploy the mobile mines and to bring the mines from base to the intended deployment location, regardless hostile or friendly.

Durability. Durability is essential for ensuring the longevity and reliability of the mobile mine system in challenging marine environments. This dimension encompasses robust construction, corrosion-resistant materials, and a pressure-tolerant design to withstand deep-sea operations and extended deployment periods.

Doctrine. Doctrine refers to the operational concepts and strategies guiding the deployment and employment of the mobile mine system within naval warfare scenarios. This includes the deployment density of the mobile mines, the effective distance between each mobile mine, and the reseeding operations necessary based on the endurance of the mobile mines. The team aims to provide some planning norms based on modeling and simulation results of the capability against various naval scenarios.

Disposal. Disposal addresses the end-of-life management of deployed mobile mines, emphasizing responsible and safe disposal practices to mitigate environmental impact and ensure post-mission safety and security.

The linkages between the capability concepts and the capability and operational requirements are summarized in Table 3.

Table 3. Categorization of High-Level Requirements

S/N	5D Capability Concept	Capability and Operational Requirements
1	Design	Reconfigurable Deployment
2	Design and Delivery	Offensive Covert Operation
3	Design and Durability	Deep Sea Operation
4	Delivery and Disposal	Mission Sustainment and Recovery
5	Design	Reduce Collateral Damage
6	Delivery and Durability	System Maintainability
7	Design and Doctrine	Surpass Static Mine Performance
8	Delivery	Agnostic Platform Delivery

B. FUNCTIONAL REQUIREMENTS

The capability and requirements analysis identified key stakeholder requirements and scoped the requirements with the 5D capability concept. To translate these requirements into actionable design and operational criteria, the team conducted a thorough functional requirement analysis. This analysis delineated the specific technical and operational capabilities required and derived the design and delivery functional requirements for the mobile minefield system.

1. Design Requirements

The design functional requirements are specific criteria or capabilities that the mobile mine system must possess to meet the needs of the stakeholders and fulfill its intended purpose. These requirements were derived from the capability and operational requirements from the previous section. Design functional requirements specify what the mobile mine system should do or how it should perform, focusing on its functional aspects. These requirements include:

Mobility and Navigation. Mobile mines shall be capable of moving and navigating on and underwater to facilitate strategic positioning and target engagement within the minefield boundaries.

Autonomous Repositioning. Mobile mines shall possess the capability to reposition autonomously within the minefield boundaries using command and control or programmed algorithms, enhancing operational flexibility and responsiveness.

Collision Avoidance. Mobile mines shall be equipped with collision avoidance systems to ensure safe and efficient deployment and operation within the minefield.

Independent Operation. Mobile mines shall have a sufficient energy source to operate autonomously for up to 30 days, supporting sustained mission capability without frequent maintenance or recharging.

Communication and Identification. Mobile mines shall be equipped with communication means to positively identify friendly forces, enhancing operational security and coordination.

Positional Stability. Mobile mines shall maintain their position within the minefield with minimal drift, ensuring operational integrity and effectiveness over extended periods.

Combined Influence Actuation. Mobile mines' actuation mechanism shall utilize a combined influence approach, integrating multiple sensor types in firing circuits for enhanced target discrimination and operational reliability.

Operational Adaptability. Mobile mines shall operate effectively in currents of up to 3 knots and at depths down to 1,000 meters, irrespective of bottom type, expanding operational capability and flexibility.

Payload Effectiveness. Mobile mines shall be equipped with payloads capable of destroying marine vessels equivalent to destroyers, both on the surface and subsurface, to achieve mission objectives and deter hostile naval activities.

2. Delivery Requirements

As the system boundaries also include aspects beyond the operational phase, the functional requirements analysis also needs to consider what and how the mobile mines are delivered to the intended deployment field from the deployment base. The delivery functional requirements focus on ensuring compatibility and versatility during deployment from various platforms. These requirements include:

Platform Compatibility. The mobile mine delivery system shall be compatible with a wide range of existing and future platforms, including aircraft, maritime vessels, and unmanned platforms.

Independent Maneuverability. The mobile mines shall possess the capability to maneuver independently, either in air or water, during the terminal phase of delivery.

3. Durability Requirements

The durability functional requirements for the mobile sea mines emphasize critical capabilities related to corrosion resistance, pressure tolerance, sustainment efforts, and maintenance infrastructure to ensure long-term operational effectiveness in challenging maritime environments. These requirements include:

Corrosion Resistance. Mobile mines shall be designed to resist corrosion resulting from prolonged exposure to deep sea conditions, ensuring reliability and operational integrity over extended deployment periods.

High Pressure Tolerance. Mobile mines shall be capable of withstanding high underwater pressure down to depths of 1,000 meters, demonstrating robustness and resilience in deep-sea environments.

Supportability and Maintenance. Efforts shall be made to re-seed the mobile minefield as part of supportability initiatives, ensuring the sustainability and effectiveness of the mobile minefield system over time. The existing and future MOMAG infrastructure shall be sufficient to maintain the mine inventory on base, facilitating timely maintenance, repair, and operational readiness.

4. Doctrine Requirements

The doctrine functional requirement underscores the importance of strategic sea mine deployment to maximize operational impact and effectiveness in naval defense and security operations. This requirement investigates the strategic and tactical deployment effectiveness to achieve the desired effects on the enemy force.

Deployment Effectiveness. Deployment of mobile mines, in numbers and position, shall match or surpass the delay/kill rate achieved by static mines if deployed in the same area.

5. Disposal Requirements

The disposal functional requirements identify the critical capabilities related to mine retrievability and electronic deactivation to ensure safe and effective disposal methods in various operational scenarios. These requirements include:

Mine Retrievability. The mobile mines shall be designed to be retrievable by other marine vessels operating in hostile territorial waters in accordance with the San Remo Manual (International Institute of Humanitarian Law,1995). This requirement ensures the ability to safely remove deployed mobile mines, minimizing environmental impact and operational risks.

Electronic Deactivation. The mobile mines shall possess electronic deactivation capabilities, allowing for remote deactivation and rendering of the mines inert. This feature enhances operational flexibility and safety during disposal operations.

6. Traceability of Requirements to Functions

Functional requirements traceability is a crucial aspect in systems engineering to ensure all requirements are fulfilled and to prevent over engineering unnecessary functions. The purpose of functional requirements traceability is to establish and maintain clear relationships between the high-level system requirements and the functional requirements. By establishing traceability, it illustrates associations of how each requirement can be decomposed from the overall system objectives and subsequently traced to design features and form; ensuring that all aspects of the mobile minefield system are aligned and validated against the specified requirements. Table 4 demonstrates the traceability between each functional requirement listed to the high-level requirements that it addresses.

Table 4. Traceability of Requirements to Functions

S/N	Capability Concept	Capability and Operational Requirements	High Level Functional Requirements
1	Design	Reconfigurable Deployment	Mobility and Navigation
2			Autonomous Repositioning
3			Independent Operation
4			Communication and Identification
5	Design and Delivery	Offensive Covert Operation	Independent Maneuverability
6	Design and Durability	Deep Sea Operation	Corrosion Resistance
7			High Pressure Tolerance
8	Delivery and Disposal	Mission Sustainment and Recovery	Supportability and Maintenance
9			Mine Retrievability
10			Electronic Deactivation
11	Design	Reduce Collateral Damage	Collision Avoidance
12			Communication and Identification
13			Positional Stability

S/N	Capability Concept	Capability and Operational Requirements	High Level Functional Requirements
14	Delivery and Durability	System Maintainability	Supportability and Maintenance
15	Design and Doctrine	Surpass Static Mine Performance	Combined Influence Actuation
16			Operational Adaptability
17			Payload Effectiveness
18			Deployment Effectiveness
19	Delivery	Agnostic Platform Delivery	Platform Compatibility

C. NON-FUNCTIONAL ANALYSIS

Apart from functional requirements, it is imperative to analyze the non-functional requirements that may directly or indirectly affect the system's functional performance. This segment analyzes the various "-ilities" relevant to the development and deployment of the minefield system, such as reliability, maintainability, supportability, and survivability (Fabrycky and Blanchard 2013).

1. Reliability Analysis

Reliability Block Diagram. Based on the functional architecture, a reliability block diagram was created to determine how the reliability of each subsystem contributed to the overall system reliability of the mobile mine (Fabrycky and Blanchard 2013). To determine the reliability of the system, the team defined failure of the system as the inability of the mobile mine to perform any of its intended functions, such as mobility, targeting, striking, and communications, when deployed. Therefore, every subsystem's reliability is critical to the overall system reliability.

From Figure 14, we see that all seven subsystems of propulsion (P1), comms (C1), command and control (C2), navigation (N), mechanical (M), power (P2), and weapon (W) are in a series arrangement, as without which the mobile mine will not be able to achieve its mission. The mobile mine's overall system reliability is thus given by the following equation:

$$R_{SYSTEM} = R_{P1}R_{C1}R_{C2}R_N R_M R_{P2} R_W$$

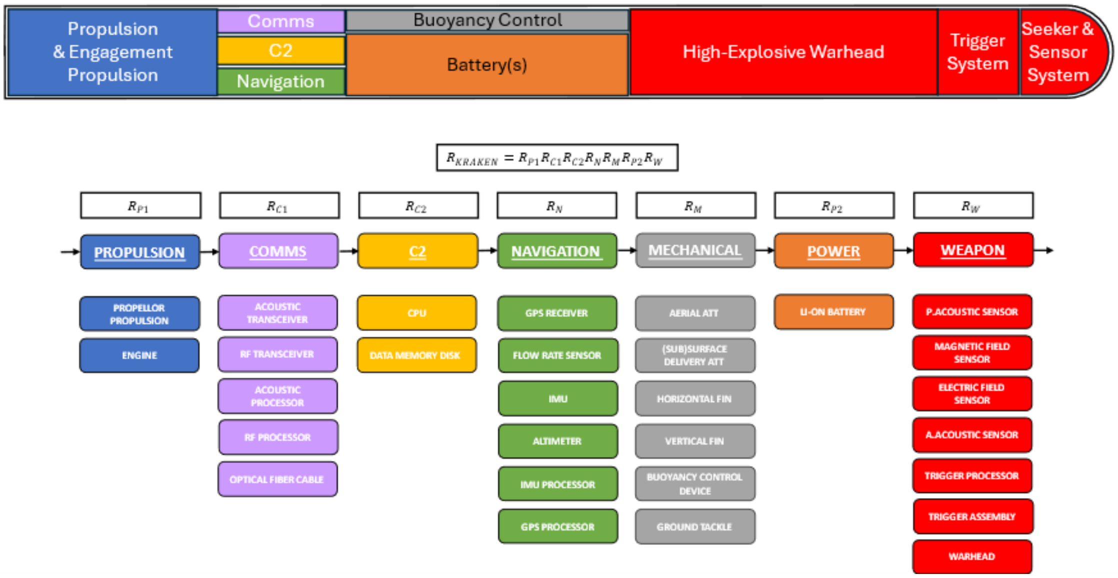


Figure 14. Reliability Block Diagram of the Mobile Mine

Required Subsystem Reliability. The team assumed an objective overall system reliability of 0.95 and a threshold reliability of 0.90. Using the reliability block diagram, the required subsystem reliability was calculated for the objective and threshold reliability respectively, as shown in Table 5.

Table 5. Summary of Required Subsystem Reliability

Overall System Reliability	$R_{SYSTEM} = 0.95$ (Objective)	$R_{SYSTEM} = 0.90$ (Threshold)
Required Subsystem Reliability (5s.f.)	0.99270	0.98506

Required Component Reliability. From the required subsystem reliability, the required component reliability within each subsystem was determined, as shown in Table 6. These figures shall serve as one of the decision criteria for the selection of components during the subsequent project development and acquisition phase should there be further interest in developing the physical mine.

Table 6. Summary of Component Reliability

Overall System Reliability	$R_{SYSTEM} = 0.95$	$R_{SYSTEM} = 0.90$
Required Subsystem Reliability (5s.f.)	0.99270	0.98506
Propulsion		
Propellor Propulsion	0.99634	0.99250
Engine	0.99634	0.99250
Comms		
Acoustic Transceiver	0.96708	0.95500
RF Transceiver	0.96708	0.95500
Acoustic Processor	0.96708	0.95500
RF Processor	0.96708	0.95500
Optical Fiber Cable	0.99634	0.99250
C2		
CPU	0.99634	0.99250
Data Memory Disk	0.99634	0.99250
Navigation		
GPS Receiver	0.99878	0.99749
Flow Rate Sensor	0.99878	0.99749
IMU	0.99878	0.99749
Altimeter	0.99878	0.99749
IMU Processor	0.99878	0.99749
GPS Processor	0.99878	0.99749
Mechanical		
Aerial Attachment	0.95143	0.93976
(Sub)Surface Attachment	0.95143	0.93976
Horizontal Fin	0.99854	0.99699
Vertical Fin	0.99854	0.99699
Buoyancy Control Device	0.99854	0.99699
Ground Tackle	0.99854	0.99699
Power		
LI-ON Battery	0.55955	0.50373
Weapon		
Passive Acoustic Sensor	0.79316	0.75244

Overall System Reliability	$R_{SYSTEM} = 0.95$	$R_{SYSTEM} = 0.90$
Magnetic Field Sensor	0.79316	0.75244
Electric Field Sensor	0.79316	0.75244
Active Acoustic Sensor	0.79316	0.75244
Trigger Processor	0.99817	0.99624
Trigger Assembly	0.99817	0.99624
Warhead	0.99817	0.99624

Components in Parallel Arrangement. Some components within the subsystems are deemed less critical to the reliability of the system as there are alternative components that perform similar functions to ensure continued overall system performance. These components include the acoustic and radio frequency (RF) unit of the comms subsystem, attachments onto delivery platforms under mechanical subsystem, the batteries, and the various sensors in the weapon subsystem. As such, these components are arranged and computed in parallel arrangement within each subsystem.

Limitations of Analysis. The fundamental assumption that frames the reliability analysis of the mobile mine system was based on the definition of failure mentioned at the beginning of the section. This definition has a holistic view on the mission of the mobile mine, such as the need to succeed in all the different phases—transportation, deployment, positioning, targeting, and striking. However, the components required for transportation and deployment, such as aerial and sub/surface attachments, may not be necessary for the mobile mine to perform its mission to destroy enemy naval assets once it is deployed at sea. The reliability analysis does not consider the reliability of the mobile mine based on individual phases of the mission, rather, it focuses on the overall reliability that is required for the entirety of the mission from the beginning to the end.

2. Maintainability Analysis

Maintenance Support Plan. A maintenance support plan was formulated, based on the different levels of support required for the components and subsystems of the mobile mine system. The maintainability of the mobile mine is determined by the complexity of the repair, and duration of repair. Based on the two factors, we would then define the level of support required.

Level of Support. The level of support is categorized based on the function of maintenance complexity and time. They are classified under original equipment manager (OEM), depot, and operator-maintainers (OMER). Generally, operators/end-users provide OMER level support, in-service technicians make up the depot level support. The level of support for both operational and peacetime missions were tagged similarly. To support subsequent efforts of maintenance, a "Level of Support" matrix has been compiled based on complexity and time taken (refer to Table 7). At the individual component level (i.e., OMER level), all maintenance done will be assumed to have the component replaced, instead of repairs done in-situ. The individual component will then subsequently be sent back to OEM/depot for repairs. This will be done for all corrective maintenance.

Table 7. Level of Support for Repairs

Complexity of Task	Time Taken for Repairs	
	< 4hrs	> 4hrs
Low	OMER	Depot
Medium	OMER	Depot
High	Depot	Depot/OMER

That said, preventative maintenance should be done to extend the life of the system/sub-system or ensuring optimal performance (Fabrycky and Blanchard 2013). This could be done by changing expendable(s) equipment or required services. All preventative maintenance should generally fall under Depot level support.

Complexity. The complexity of the system maintenance further depends on the system's composition and the number of external systems involved with the system of interest. For individual components (i.e., sensors, receiver), it is generally considered as low. Medium complexity generally involves up to two additional external systems, and high complexity for those which involve three or above additional external systems.

Duration of Repair. Though the complexity of tasks is segregated based on the system's composition and external systems' involvement, there is also a degree of correlation between time taken for repairs. For repairs that require more than 60-man hours, it is generally categorized as high complexity. This accounts for the overall depot capacity and prevents possible congestion and efficiency issues.

Logistics Support Plan. A comprehensive logistic support plan will yield a high operational readiness for the mobile minefield system. Considering that components subject to significant wear and tear and specialized components that will require long delivery/manufacturing lead times, we can recommend which components require stockpiling. The quantity can only be determined upon developing the systems as the selection of suppliers can affect the delivery/manufacturing lead time (i.e., local versus international suppliers).

Component Degradation. Components that are exposed to harsh operational environments (i.e., underwear conditions) or components that are used more frequently or are subjected to higher levels of stress during operation are more likely to face increased wear and tear. Components that are more complex or sophisticated, such as processors, sensors, and communication systems, may be more prone to wear and tear due to their intricate designs and delicate components. The quality of materials used in components and the manufacturing processes employed can impact their durability and resistance to wear and tear (Vijayaraghavan, Gangadharan, and Sitaram 2008).

Long Delivery Lead Time. Components that are complex or specialized, such as signal processors, communication systems, and propulsion systems, often require specialized manufacturing processes and materials, leading to longer delivery times. Components that require customization or integration into the mine system, such as sensors, processors, and communication systems, may have longer lead times.

The relationship of a component's subjectivity to wear and tear and delivery lead time, to the recommendation of stockpiling is shown in Table 8.

Table 8. Stockpile Matrix

Subject to Wear and Tear	Recommended Stockpile	
	Short Delivery Lead Time	Long Delivery Lead Time
Low	Not Recommended	Not Recommended
Medium	Not Recommended	Recommended
High	Recommended	Recommended

3. Supportability Analysis

A supportability analysis was done to examine the effect that the operating environment will have on the system, methods to provide support for the mobile mine system after it is deployed, the compatibility of the system to delivery and communications within the larger campaign system-of-systems, and ways to enhance compatibility based on modular design.

a. Marine Effects

Underwater corrosion (Phull and Abdullahi 2017) and marine growth can significantly impact the performance of mobile mines deployed in marine environments. The effects may include compromised functionality, reduced effectiveness, and increased maintenance requirements. Here are some ways in which these factors can affect the mobile mines' performance:

<u>Corrosion</u>. Sea mines are typically made of metal, and exposure to saltwater accelerates the corrosion process. Over time, corrosion can weaken the structural integrity of the mobile mines, leading to potential failures. Corrosion of electrical components can interfere with the mobile mine's electronic systems, affecting communication, sensing, and detonation mechanisms.

<u>Marine Growth</u>. Marine growth, including slime, algae, and barnacles, can accumulate on the mine's surface (Soares et al., 2011). This growth adds additional weight to the mobile mine, potentially affecting its buoyancy and stability. Marine growth can

cover sensors, antennas, and other external components, diminishing the mobile mine's ability to detect and respond to threats effectively. Accumulation of marine organisms can increase drag and alter the mobile mine's hydrodynamics, affecting its movement through the water.

Reduced Stealth. Increased marine growth may alter the acoustic, magnetic, or hydrodynamic signatures of the mobile mines, making it more easily detectable by enemy vessels or underwater sensors (Carvalho 2014).

Impact on Deployment Duration. Mobile mines deployed for extended periods are more susceptible to significant marine growth, especially in warmer waters (Soares et al. 2009) where growth rates are faster. This may necessitate more frequent maintenance or replacement of the mobile mines to ensure their continued effectiveness.

Increased Maintenance Costs. Regular cleaning and maintenance are required to remove marine growth and prevent excessive corrosion. This can be resource-intensive, especially in areas with rapid marine growth.

Preventing corrosion underwater requires an approach aimed at inhibiting the electrochemical reactions that degrade metal surfaces in marine environments. Studies conducted by Melchers (2016) showed that applying anti-corrosion coatings such as epoxy or polyurethane, using cathodic protection systems like sacrificial anodes or impressed current systems, and employing corrosion-resistant materials such as stainless steel and aluminum alloys, could prevent corrosion underwater. In addition, galvanic isolation techniques, regular maintenance, and design considerations to minimize water collection areas are crucial. Monitoring environmental conditions, using corrosion inhibitors, conducting regular inspections, and providing education and training on corrosion prevention practices further enhances the effectiveness of these measures. By implementing these strategies comprehensively, the sustainability of underwater structures and equipment can be preserved, mitigating the damaging effects of corrosion (Melchers 2016).

b. Methodology of Support Systems

Support for the mobile minefield system will be accomplished via a combination of remote methods unique to the system and existing conventional methods. Integrated systems will neutralize the mobile mine's explosive capabilities upon receipt of a signal from friendly forces or based upon a timeout value to eliminate the possibility of unexploded mobile mines continuing to pose as a threat beyond the duration of the conflict (Noack 2018; Public Affairs Office at MARCOM 2023). Mooring will remain intact to prevent drift and to maximize likelihood of retrieval.

Existing anti-mine vessels and personnel will retrieve the inert mobile mines. Although the possible incorporation of manned explosive ordnance disposal missions increases risk relative to other models, such as a fully autonomous disposal or retrieval method (Savitz 2017), risk is mitigated by the capability to disable explosives prior to disposal. Furthermore, manned missions can be obviated in many instances by technology. Current programs of record provide the capability to sever mooring to allow collection by surface-based mine countermeasure (MCM) platforms (George 2020). Reliance upon the program of record for disposal also serves to mitigate the overall cost and complexity of the program, minimizing the acquisition of new supporting platforms and the associated preparation time.

Re-seeding of an active minefield will be conducted via the same methods as the initial deployment. If risk to a platform during conflict mandates clandestine delivery, change of platform (including subsurface vessels) remains a possibility. Therefore, additional mobile mines can be added over time as attrition mandates.

c. System Compatibility

The system compatibility aspect of system supportability can be associated with the delivery platforms that can support its delivery, the C2 systems that can support the operation of the mobile minefield system, and the modular design of the system to enhance supportability.

(1) Compatibility with Delivery Platforms

It is essential to evaluate the mobile mine's compatibility with various types of delivery platforms, including submarines, surface ships, aircraft, and unmanned underwater vehicles (UUVs), ensuring seamless integration with existing launch and deployment systems.

To ensure the mobile minefield system's delivery platform compatibility as a platform-agnostic system, we need compatibility with specialized launching mechanisms, such as torpedo tubes, mine deployment racks, aerial bomb bays, or unmanned aerial vehicle (UAV) launchers, to accommodate different delivery methods and platform configurations.

(2) Integration with Command-and-Control Systems

It is essential to achieve seamless integration between the control interfaces of the mobile mines and the onboard command and control systems. This integration enables remote activation, monitoring, and mission planning capabilities, accessible from centralized command centers or onboard control stations.

To ensure interoperability with allied forces' command and control systems, standardized data exchange protocols like Link 16 or North Atlantic Treaty Organization (NATO) Standardization Agreements (STANAGs) should be implemented. This facilitates smooth information sharing and joint mission coordination between different military entities.

(3) Modular Design for Versatility

The mobile mine should be designed with interchangeable payload modules and standardized mounting interfaces to accommodate a wide range of mission payloads, including various types of sensors, warheads, or electronic warfare systems. This design flexibility allows for easy customization to meet specific mission requirements and adapt to evolving threats. Implementing modular construction techniques and common component standards further enhances versatility, enabling rapid reconfiguration of the mobile mines for different mission profiles, operational theaters, or emerging threats. This approach streamlines maintenance, logistics support, and overall operational efficiency, ensuring the mobile mine remains adaptable and effective in dynamic environments.

d. Compatibility with Logistics Infrastructure

It is crucial to ensure that the mobile mine is compatible with existing logistics infrastructure and support equipment for maintenance, replenishment, and storage operations across various naval bases, forward operating locations, or mobile expeditionary sites. This includes assessing compatibility with standard ammunition handling equipment, transportation vehicles, and storage facilities to streamline logistics planning and support the mobile mine's deployment and sustainment requirements.

By evaluating and ensuring compatibility with these logistics elements, the mobile mines can be efficiently integrated into existing support systems, enabling seamless operations and mission readiness in diverse operational environments.

e. Adherence to Safety and Handling Standards

It is imperative to ensure that the mobile mines comply with international safety standards and handling procedures for hazardous materials and ordnance, encompassing transportation regulations, storage guidelines, and handling protocols. This comprehensive approach mitigates risks during storage, handling, and transportation, safeguarding personnel, and assets throughout the logistics chain.

To further enhance safety, the implementation of safety features and fail-safe mechanisms is essential. These mechanisms prevent accidental activation, unauthorized tampering, or unintended detonation during storage, transit, or handling operations. By adhering to stringent safety measures and integrating fail-safe mechanisms, the sea mine maintains operational integrity while minimizing risks to personnel and assets across all phases of the logistics process.

4. Survivability Analysis

Contrary to a static sea minefield system, the deployment of the mobile mines can be done at a distance from the area of operation; possibly even before the forward edge of the battle area (FEBA) where there is little/no risk of detection and attack. This significantly increases the survivability of platforms used in the deployment of the mobile mines. In addition, the automated/autonomous nature of the designed mobile mines allows operators to remain safely hidden at a holding distance away from the area of operation, and only return when there is a need to transmit commands to the mobile minefield system. On the deployment and clearance of mobile mines, they are unarmed or can be remotely disarmed for safer physical handling (i.e., no risk of accidental detonation).

D. HUMAN-SYSTEMS INTEGRATION ANALYSIS

Human-System Integration (HSI) is defined as "the systems engineering process and program management effort that provides integrated and comprehensive analysis, design, and assessment of requirements, concepts, and resources for human factors engineering, manpower, personnel, training, safety and occupational health, force protection and survivability, and habitability" (Office of the Under Secretary of Defense for Research and Engineering n.d.). To ensure that the system design is optimized for human performance and human-machine teaming, design features and requirements relevant to the system are further detailed for each HSI domain.

1. Human Factors Engineering

Contrary to a static sea minefield system, the designed mobile mine system enabled redeployment of the sea mines autonomously in accordance with a preset layout (programmed prior to launch) or a specified new layout in a manner that required little manual allocation of the mobile mines within the minefield. The adoption of swarm-based control methods helps reduce the cognitive workload of the operator managing the mobile minefield system. Manual intervention to maintain deployment policy is not required despite external perturbations from the sea currents and the loss of any mobile mines due to technical faults or engagement.

2. Manpower, Personnel, and Training

The simple employment of the mobile minefield system requires little manpower to manage the system and could only require partial involvement from an operator that is adept in mapping, navigation, and naval operations. The profile of such an operator fits many of the officers or specialists working in the Combat Information Center room of naval vessels, and thus require only some training in robotic control, and on the interface of the system to transit an eligible candidate to a trained operator. The physical handling of the mobile mines is simple and like many other systems (e.g., aerial-dropped bombs and naval torpedoes).

3. Environment, Safety, and Occupational Health

Having the arming/disarming feature enabled while deploying/recovering platforms (where applicable) allows one to remain safe when handling the mobile mines. In addition, the augmentation of the Identification of Friend or Foe (IFF) system will ensure that only programmed hostile targets will be engaged upon. This improves the safety for passing vessels while ensuring their safe passage in contested environments.

E. SYSTEM DESIGN

The following subsections provide more information about the system design of the mobile minefield system.

1. Purpose and Functions

The primary purpose of the mobile mines is that they are able to operate independently and redeploy while within the minefield system. Since the mobile mines can form a network that enables communication with one another within and around the minefield boundaries (used only when required), it can support communication between a friendly operator ship and the entire minefield when at least one mobile mine is in range. The operational architecture of the mobile minefield system can be succinctly described by high level operational concept (OV-1, Figures 15–17), capability to operational activities mapping (CV-6), and mission threads (OV-5).

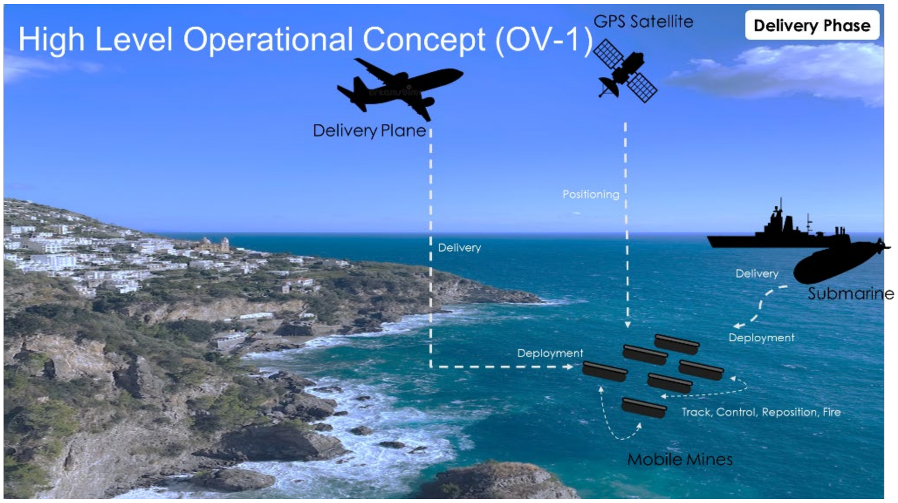


Figure 15. High Level Operational Concept of Mobile Minefield System (OV-1, Delivery Phase)

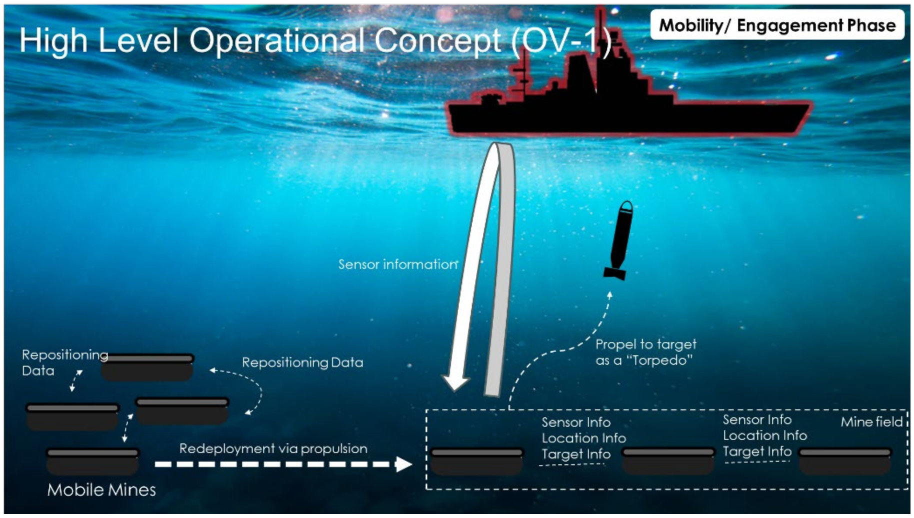


Figure 16. High Level Operational Concept of Mobile Minefield System (OV-1, Mobility/Engagement Phase)

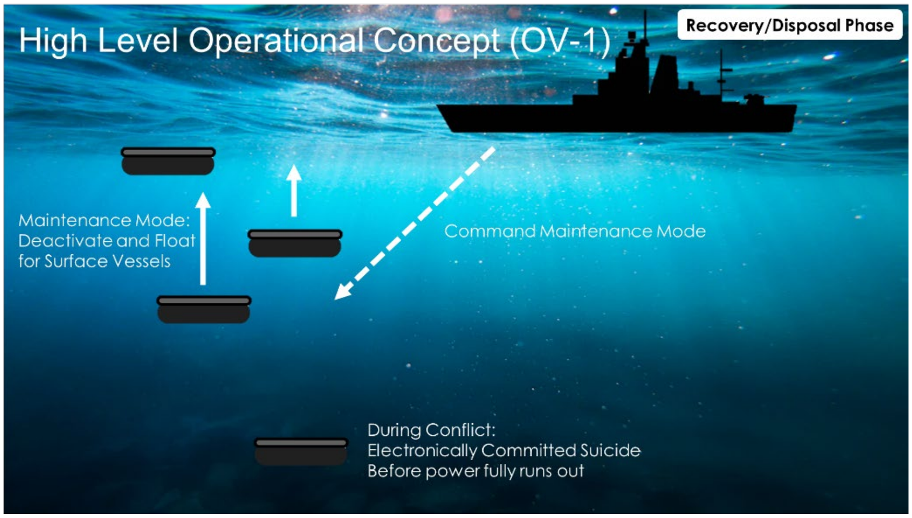


Figure 17. High Level Operational Concept of Mobile Minefield System (OV-1, Mobility/Engagement Phase)

Based on the requirements, the system functions explored to guide system design are described below.

Mobile mines can be delivered via different types of delivery platforms with little to no modifications required.

Mobile mines can sense and discern tracks/contacts using multiple types of sensor systems and correlate sensed data for superior recognition and classification of tracks/contacts.

Mobile mines can ascertain their own location and navigate based positional reference system adopted using both Global Positioning System (GPS) and Inertial Navigation System (INS) where applicable.

Mobile mines can conduct system status checks at regular intervals and, when commanded, gather feedback on their own system health.

Mobile mines are capable of recognizing foes from friends and other neutral entities through coded signal processing.

Mobile mines can communicate with other authorized entities in both wired and wireless conditions.

Mobile mines are self-powered with an energy storage system that is rechargeable in nature.

Mobile mines move to desired positions, without external forces, based on adopted positional reference system.

Mobile mines are drift resistant when deployed to the bottom of the sea.

Mobile mines contain, trigger, and detonate a payload that delivers damage to an eligible target.

Mobile mines are compatible in size and weight and have compatibility hardware interfaces (where applicable) to support delivery via different delivery platforms.

Mobile mines can commit electronic suicide through the electronic termination of central processing units and memory disks.

Mobile mines avoid one another after being delivered to the area of operation.

Mobile mines can automatically or autonomously redeploy through mobility capabilities to adhere to the minefield distribution map, so as to recover from a degraded minefield system performance.

Mobile mines can automatically or autonomously redeploy through mobility capabilities after sensing that a MCM operation was executed to detect and mark it for subsequent demolition.

Mobile mines can autonomously redeploy through mobility capabilities to block an established Q-route after sensing that it was established within the minefield when the density of the mobile mines is sparse.

A functional block diagram of the mobile mines that can help achieve the operational requirements described in Figure 13 is provided in Figure 18. Figure 19 provides the mapping for functions to operational activities (CV-6). Thereafter, expounding on detailed activities that will happen after the mobile mines are delivered and deployed, Figure 20 provides the flow and logic of activities executed when it is activated/ deactivated, how it will react based on different signals from various types of vessels, and how maintenance and disposal could be done for the mobile minefield system.

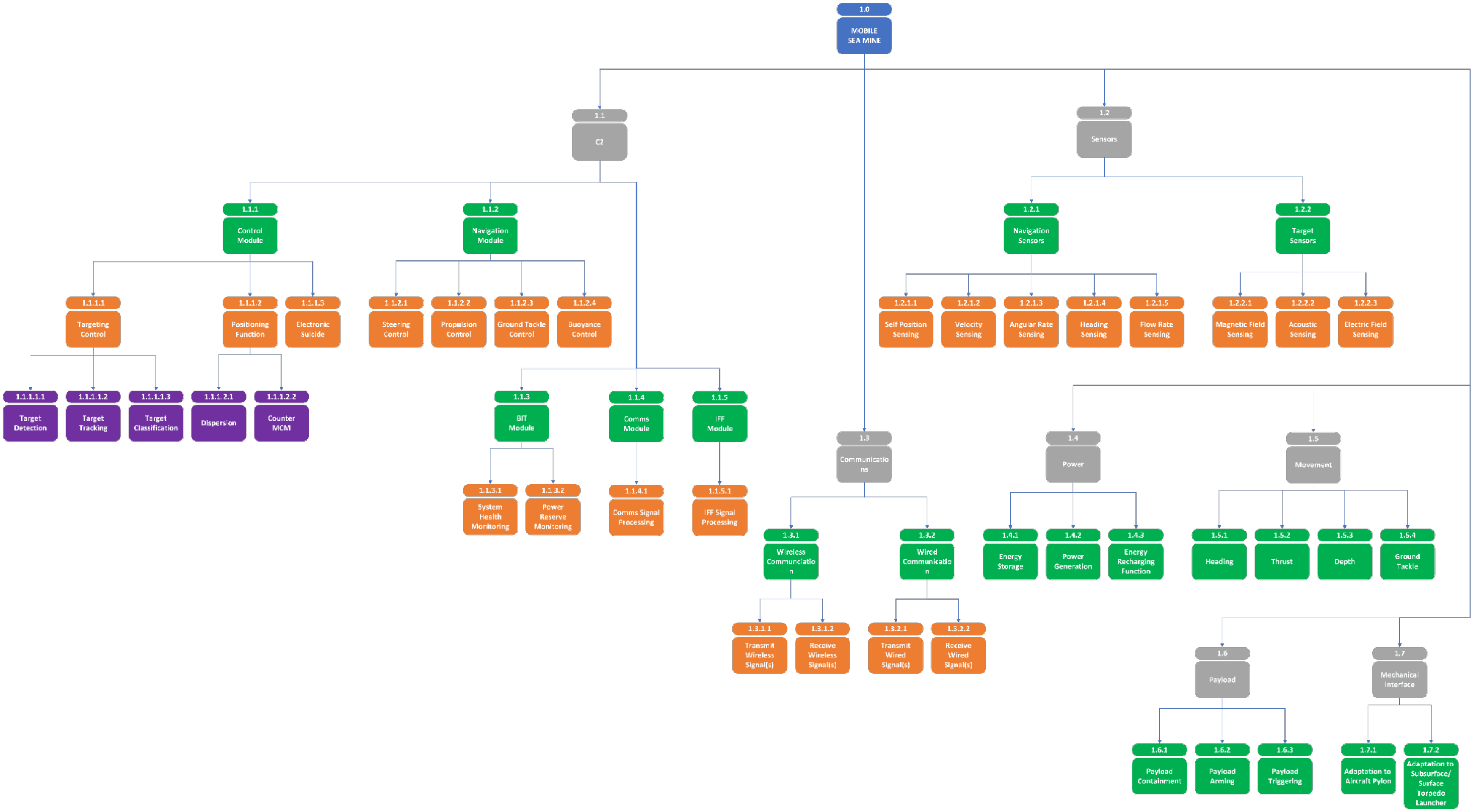


Figure 18. Functional Block Diagram of Mobile Mine

Functions Operational Activities	Target Detection	Target Tracking	Target Classification	Dispersion	Counter MCM	Electronic Suicide	Steering Control	Propulsion Control	Ground Tackle Control	Buoyance Control	System Health Monitoring	Power Reserve Monitoring	Comms Signal Processing	IFF Signal Processing	Self-Position Sensing	Velocity Sensing	Angular Rate Sensing	Heading Sensing	Flow Rate Sensing	Magnetic Field Sensing	Acoustic Sensing	Electric Field Sensing	Transmit Wireless Signal(s)	Receive Wireless Signal(s)	Interface with Physical Comms Port(s)	Energy Storage	Power Generation	Energy Recharging	Heading	Thrust	Depth	Ground Tackle	Payload Containment	Payload Aiming	Payload Triggering	Adaptation to Aircraft Pylon	Adaptation to Sub-Surface/Surface
Delivery											✓	✓			✓	✓	✓	✓								✓	✓									✓	✓
Deployment and Redeployment				✓			✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓							✓	✓		✓	✓	✓	✓					
Identification of Foe/Friend											✓	✓		✓										✓		✓	✓										
Target Sensing	✓		✓								✓	✓								✓	✓	✓		✓		✓	✓										
Target Tracking	✓	✓	✓								✓	✓								✓	✓	✓				✓	✓										
Counter MCM Detection	✓	✓	✓		✓									✓						✓	✓	✓															
Engagement											✓	✓			✓	✓	✓	✓	✓	✓	✓	✓				✓	✓		✓	✓	✓	✓	✓	✓	✓		
Remote Communication											✓	✓											✓	✓		✓	✓										
Maintenance				✓			✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓						✓	✓	✓	✓			✓	✓					
Autonomous Disposal						✓					✓	✓														✓	✓										

Figure 19. Capability to Operational Activities Mapping for Mobile Minefield System (CV-6)

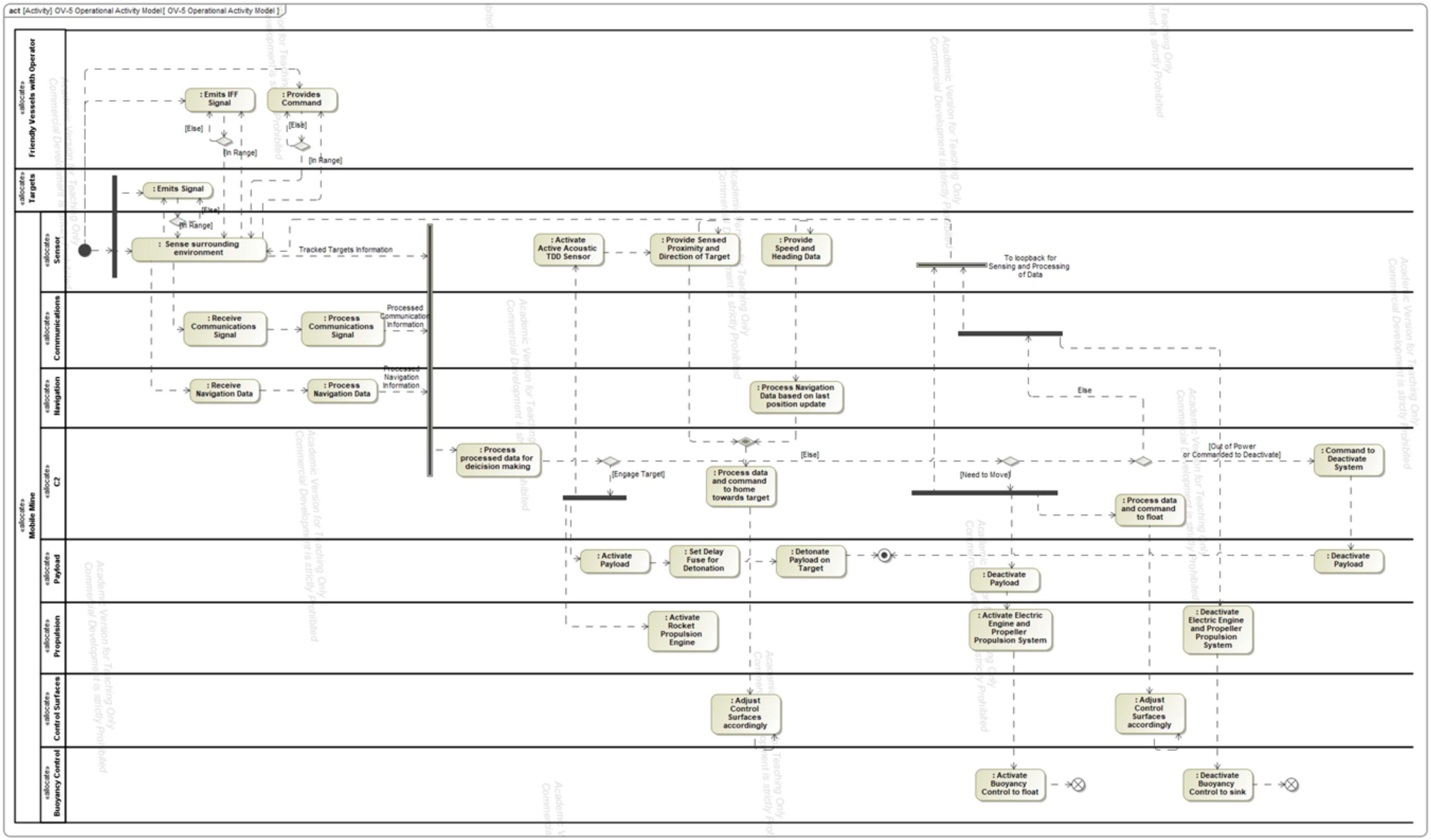


Figure 20. Mission Threads of the Mobile Mine after Delivery and Deployment

2. System Life Cycle

The development of the mobile mine will undergo the following phases throughout its system life cycle.

a. Non-Operational Phase

Prior to operation, the mobile mines undergo three non-operational phases before they are delivered into operation.

1. Manufacturing. After the mobile minefield system is designed and developed, the mobile mines are manufactured in a production facility according to specific sets of instructions to ensure that they are produced according to the design specifications; assembled of its modules, loaded with its ordnance package, and checked in terms of its quality for its operational readiness.
2. Warehouse Storage. The mobile mines are stored in secure, long-term storage facilities to be ordered for loading onto the delivery vehicle. The storage conditions are monitored and maintained as prescribed, and uncrating/crating may be done as part of planned preventative maintenance.
3. Standby Storage. The mobile mines are transported, loaded, and stored within the delivery vehicle to get it ready for potential deployment. They may be held at this state until the unit decides that there are no deployment requirements; returning them back to warehouse storage.

b. Operational Phase

The mobile minefield system enters operational state when the mobile mines are planned for delivery into operation and begins with pre-delivery programming. Subsequently, it is deployed and engages in other necessary operational activities. It may become non-operational if the mobile mines are recovered or end their lives through engagement and disposal.

1. Pre-Delivery Programming. The mobile mines are programmed with information associated with friend recognition, map data of the operational area and areas that it will transit through from the delivery point, and automated behaviors that it will take based on sensed condition.

2. Delivery. The mobile mines are strategically placed in underwater locations where they are technically and operationally feasible to encounter and engage anticipated enemy surface vessels or submarines. At the desired deployment site, the mobile mines are delivered either by surface vessels, aircraft, or submarines—regardless of whether it is manned or unmanned. The delivery method adopted varies depending on operational and deployment requirements.

3. Deployment and Redeployment. When the sensors sense that the conditions are met for deployment to take place underwater, the deployment mechanism is activated. The deployment mode varies depending on operational requirements from the mission.

4. System Health Monitoring. Mobile mines may be periodically inspected and maintained (if necessary) to ensure their operational effectiveness as they are deployed. Monitoring sub-systems are used to detect, assess, and respond to changes in the status of deployed mobile mines.

5. Remote Communication. Mobile mines can carry out remote communication when they are fielded in the minefield for various purposes (e.g., rebroadcasting information).

6. Operational (Deactivated). Mobile mines by default are deactivated until activation is triggered via a target detection system. A specific set of conditions must be met, such as the proximity of a target leading to a change in pressure sensed by the on-board sensors. Otherwise, it will remain as just a sensing entity in its deployed mode that will not engage targets even if it was technically possible.

7. <u>Operational (Activated)</u>. Mobile mines, when activated, will have their sensors on for target detection, IFF, and sensing of MCM activities. These are done simultaneously until engagement happens when the mobile mine is armed and engagement protocols take over.

   a. <u>Identification of Foe/Friend</u>. IFF is a system that allows positive identification of friendly manned and unmanned aircraft as well as vessels through cooperative identification; separating these tracks from other signal generating sources that are likely hostile or a foe.

   b. <u>Target Sensing</u>. When a target that is not yet identified as a friend, the system will sense the target's signal signatures to ensure detection, identification, recognition, and classification is done subsequently to inform the targeting algorithm for any engagement requirement.

   c. <u>Target Tracking</u>. Once classified as a foe, the target is continually tracked until it is within its weapon engagement zone (WEZ).

   d. <u>Engagement</u>. Once a target enters the WEZ and can be engaged within the weapon's range, the engagement protocol will take over by arming the mobile mine, propelling the mobile mine toward the target, and detonating the high explosive warhead against it to deliver precise damage.

   e. <u>Counter MCM Detection</u>. When the mobile mine is under threat of being detected by MCM operations, it will trigger a redeployment so that it will not be destroyed by the ensuing mine clearance operations.

8. <u>Maintenance</u>. In some cases where a mobile mine is required to be maintained, it can deactivate itself upon command and surface for ease of access.

9. <u>Recovery.</u> In some cases, mobile mines are intended to be recovered after a certain period, which may also require them to be deactivated before they are recovered by a surface vessel. This phase involves safely retrieving the mobile mines or rendering them inert to prevent any accidental explosions.

10. Disposal. When mobile mines reach the end of their operational life or when they become obsolete, in accordance with the San Remo Manual (International Institute of Humanitarian Law 1995), they need to be safely disposed of to prevent any harm to the environment or unintended consequences. Proper disposal procedures are followed to reduce the risk of accidents. Disposal may also be done as an alternative to recovery when the mobile mines are deemed not reuseable (if they have not reached the end of their operational life).

    a. Autonomous. Under the operational policies (e.g., staying within the minefield, out of power, etc.), it may be required for a mobile mine to dispose of itself as a last resort. Hence, it will autonomously destroy and dispose of itself once required conditions are met.

    b. Manual. Mobile mines may be manually disposed of with the aid of divers or UUVs. To ensure the safety of those interacting with it during the disposal process, a mobile mine will be commanded to be deactivated before any other activities (e.g., explosive charge) are done.

The operational phases and states are illustrated in Figure 21 which provides a systems state transition diagram of the mobile mine.

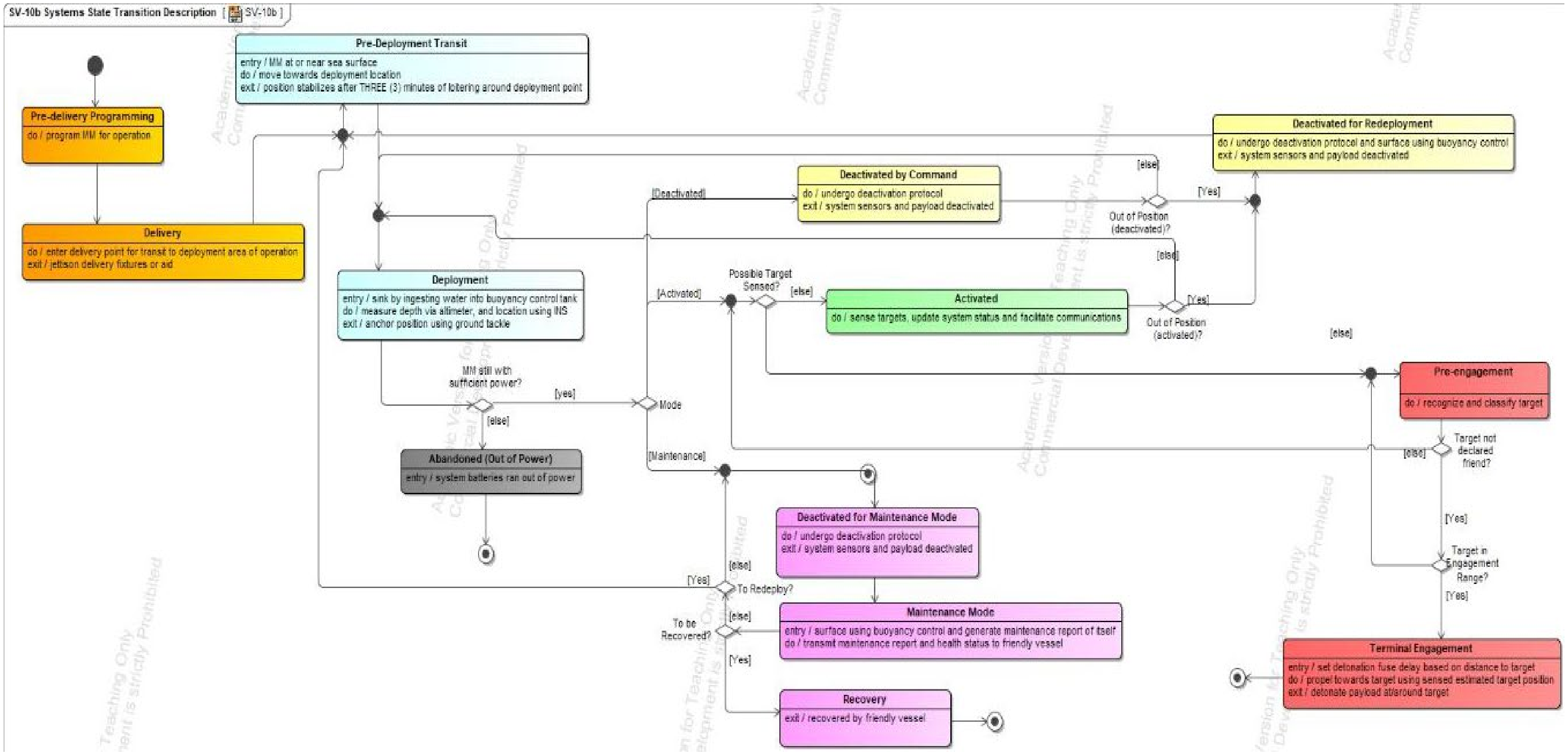


Figure 21. System State Transition Diagram of the Mobile Mine (SV-10b)

3. System-of-Systems Design Considerations

The mobile minefield is a system of systems because each individual mobile mine is a system in itself and they operate together in the minefield to provide capabilities beyond what one mobile mine can provide. In this section, the System-of-Systems design considerations are explored. Then, in the next sections F and G, the design of the mobile mines is explored in greater detail.

a. Position and Navigation

As the mobile minefield system operates in both surface and sub-surface levels, the permeability of the sea water poses as a challenge for the system to define its position and navigate itself with respect to its environment. The reference system that most systems adopt is the World Geodetic System 1984 (aka WGS-84; National Imagery and Mapping Agency 1991).

A hybrid approach is adopted for the system to position and navigate effectively in both surface and sub-surface levels with respect to the WGS-84 system. Following the norm of maritime entities, GPS, being the de facto system used for positioning and navigation, is the subsystem of choice when the mobile mines are traversing on the surface. However, due to the weak signal penetrability of GPS signals in subsurface environments, and the possibility that mobile mines may operate in GPS-denied environments, the INS is used by the mobile mines to trace their relative position to the reference system that has a datum position provided by the last known position of the mobile mine provided by the GPS when it just began entering the water surface. An INS system is composed of at least three gyroscopes (measuring angular rotations about a defined direction/axis), three accelerometers (measuring acceleration in a defined direction/axis), and an inertial measurement unit to compute its motion in six degrees-of-freedom (DOF; Harris 2023). Unfortunately, because the INS does not account for the rotation of the Earth, it will incur positional errors (aka drift errors) over long periods of time it remains sub-surface.

To eliminate these accumulated errors, resurfacing provides the navigation system with another datum position to effectively position and navigate itself on the water's surface again (Casual Navigator n.d.). This should allow the mobile mines to maintain a positional accuracy of at most 0.1 nm. While sound navigation and ranging (SONAR)–based navigation assistance system is also being developed to improve underseas navigation (Keller 2019), it will require bathygraphy mapping of high fidelity for the system to effectively cross-reference against the positions defined by the bathygraphy maps—a resource that is typically unavailable for offensive mining. The additional computational load and memory space to support such navigational aid will also increase the size, weight, and power (SWaP) requirements of the system.

The subsection on the system autonomy design will elaborate on how the mobile mine will deploy itself within the designated minefield boundaries by referencing the WGS-84 reference system, an artificial local influence mapping reference that defines the perimeters, and the optimal deployment location for all mobile mines assigned to the mobile minefield system.

b. Communications

This section delves into the communications schemes employed as part of the system design and the communication systems used to facilitate communication under different operating conditions.

(1) Communication Schemes

The communication schemes used depend on whether the communication is done wirelessly or in a wired setting.

<u>Wired Point-to-Point Communications</u>. Before deployment, an operator loads the software and pre-programmed data (e.g., deployment topology) via wired communication onto the mobile mines. This will facilitate high-speed information transfer via data cables. Where necessary, they will be compliant with MIL-STD-188: Military Communications System Technical Standards.

<u>Wireless Rebroadcasting</u>. As communication after deployment will be affected by range and atmospheric and water attenuation, rebroadcasting information is required to ensure that information is passed on to all mobile mines within the minefield boundaries.

Hence, when wireless information sharing is initiated by a mobile mine based on its own program or by another friendly surface vessel, the signal sent will be rebroadcast to all other mobile mines for propagation to other entities within the minefield boundaries under the water surface using acoustic communications. They will extend the reach of wireless information dissemination to ensure that those that are within the mesh-network can receive that information.

Wireless Ad-hoc Receive-Only Communication. To reduce the communication signature to hide the position of mobile mines, they can also receive ad-hoc communication from other friendly surface vessels without replying with an acknowledgement message. This facilitates the IFF function that different registered vessels (including merchant and friendly navy vessels) use to signal to the mobile mines to deactivate for a finite period whenever the signal is received.

(2) Communication Subsystem

The communication network is supported by communication both on- and sub-surface to overcome limitations on the permeability of signals in different mediums.

On-Surface. When the mobile mines are on-surface for redeployment or in the maintenance mode, they can communicate via radio frequencies in the very low frequency (VLF) channels, and such RF communication attenuates exponentially underwater. Operating at VLF will ensure that there will not be a requirement for additional communication equipment installed onto naval vessels to work with the mobile mines, as it is already the de facto configuration for naval vessels when communicating with submarines of up to 20 meters (65.6 feet) of depth (Uppal 2021).

Sub-Surface. When the mobile mines are below the water surface or communicating with sub-surface mobile mines, they can communicate using acoustic communication. Acoustic communication uses sound waves to transmit information, supporting around 500 bits/s for commercial products. However, it faces a limited frequency band of 10–30 kHz. As such, slow propagation speed (1,500 m/s) increases the latency and decreases the data rates of acoustic communication. On the other hand, using wider bandwidth acoustic communication can achieve up to 1Mbps data rates for up to 100 meters (Zhilin et al. 2023). However, since any form of acoustic transmission can be received and heard by others as part of signal intelligence, encrypted communication will have to be implemented to ensure that the communications are indecipherable without the secret key. While acoustic communications might be vulnerable to adversary jamming, spread spectrum techniques such as frequency hopping spread spectrum (FHSS) could be used to mitigate it. The requirement for communication will typically be limited to short commands and periodic updates for IFF signal processing. Larger data packages such as map files will be processed to trim the file size by omitting non-essential information.

While RF can also communicate in sub-surface conditions, this was not considered in this project as there is a high power and size requirement and it has a short operating range (only support short commands to be transmitted when it is in longer range). RF could only reach up to 60 meters in depth when operating at VLF (3–30 kHz, ~50 meters), super low frequency (SLF; 30–300 Hz, ~300 meters), and extremely low frequency (ELF; 3–30 Hz, ~1,000 meters) with modulation using Code Division Access Scheme and ultra-wideband spreading (Ghaffarivardavagh et al. 2020; Sun, Cui, and Chen 2021). Due to the inefficiency in transmitting over long distances, only short commands can be transmitted. Based on the details presented earlier, the adopted communication scheme among the systems is illustrated in Figure 22.

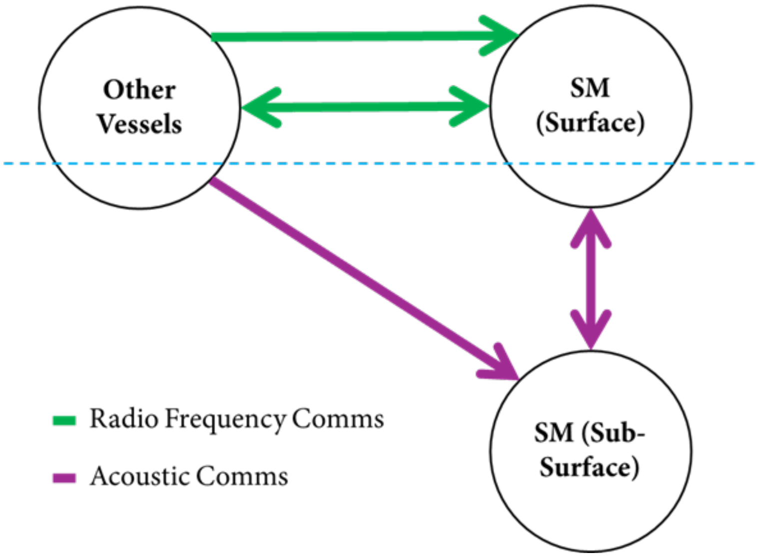


Figure 22. Adopted Communication Schemes and Systems

c. *Command and Control*

To ensure that the mobile mine can achieve its mission objectives, especially in situations where human-operator intervention is minimized, a robust C2 design for the system is required. As the mobile mines are designed to be non-collaborative, an effective communication network is still useful for occasional dissemination of information to among the sea mines when initiated by the operating surface vessel.

On the mobile minefield system level, the C2 design can be defined to be decentralized, where each mobile mine can make decisions on its own behalf if it is compliant with the rules and policies programmed into its behavior logic. In addition to decentralized decision-making enabled by system autonomy programmed into its behavior logic, designated friendly naval vessels that are connected can provide commands to the mobile mine to influence its behaviors. The operator command-based controls are tabulated in Table 9.

Table 9. Operator Command-Based Controls

Command	Description
New deployment map	Provide the mobile mines in the minefield with a new deployment map to comply with for subsequent redeployment.
Request for status update	Request for status updates on all mobile mines within the minefield boundaries to understand their health, power level, position, and count of enemy targets sensed but not engaged.
Request for sensed target information sharing	Request to subscribe for any sensed target information sharing while connected to any parts of the mobile minefield system.
System deactivation/activation	By default, mobile mines are activated upon deployment unless programmed otherwise. The command will deactivate all mobile mines in the minefield boundaries until further notice—or activate them (given that they were previously deactivated).
Maintenance mode	Command a mobile mine to go into maintenance mode that causes it to deactivate, surface itself, and generate a status update to the commanding operating vessel.

d. System Autonomy Design

Given that the mobile mine is expected to operate autonomously for extended periods of time and respond to different events or environments accurately and promptly, the system will need to have decentralized control over itself while interacting accordingly with other mobile mines within the minefield as a System-of-Systems. Scrutinizing the system phases/states mentioned earlier, the robotic logic can be clearly separated for interactions with other mobile mines within the minefield and with other internal and external factors

To facilitate the operation of mobile mines in a communications-denied environment, it is assumed that each mobile mine operates independently from others in the vicinity or within the minefield. To ensure that there are no unintended consequences with operating multiple mobile mines within the same minefield, the delivery of these mobile mines will be done in a manner that deliberately separates the mobile mines and provides interaction buffers to separate their operational zones. The mobile mines can be easily controlled using behavior-based control scheme as its autonomy design.

Behavior-Based Control. Each mobile mine behaves according to a set of rules that govern the activities of the mobile mine. These behaviors are described Table 10.

Table 10. Behavior-Based Control for Automated System

No.	**Autonomous Behaviors**	**Description**	**Precondition**
1	Delivery	Facilitate behaviors during delivery process	• Released from delivery platform • Mobile mine not reached designated delivery location • Buoyancy control deactivated by releasing water from containment for positive buoyancy when reached water surface (aerial) or launched (subsurface)
1.1	Get Position	Obtain own GPS position estimate (at least five linked satellites)	
1.2	Calculate Deviation to Destination	Calculates deviation between pre-programmed destination and own GPS position to inform movement algorithm	
1.3	Move into Minefield Boundaries	Move into minefield boundaries for deployment	
2	Deployment	Facilitate deployment and subsequent repeated redeployment process	• Within minefield boundaries • Dive and sink when mobile mine can loiter around deployed location for a significantly long period of time. • Surface when position is not near expected deployed location (changes over time). • No known targets are detected around the minefield by any mobile mines.
2.1	Get Position	Obtain own GPS/INS position estimate	
2.2	Calculate Deviation to Deployed Location	Calculate the deviation to the deployed location at a suitable frequency.	
2.3	Get Environment	Obtain surrounding water flow magnitude and direction	
2.4	Movement to Deployed Location	Move to deployed location and slowdown in consideration of surrounding water flow magnitude and direction. Pre-diving loiter: Loiter in situ around the deployed location (threshold distance of 5 meters) for around 3 minutes before diving into the water surface.	
2.6	Dive and Anchor	Buoyancy control activated by pulling piston back using electric motor and release ground tackle when altimeter reading stabilizes.	
2.7	Surface	Buoyancy control deactivated by releasing water from containment.	
3	Communicate	Facilitate communication to mobile mines or vessels within communication range.	• Delivered • Rebroadcast frequency variable. • Acoustic communications mode among mobile mines, RF communications between mobile mines and communicating ship
3.1	Rebroadcasting	Rebroadcasting at a limited range to neighboring mobile mines to communicate any commands sent (e.g., engagement policy and new deployment layout) and own position.	
3.2	To Ship Communication	Acknowledge message sent from ship and communicate to ship in accordance with command and queries.	

No.	Autonomous Behaviors	Description	Precondition
4	System State Update	Facilitate system state updating and sharing/ calculation thereafter	• Occurs at all phases
4.1	Monitor and Record Own Position	Monitor and record own position based on INS (subsurface) and GPS (at surface)	
4.2	Monitor and Record Own Movement Parameters	Monitor and record own movement parameters using water flow meter, inertial measurement unit (IMU), and altimeter	
4.3	Monitor Power Status	Monitor status of battery and remaining capacity	
5	Maintenance	• Deactivate targeting sensors and arming mechanism. • Buoyancy control deactivated by releasing water from containment. • Generate a detailed system status report	• Commanded to enter maintenance mode
6	Engagement	Facilitate engagement of known targets.	• Within minefield boundaries
6.1	Check Engagement Policy	To check if the mobile mine is activated/ deactivated for further actions	
6.2	Sense Targets	Sense targets based on different sensor range and push data to fusion system for recognition and classification of entities detected.	• Within minefield boundaries • Activated
6.3	Recognize and Classify Targets	Facilitate IFF and target type recognition to inform engagement sizing	
6.4	Estimate Target Location	Calculate target estimated location based on estimated heading and speed.	• Within minefield boundaries • Activated
6.6	Arm and Engage	Arm and activate rocket propulsion towards target estimated location	• Within minefield boundaries • Activated • Armed
7	MCM Evasion Maneuver	After detecting and tracking position of MCM-like SONAR signature, deactivate and remain in position for 2 hours. Activate for redeployment in random direction for at least 500 feet.	• Within minefield boundaries • Activated
8	Q-route Coverage Maneuver	After detecting and tracking at least two targets passing without engagement within 1 hour, activate for redeployment along estimated Q-route.	• Within minefield boundaries • Activated

There are some additional rules that the deployment and engagement will have to abide by.

1) Target is Beyond Minefield Edge. The mobile mines may detect a target within its detection range but outside of the minefield. However, the mobile mine will only engage a target when the target gets into the minefield, with the boundaries being the engagement frontier.

2) Mobile Mine Lost in Communication. If the mobile mine is not able to receive (detected through feedback from system health checks), it will also deactivate itself and electronically terminate its own memory and computing processors (i.e., electronic suicide protocol).

3) Mobile Mine Out of Power. The mobile mine will have a shutdown procedure that will deactivate itself and electronically terminate its own memory and computing processors.

4) Mobile Mine Drifts Out of Boundaries. In cases where the currents are too strong and the mobile mine enters a "demilitarized zone" (DMZ) buffer zone of around 100 feet outlining the minefield parameter, it will deactivate itself until it redeploys back within the minefield. If the mobile mine crosses the DMZ buffer zone, it will activate the buoyancy control to sink and electronically terminate its own memory and computing processors.

F. DELIVERY DESIGN

It is a system requirement for the payload to be platform agnostic to better interoperate and operationalize the system subsequently into the U.S. Navy. The delivery of the system into operation can be viewed in three phases to better support the deployment of the mobile mines (Figure 23). Phase 1, known as the transportation phase, consists of preparation of the mobile mines onto the delivery platform of choice (aerial, surface, or subsurface) and, subsequently, the movement of the projectile on the platform of choice towards the launch site. Phase 2, the deployment phase consists of the launching of the mobile mines towards the site location. Once the mine reaches the site location, Phase 3, the positioning phase will begin. The mobile mine will carry out its final precise positioning in the minefield.

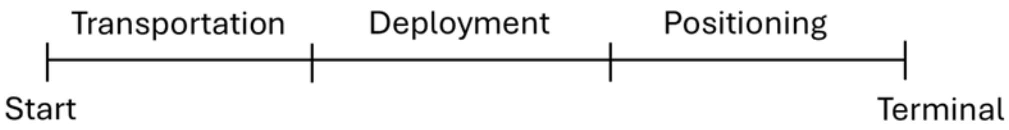


Figure 23. Overview of Delivery Phases

1. Transportation Methods

Depending on the specific operational requirements and tactical considerations, a combination of aerial, sub-surface, and surface transportation methods could provide a comprehensive minefield that maximizes effectiveness while minimizing vulnerabilities. Each transportation method has its advantages and tradeoffs, and the choice of transportation means should be based on the operational environment and mission objectives.

Aerial. For aerial deployment, using aircraft like the B1-B, B-52, P-8, or F/A-18 to drop the mines offers the advantage of covering large areas quickly and can be effective in denying access to enemy ships. However, mobile mines released from aircraft may be more susceptible to detection due to their descent trajectory. Hence, aerial deployment will be more suited for quick and overt mission objectives where speed is critical to mission success.

Sub-Surface. Sub-surface deployment offers the advantage of stealth and surprise. Sub-surface platforms like the LA-Class SSN can deploy the mobile mines covertly, making them difficult to detect and avoid. However, due to space constraints, sub-surface systems must be specifically equipped for the mission profile prior to deployment. Hence, sub-surface deployment will be more suited for covert and special operations where stealth is critical to mission success.

Surface. Surface deployment offers the advantage of flexibility and versatility. Surface vessels such as cruisers and destroyers can deploy mobile mines in a variety of locations, including shallow waters and coastal areas. Surface deployment can also be done relatively quickly, allowing for rapid deployment of mobile minefield systems in response to changing tactical situations. However, surface vessels deploying mines may be more vulnerable to detection and attack, especially in hostile environments.

2. Deployment Requirements

For offensive mining, relevant delivery methods include the use of aircraft to lay QuickStrike mines and sub-surface platforms to lay the MK60 enCAPsulated TORpedo (CAPTOR) mines and Submarine-Launched Mobile Mine (SLMM; United States Navy 2021). The idea of clandestine delivery for offensive mining would alleviate the issue of power projection for the individual mine and was, therefore, conceived. The requirements for a potential clandestine delivery platform that could power project the mobile mines to the deployment site were defined, and a traceability matrix is furnished (in Table 11) to ensure top level functions were satisfied with the potential design.

Table 11. Traceability of Delivery Forms to Functions

Top-Level Function	**Power**	**Mobility**	**Navigation**	**Comms**
Expendable Mobility System	• Batteries and Electric Motor • Mono- or bio propellant powered engines (current stockpile)	• Propulsion System (electric thrusters) • Pump jets	-	Pre-programmed instructions
Autonomous			• GPS • Swarm Master and Slave Guidance	Adjustable pre-coded mission sets, short/low-data subsurface low frequency comms (1-way)
Able to move in all 3 axes (3 DOF)		• Pump jets	-	-
Unmanned functions		• Propulsion system (electric thrusters) • Pump jets	-	1-way communication with large shore site

In addition, the Naval Sea Systems Command (NAVSEA) was also working on prototyping for the Mining Expendable Delivery Unmanned Submarine Asset (MEDUSA). Paired with the ORCA XLUUV, the MEDUSA could be a means to potential offensive mining capability (Abdi 2023). With limited information on the MEDUSA, which is potentially designed for a SLMM, it could be a potential deployment candidate for the mobile mines. Rather than having different platforms to deliver different types of mines, using the MEDUSA allows the U.S. Navy to enjoy economies of scope by exploiting a common platform for varying capabilities. This has potential to enhance and alleviate operational dilemmas and optimization. The MEDUSA is still at an early stage of development and it could very well not be operationalized by the U.S. Navy.

Further alternative of analysis was done to pit the bespoke platform design and MEDUSA, alongside the possibility of the mobile mines owning the capability of projection on their own. It was subsequently decided that the mobile mines possess the power projection capability to reduce the interoperability issues with a deployment platform, reduce maintenance issues of two subsystems vis a vis one system, and reduce costs. With the power projection capability, the mobile mines have the capability to complete both the deployment and positioning phase independently.

3. Sortie Analysis

This section estimates the number of sorties required per delivery platform for full deployment according to the simulation scenario described in Chapter III. Achieving the upper-bound mine density of the simulation, or four mines deployed into each of 10 sectors, would require 40 mines to fully seed the 5 nm x 2 nm test field.

Using an estimated weight of approximately 1000 lbs, the estimated number of mines per sortie were drawn from each platform's weight capacity as well as each platform's current capacity to transport comparable form-factors such as the MK-65 QuickStrike mine. As the platforms are currently used for diverse mission sets, some variation exists in which munition was used as a form-factor approximator for each delivery platform. These variations are displayed in the third row of Table 12.

Risk assessments were made based on the assumption of delivery taking place during an active conflict, taking account of the likelihood of detection and each platform's susceptibility to enemy fire in the event of engagement. Due to the standoff distance of the mine system, no platforms were assessed at above a moderate level of risk, however the B-52 and P-8 were assessed as higher risk aerial platforms relative to other options due to their relatively lower speeds, defenses, and radar cross section reduction measures compared to the B-1B and F/A-18. Table 12 provides the estimated required number of sorties per platform for mining within the assumed 10 square nm test field (Air Force Global Strike Command, Public Affairs Office 2016, 2019; Carlin 2024; ComNavOps 2022; Kass 2023; Naval Air Systems Command Public Affairs 2021; Naval Technology 2024).

Table 12. Required Sorties Per Platform for 10 sq. nm Test Field

Delivery Platforms	**Aerial**				**Subsurface**	**Unmanned Subsurface**
	B-1B (AF)	**B-52**	**P-8 Poseidon (NAVY)**	**F/A-18 (NAVY)**	**LA-Class SSN**	**ORCA XLUUV**
Total Capacity	75,000 lb (Internal)	70,000 lb	50,900 lb	13,700–20,000 lb	37 tubes projectile	16,000 lb
Current Sea-Mines Payload	8x 2,000 lb Mk-65	12x JDAM	5x Mk-54 or 4x Mk-63 (500 lb)	10× GBU-32/35/38/54 (559 lb) or 4× GBU-31 (2,000 lb)	25x torpedo tube launched weapons	Unknown
Mobile Mines (~1,000 lb)	8	18	5	10	25 (max)	14
Risk to Deployment Platform	Low	Moderate	Moderate	Low	Low	Low
Number of Sorties for 40 Mobile Mines	5	3	8	4	2	3

Estimates for the capacity of the B-1B were drawn from its current capacity for Mk-65 mine, assessed to have comparable requirements based upon its form factor and weight (Air Force Global Strike Command, Public Affairs Office 2016). The B-52 has the highest weight capacity and is least restrictive in its form-factor requirements but also faces trade-offs regarding speed and susceptibility to detection when seeding a denied environment. Estimates of the B-52's mine capacity were made based upon its current Joint Direct-Attack Munition (JDAM) capacity of 12 (Air Force Technology 2023), adjusted to account for the approximate 50% difference in weight between the 2000 lb JDAM and the 1000 lb mobile mine. The munition capacity of the P-8 is driven primarily by form factor, thus the estimate shown relies upon mines occupying the aircraft's five internal hardpoints (Memon 2024). In the case of the F/A-18 strike fighter, estimates were drawn from the current number of munitions currently able to be fitted to the 11 existing weapons stations on the platform (Naval Technology 2000). The estimated capacity of the Los Angeles class nuclear powered submarine (SSN) is based strictly upon its torpedo-tube-launched weapons capacity (Carlin 2024; Kass 2023). In the case of the ORCA XLUUV, due to the current classified development status of the platform, not all technical specifications on the system were available publicly. The estimated capacity of 14 is based upon the ORCA's capacity of 16,000 lbs or 8 tons of payload (Naval Technology, 2024), adjusted down by one ton to account for form factor considerations and other hardware occupying payload space.

G. PHYSICAL ARCHITECTURE

The physical architecture of an individual sea mine is shown in Figure 24 and further decomposition of each subsystem is shown in the structural hierarchy in Figure 25. The following subsections will elaborate on the system and physical architecture of the mobile minefield system, each subsystem, and their physical interaction with the other subsystems to operate effectively.

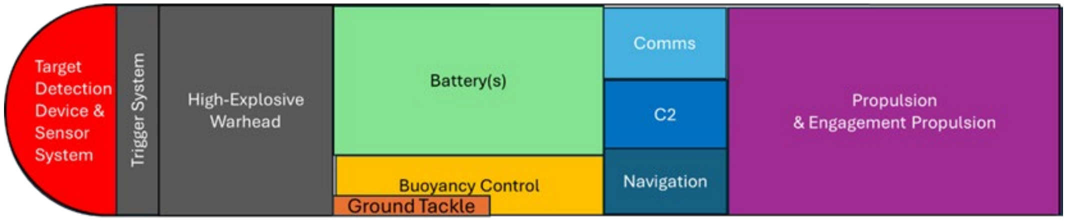


Figure 24. Physical Architecture of Sea Mine

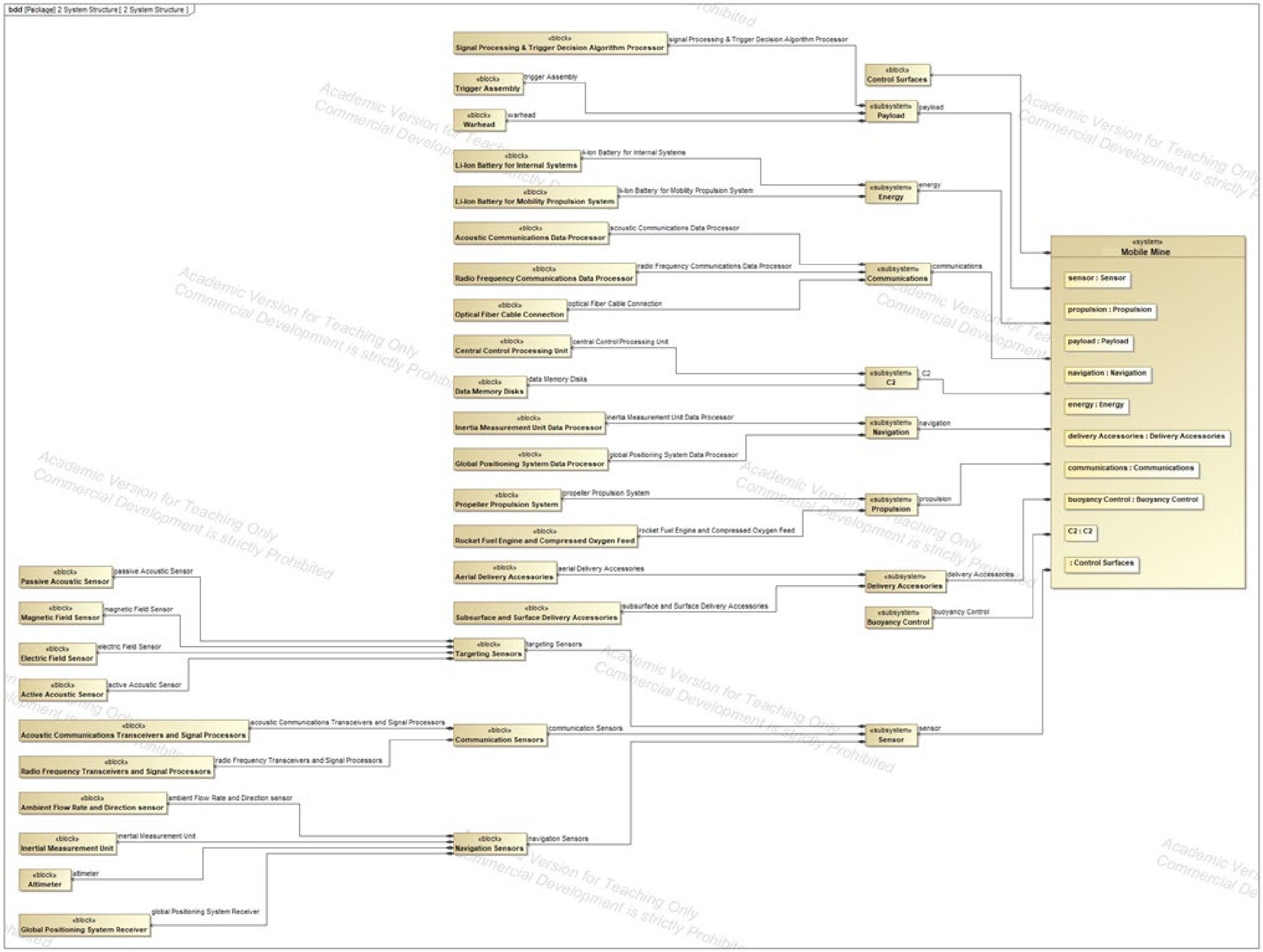


Figure 25. Mobile Mine System Structural Hierarchy of Subsystems and Components

Greater clarity on the interaction between the subsystems are shown in the systems interface description (SV-1; Figure 26) and systems resource flow description (SV-2) (Figure 27) that consist of an internal block diagram of the mobile mine interacting with other external systems and an internal block diagram of the mobile mine's subsystems interacting with one another. In addition, Figure 28 provides the mobile mine systems functionality description (SV-4) that explains how each component works with one another to fulfill the key function relating to positioning, communications, targeting, and power/ health.

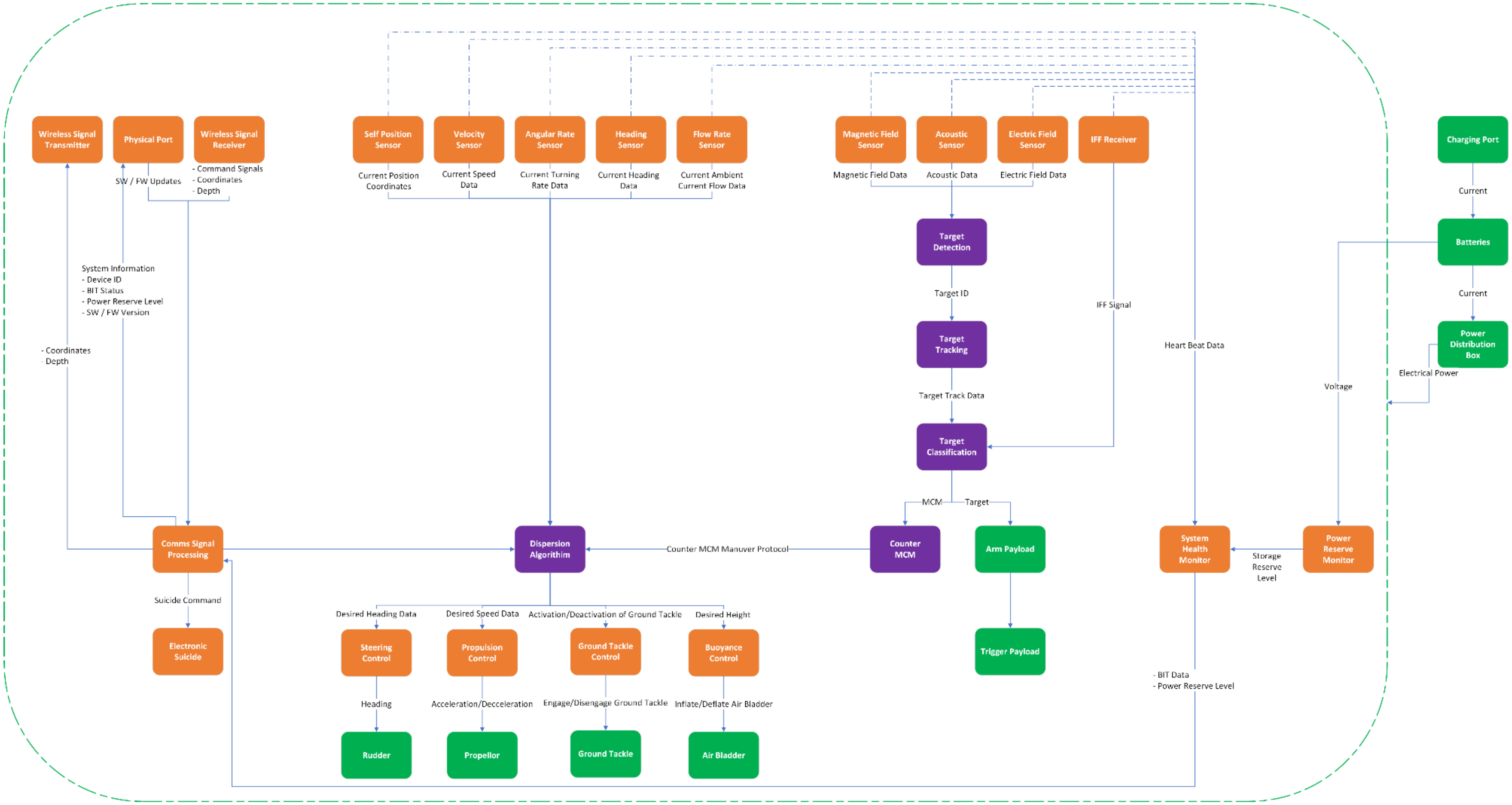


Figure 26. Mobile Minefield Systems Interface Description (SV-1)

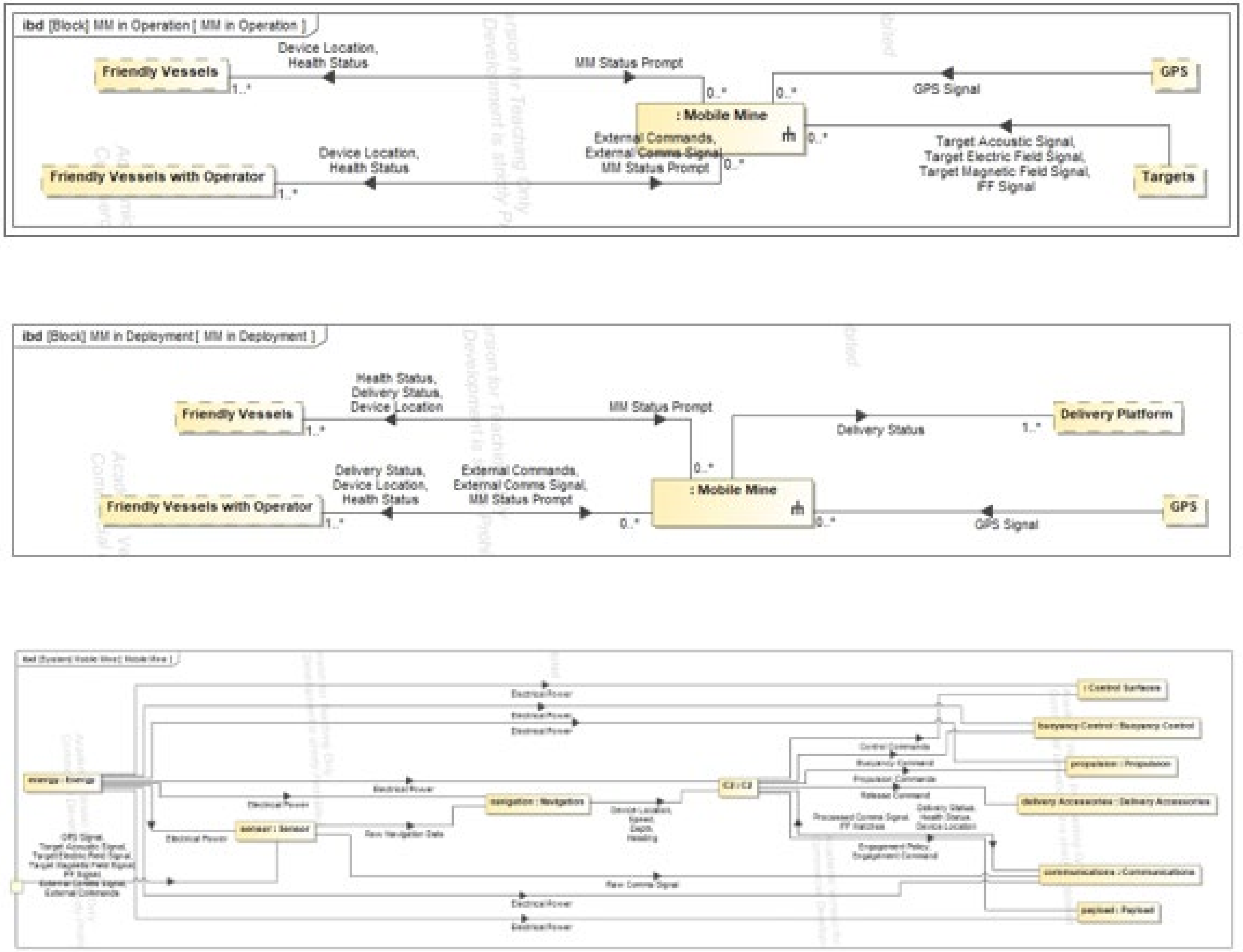


Figure 27. Mobile Minefield Systems Resource Flow Description (SV-2)

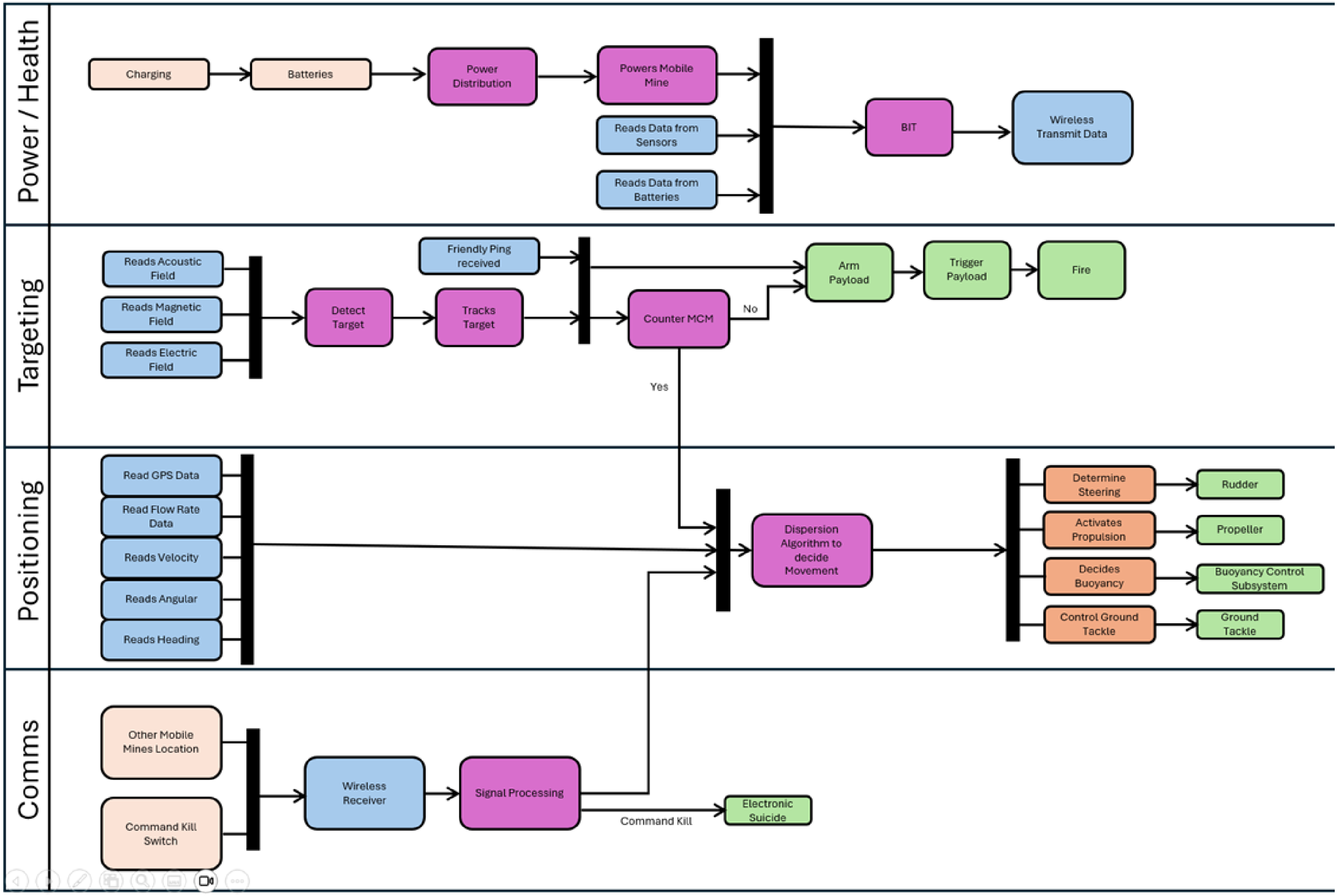


Figure 28. Mobile Mine Systems Functionality Description (SV-4)

Next, the subsystems of the mobile mine system are elaborated in greater detail.

1. Sensor Subsystem

The sensor subsystem will house the sensors facilitating navigation, targeting, and communication. Each sensor will be elaborated in the following subsections.

a. Navigation Sensors

Navigation sensors are used to aid the system in the perception of its position with respect to attitude, depth, and altitude from the seabed and to inform it of responses for movement or redeployment in accordance with its deployment plan.

<u>GPS Receiver.</u> The GPS receiver is used to collect GPS data when it is connected, when operating at up to 1 meter depth from the water surface. The data will facilitate the C2 system in resolving its position and provide a reference for subsequent INS's processing with the data from the IMU.

<u>Ambient Flow Rate and Direction Sensor</u>. An underwater pitot-tube is used to measure the stagnation and static pressure of the water flow around the system (and thereby calculate dynamic pressure). This will allow the mobile mine to be able to resolve for the magnitude and direction of the ambient fluid flow, which can support navigation and propulsion control by allowing the system to incorporate a compensatory term in its movement so that it can move in its intended direction.

<u>Inertia Measurement Unit</u>. The IMU will house three pairs of accelerometers and gyroscopes to measure the motion in six DOFs in (and about) the three axes—longitude (roll), lateral (pitch), and vertical (yaw). A limitation to the use of INS for navigation is the drift errors that will accumulate over time due to noise from measurement and sensor bias (if any) even if the system is static.

<u>Altimeter</u>. Given that the area of operations in the South China Sea whose deepest section has a maximum depth of 5,016 meters (16,457 feet; LaFond 2024), an underwater altimeter that can measure at least an operating depth of 5,000 meters (1,640 feet) at a resolution of 1-dm (0.328 ft) shall be used for measurement of system's height from the seabed to facilitate navigation and the deployment process.

b. Targeting Sensors

Targeting sensors operating with varied effective ranges work simultaneously to gather data for target detection, identification, recognition, and classification as the target becomes closer in range. Thereafter, the active acoustic sensor is used as the guided-system seeker for the terminal engagement process.

Passive Acoustic Sensor. A passive acoustic sensor (i.e., SONAR) is able to operate at range of up to 370 km (200 nm) with a wide field-of-view (Tyler 1992) giving the mobile mines the ability to form tracks when the signatures are deemed reliable (not false alarms). As such, a SONAR of good resolution (at most 1 meter) that is at least able to operate at ranges of at least 10 km (5.4 nm) is recommended for the system. When the target not verified to be a friend is within the effective range of other targeting sensors, they are processed further to support multiple influence target correlation by the trigger decision algorithm. Unfortunately, SONAR is affected by environmental conditions such as temperature, salinity, and clarity of water. It can also be affected by environmental scatters such as bubbles, particulate matter, and noise from other surface sources and marine life. As such, issues such as increased latency and transmission losses, as well as Doppler spread, may arise. Nevertheless, it is still the indispensable mode of detection used by both mines and countermine measures (i.e., detectors) alike.

Magnetic Field Sensor. Magnetic field sensors, being one of the oldest sea mine sensors in the world, works on all magnetized objects and are not vulnerable to influence from water clarity or visibility. Generally, these sensors can detect at long ranges but can be affected by noise from other magnetic fields such as underwater power lines and the Earth’s own magnetic field (Selvag 2006). Such sensors can detect different materials at a long range and can support classification when processed with data from SONAR (if military vessels have very different material compared to commercial or private surface vessels).

Electric Field Sensor. Electric Potential sensors work in a similar way as magnetic sensors, measuring low level electric fields and ELF electromagnetic signals generated by both alternating/direct currents. Electric Potential will be available for metallic objects in the water, especially for surface ships that use cathodic protection currents for corrosion protection of their hulls. Some benefits that these sensors enjoy are ultra-low noise electrodes, precise and high-sensitivity, large bandwidth, and being able to operate in low-visibility conditions. However, they are also affected by lightning strikes and geothermal activity that are in the proximity of the sea mine. Currently, underwater tracking can be done at 200 meters numerical simulation, and 150 meters in sea trial experiments (Yu, Chang, and Zhang 2019). Due to its sensitivity, it is a good addition to the multi-influence sensor suite for targeting to differentiate targets due to their unique signature.

Active Acoustic Sensor. An active SONOR that has a narrower field-of-view compared to the passive SONAR will be an effective guidance seeker for the mobile mine as it propels itself towards the target after it is armed and triggered to engage it. The higher sensitivity and sampling frequency will facilitate fine-tuning of heading toward the target's dominant source of acoustic noise—typically the engine room so it can at least disable it if the target survives the strike.

c. Communications Sensors

Acoustic Communications Transceiver and Signal Processor. When the mobile mines are underwater, encrypted acoustic communication will be used to transmit data at around 500 bits/s at long distances at frequency of 10–30 kHz. This form of communication may be inefficient with encryption and with increased latency and low data rates at slow speed. However, given the transmission distance advantage, communication can still be implemented with short commands.

Radio Frequency Transceiver and Signal Processor. When the mobile mines are above surface or just below surface, RF in the VLF band (3–30 kHz, ~60 meters of operating distance) is used. Being a system that is already used for secure military communication with submarines given the penetration capability of VLF waves (penetrate at least 20 meters, or 65.6, feet into salt water), it is an appropriate system that can be employed.

2. Payload (Ordinance Subsystem)

Signal Processing and Trigger Decision Algorithm Processor. Being fed with data from the sensors, communication subsystem, and the central control processing unit, the processor will process and fuse data and make decisions on engagement when it is activated. The trigger decision algorithm hosted in this processor will compare and correlate received data with a loaded library to identify, recognize, and classify targets if a track is not successful in verifying that it is a friendly entity. If it is deemed to be a feasible target that needs to be engaged, it will activate the trigger assembly and engagement propulsion subsystem.

Trigger Assembly. The trigger assembly sets the fuse delay for the warhead based on the sensed target distance throughout the terminal engagement homing towards the target.

Warhead. The high explosive warhead is triggered to detonate by the trigger assembly when the mobile mine is near or has reached the target.

3. Buoyancy Control Subsystem

The mobile mine can regulate its own buoyancy to allow the device to float up or sink down without sustained propulsion. After doing engineering estimation, the device is net positively buoyant and will, thus, require ingestion of water into compartments within the mobile mine to make itself neutrally or negatively buoyant. This is done through a water inlet on the belly of the mobile mine that leads to a piston that is controlled by an electric motor. More details on the buoyancy control design can be found in Appendix B.

4. Energy Subsystem

Battery systems are used to support the operation of the mobile mine and are separated for the internal systems and mobility propulsion system. Lithium-ion batteries continue to hold the energy density record and is thus the best option for the battery system (Dumé 2023). Based on the energy and power analysis documented in Appendix A, 65 kg of battery will be able to provide the mobile mine with an endurance of around 90 days.

a. Battery for Internal System

An independent Li-Ion Polymer battery is allocated for internal systems including the sensors, communications, C2, and navigation subsystems. Separation from the other battery unit will ensure that the mobile mine can still operate without the ability to redeploy.

b. Battery for Mobility Propulsion System

An independent Li-Ion Polymer battery is allocated for mobility propulsion system to provide the propulsion electric motor with a suitable power rating for its requirement. Separation from the other battery unit will ensure that the mine can still operate without the ability to redeploy if this battery fails.

5. Communications Subsystem

Communication subsystems work with communication sensors to process the data and facilitate subsequent responses. On shore, wired communication is used to set up or configure the mobile mine.

Acoustic Communications Data Processor. After the acoustic signal is processed by the sensor subsystem, the data is processed (e.g., decryption) for the central control processing unit to decide on a suitable response.

Radio Frequency Communications Data Processor. After the RF signal is processed by the sensor subsystem, the data is processed (e.g., decryption) for the central control processing unit to decide on a suitable response.

Optical Fiber Cable Connection. Optical fiber cable is used to connect an external system with mobile mines to upload information to the system, including maps, software, and encryption keys for communications.

6. C2 Subsystem

Central Control Processing Unit. A central control processing unit is used as the main processor of the system to process and facilitate different functions, including IFF, controlling the mobile mine in its movement based on sensor data, and activation of propulsion systems.

Data Memory Disks. To support software and to store readable files required for the operation of the system, solid-state memory disks are used to provide faster transfer time and reduction of moving parts that generate signal signature to the environment.

7. Navigation Subsystem

To facilitate the navigation of the system, data processors are required to process the raw data and inform the central control processing unit to support it in decision making.

Inertia Measurement Unit Data Processor. An IMU data processor is used to process data from the IMU under the sensor subsystem. This component will aid the system in navigating under the water where there is no GPS reception.

Global Positioning System Data Processor. At the surface, a GPS signal can be received to provide the mobile minefield system with locational information to guide its navigation. A GPS data processor is required to resolve the position of the mobile mine subject to positional error that can be reduced with more satellite connections.

8. Propulsion Subsystem

Propeller Propulsion System. A propeller propulsion system is required to move the system from delivery to deployment and facilitate redeployment. It will have enough thrust power to propel the mobile mine in accordance with system requirements (i.e., to move in poor sea state).

Rocket Fuel Engine and Compressed Oxygen Feed. To facilitate high velocity propulsion towards the target, and in consideration of the system being largely underwater, a rocket fuel engine is required to provide sufficient thrust and to support the combustion of solid rocket fuel, a clean supply of compressed oxygen feed is fed to the fuel for combustion.

9. Delivery Accessories

To support the delivery process using various platforms, some accessories will be required to help the mobile mine adapt to the delivery platforms.

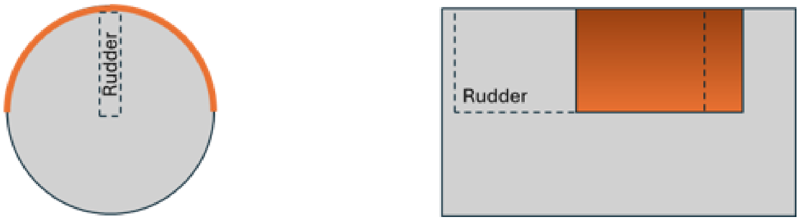
Aerial Delivery Accessories. Aerial delivery platforms can deliver the mobile mines akin to bombs and will only require holding attachments on the casing of the mobile mine to adapt to the pylons under their wings or fuselage. These attachments can break off from the sea mine once it is delivered by the aircraft. Given the size and weight, an inboard pylon with two attachment points will be required.

Subsurface and Surface Delivery Accessories. Subsurface vessels use a water ram to launch their torpedoes using the torpedo tubes; while surface vessels use gunpower charge explosions to force their torpedoes out from the launch tubes. To ensure that the mobile mines will not suffer any damage from the launch process, a thin layer of separator may be required for the sea mine to ensure safe delivery.

10. Control Surface

To ensure that the sensors and buoyancy control subsystems are maintained in a posture that is most effective, horizontal stabilizers will be required to maintain an upright orientation. To direct the mobile mine to travel towards the deployment location and target during engagement, a rudder will be required. As such, a set of control surfaces that is kept in or around the mobile mine that will not obstruct its delivery will be required. After delivery is done and the mobile mines are about to make their way to the deployment location, the control surfaces are released and locked into place. The proposed design for the control surfaces is shown in Figure 29.

Before Deployment:



After Deployment:

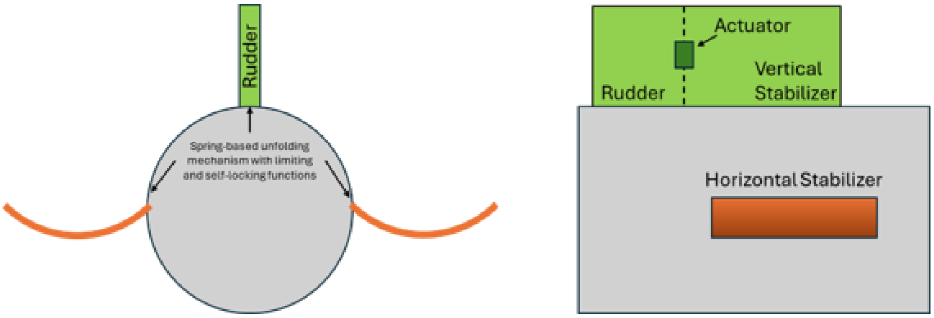


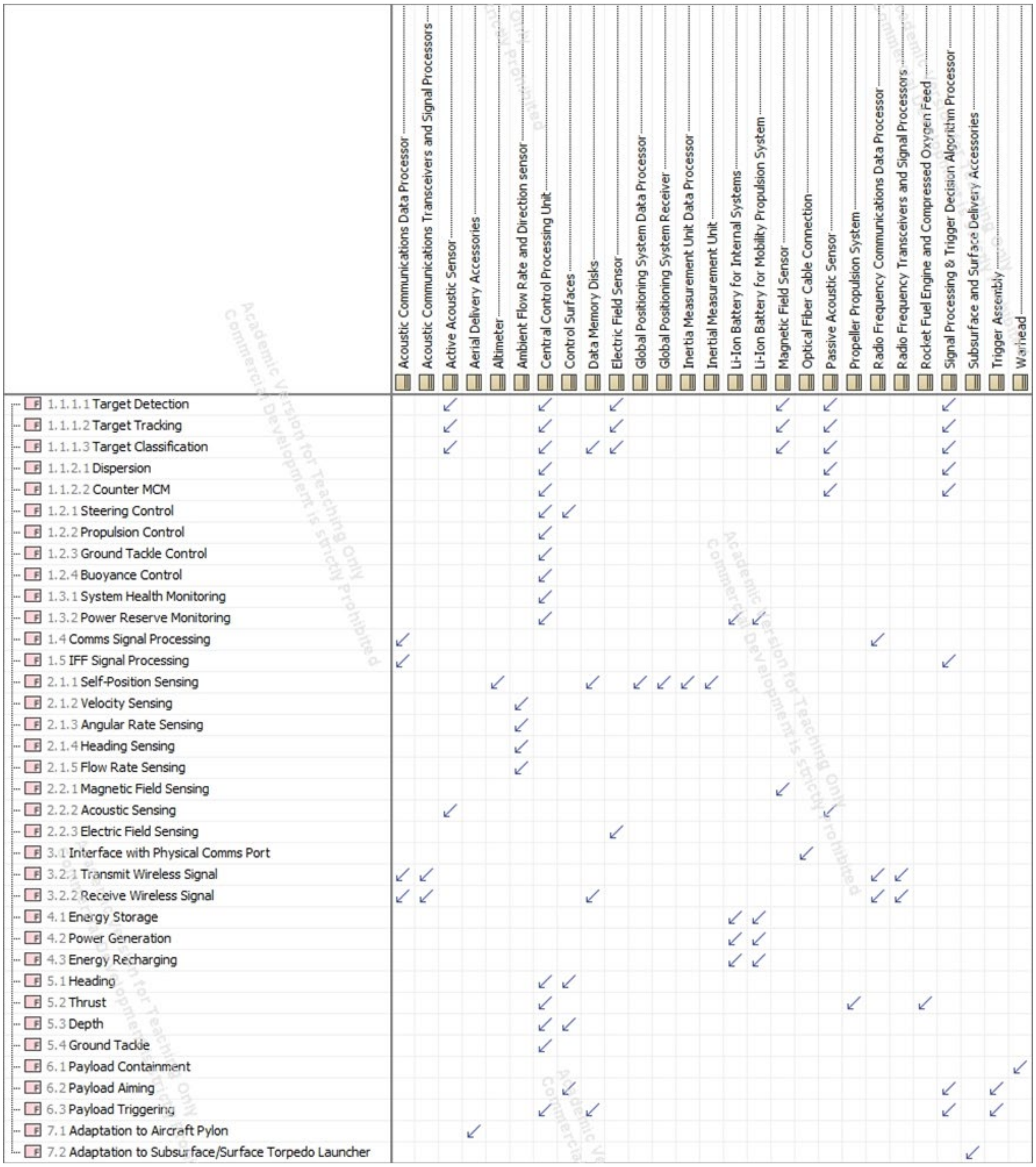
Figure 29. Control Surfaces of the Mobile Mine

11. Ground Tackle

After sinking to the desired depth as informed by the altimeter the mobile mines will release the ground tackle to anchor itself to be resistant to underwater currents.

12. Traceability of Form to Functions

The physical components of the mobile mine can be traced to the functions using Figure 30 that provides the traceability diagram for form to functions.



	Acoustic Communications Data Processor	Acoustic Communications Transceivers and Signal Processors	Active Acoustic Sensor	Aerial Delivery Accessories	Altimeter	Ambient Flow Rate and Direction sensor	Central Control Processing Unit	Control Surfaces	Data Memory Disks	Electric Field Sensor	Global Positioning System Data Processor	Global Positioning System Receiver	Inertia Measurement Unit Data Processor	Inertial Measurement Unit	Li-Ion Battery for Internal Systems	Li-Ion Battery for Mobility Propulsion System	Magnetic Field Sensor	Optical Fiber Cable Connection	Passive Acoustic Sensor	Propeller Propulsion System	Radio Frequency Communications Data Processor	Radio Frequency Transceivers and Signal Processors	Rocket Fuel Engine and Compressed Oxygen Feed	Signal Processing & Trigger Decision Algorithm Processor	Subsurface and Surface Delivery Accessories	Trigger Assembly	Warhead
1.1.1.1 Target Detection			↙				↙			↙							↙		↙					↙			
1.1.1.2 Target Tracking			↙				↙			↙							↙		↙					↙			
1.1.1.3 Target Classification			↙				↙		↙	↙							↙		↙					↙			
1.1.2.1 Dispersion							↙												↙					↙			
1.1.2.2 Counter MCM							↙												↙					↙			
1.2.1 Steering Control							↙	↙																			
1.2.2 Propulsion Control							↙																				
1.2.3 Ground Tackle Control							↙																				
1.2.4 Buoyance Control							↙																				
1.3.1 System Health Monitoring							↙																				
1.3.2 Power Reserve Monitoring							↙								↙	↙											
1.4 Comms Signal Processing	↙																				↙						
1.5 IFF Signal Processing	↙																							↙			
2.1.1 Self-Position Sensing					↙				↙		↙	↙	↙	↙													
2.1.2 Velocity Sensing						↙																					
2.1.3 Angular Rate Sensing						↙																					
2.1.4 Heading Sensing						↙																					
2.1.5 Flow Rate Sensing						↙																					
2.2.1 Magnetic Field Sensing																	↙										
2.2.2 Acoustic Sensing			↙																↙								
2.2.3 Electric Field Sensing										↙																	
3.1 Interface with Physical Comms Port																		↙									
3.2.1 Transmit Wireless Signal	↙	↙																			↙	↙					
3.2.2 Receive Wireless Signal	↙	↙							↙												↙	↙					
4.1 Energy Storage															↙	↙											
4.2 Power Generation															↙	↙											
4.3 Energy Recharging															↙	↙											
5.1 Heading							↙	↙																			
5.2 Thrust							↙													↙			↙				
5.3 Depth							↙	↙																			
5.4 Ground Tackle							↙																				
6.1 Payload Containment																											↙
6.2 Payload Aiming								↙																↙		↙	
6.3 Payload Triggering							↙		↙															↙		↙	
7.1 Adaptation to Aircraft Pylon				↙																							
7.2 Adaptation to Subsurface/Surface Torpedo Launcher																									↙		

Figure 30. Traceability Matrix for Form to Function

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V. EXPERIMENTS AND ANALYSIS

This chapter describes the experiments and analyses conducted on the mobile mine system including a model-based simulation of a static and mobile minefield with enemy vessels crossing it, a feasibility analysis, life cycle cost estimate, and a risk analysis. The results of these analyses give information to the stakeholders to help make strategic and operational decisions involving the pursuit of this new technology.

A. SIMULATION

This section covers the input parameters for the model created in the Modeling and Simulation Toolkit (MAST) and the results and conclusions of the simulations. The simulation results impact the design by quantifying the strengths of the system concept and exposing the areas of possible improvement. The areas of improvement highlighted in this section have recommendations for mitigation or resolution.

1. Simulation Parameters: Overview and Execution

The simulation was designed to compare the threat to transiting surface ships from underwater mines using a consistent set of parameters, tailored to specific scenarios involving static and mobile mines. As described in Chapter III Section D, the simulation is comprised of three entity classes: mines, enemy MCMs, and enemy transiters. The enemy MCM platforms, intended to evaluate mine survivability and adaptability, proceeded along a preplanned route at 5 knots detecting mines within 1000 yards and engaging at ranges within 600 yards. The enemy transiting platforms, intended to test mine detection and engagement capabilities, operated at a uniform transit speed of 20 knots and incorporated an allowed variable path deviation of 500 yards. The enemy transiting platform route is shown in Figure 31.

Figure 31. Enemy Transiting Platform Route

In Scenario 1, static mines were deployed in each sector at a depth of 90 feet and a detection radius of 5,000 yards. These mines simulate a defensive barrier against the enemy platforms and are programmed to activate upon detecting enemy vessel acoustic signatures within 500 yards. This scenario tested the enemy transiting ships' ability to navigate a predetermined route lined with static mines to determine a baseline level of mine barrier effectiveness.

Scenario 2 featured mobile mines capable of dynamic repositioning upon sensing certain external stimuli thereby complicating adversary mine countermeasure (MCM) efforts. The mines' detection and engagement parameters remained unchanged from Scenario 1 with the addition of the variable mobility post-MCM sweep. Scenario 2 tested the relative effectiveness improvement compared to static mines and the enemy MCM's ability to dynamically adapt to changing minefield conditions.

Each scenario was run 10 times to ensure robust data collection and analysis, with variations in the number of mines deployed ranging from one to four per sector within the barrier. This iterative approach allowed for a thorough evaluation of how increasing mine density affects the expected transiting platform attrition and the delay induced by the required MCM route clearance operations. The simulation generated data on the following outputs: the accuracy of threat detection, the time for all platforms to transit the barrier, the success rate of mine engagement strategies, and the effectiveness of MCM efforts. The analysis of these results leads to three recommendations to improve the system design.

2. Scenario 1 (Static Mines) Results

The static mine results for Scenario 1 are shown in Table 13, revealing an expected progressive increase in threat severity as the mine density per sector increases from one to four.

Table 13. Simulation Results for Scenario 1 (Static Mines)

Mine Density (mine/sector)	Average Enemy Platforms Killed	Average Enemy Platforms Survived	Average Mines Neutralized by Enemy MCM	Induced Enemy Delay Time (mins)
1	1.2	8.8	1.2	154.0
2	1.7	8.3	2.6	236.1
3	2.3	7.7	4.3	338.5
4	3.4	6.6	5.8	400.6

The main takeaway from the static scenario is that once the Q-route was established by MCM assets, there was very little threat imposed by the remaining mines which was evident by the observation that transiting platforms in the second and third clusters were rarely engaged. This phenomenon is depicted in Figures 32 and 33, respectively. It is important to note the limitations of the static mines going into Scenario 2 to highlight the difference in risk to the enemy vessels. The mobile mines in Scenario 2 aim to improve overall barrier effectiveness and mitigate the need to reseed a mine barrier to maintain a constant threat level via mine mobility.

Figure 32. Static Field Prior to MCM Sweep

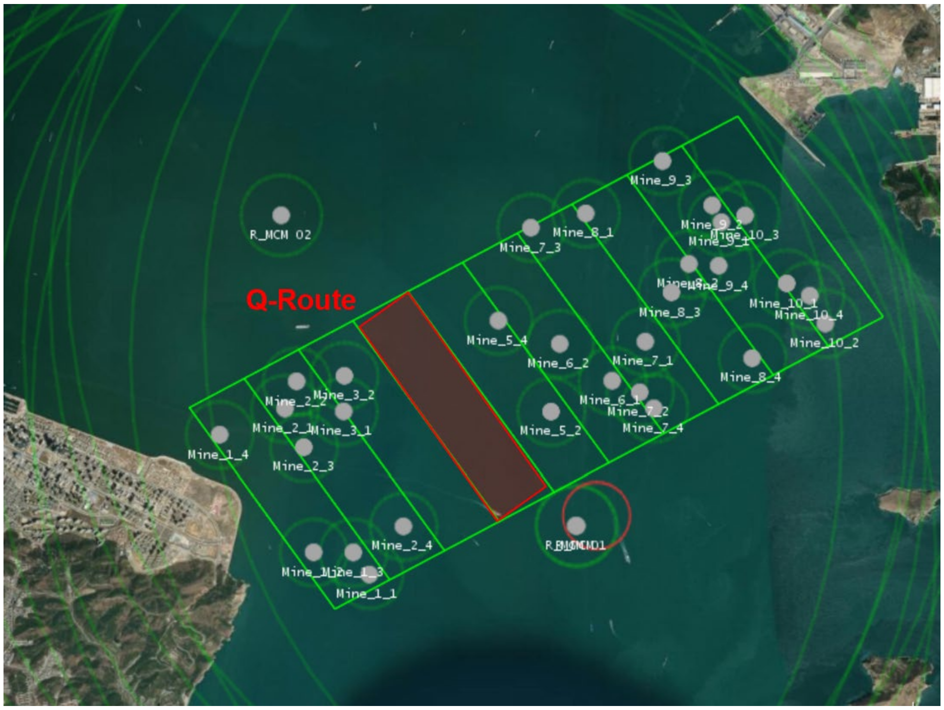


Figure 33. Q-Route Cleared through Static Field

3. Scenario 2 (Mobile Mines) Results

The mobile mine (Scenario 2) results are documented in Table 14 and consistently demonstrate a marked increase in risk and operational challenges as the density of mines per sector increases from one to four and a significant improvement in effectiveness as compared to Scenario 1.

These simulations illustrate that an increase in mine density and mine mobility provides increased effectiveness and lethality against enemy units. This showcases not only heightened fatalities but also significant operational impacts on adversary breakout plans due to extended and more complex route clearance measures.

Table 14. Simulation Results for Scenario 2 (Mobile Mines)

Mine Density (mine/sector)	Average Enemy Platforms Killed	Average Enemy Platforms Survived	Average Mines Neutralized by Enemy MCM	Average Induced Enemy Delay Time (mins)
1	3.5	6.5	1.8	218.0
2	5.6	4.4	5.1	373.5
3	9.3	0.7	8.3	515.8
4	9.8	0.2	9.8	573.8

This pattern of escalating risk underscores the imperative for advanced strategies and technologies in naval offensive mine mobility. Figures 34 and 35 show the Q-route cleared through the mobile minefield and the subsequent movement to close the gap in coverage. Figure 35 is also overlaid by the Q-route that existed in the static field from Figure 33 and demonstrates the sustained threat level provided by mine mobility. This simulation demonstrates that mobile mines are more effective than their static counterparts and present a highly lethal threat, especially at higher densities. The findings highlight the urgent need for more advanced, capable, and efficient weapons at a time where the technology is out of date (Wester and Mancini 2023) These insights are crucial for informing future developments and operational planning in naval weapons systems to ensure preparedness in complex underwater environments.

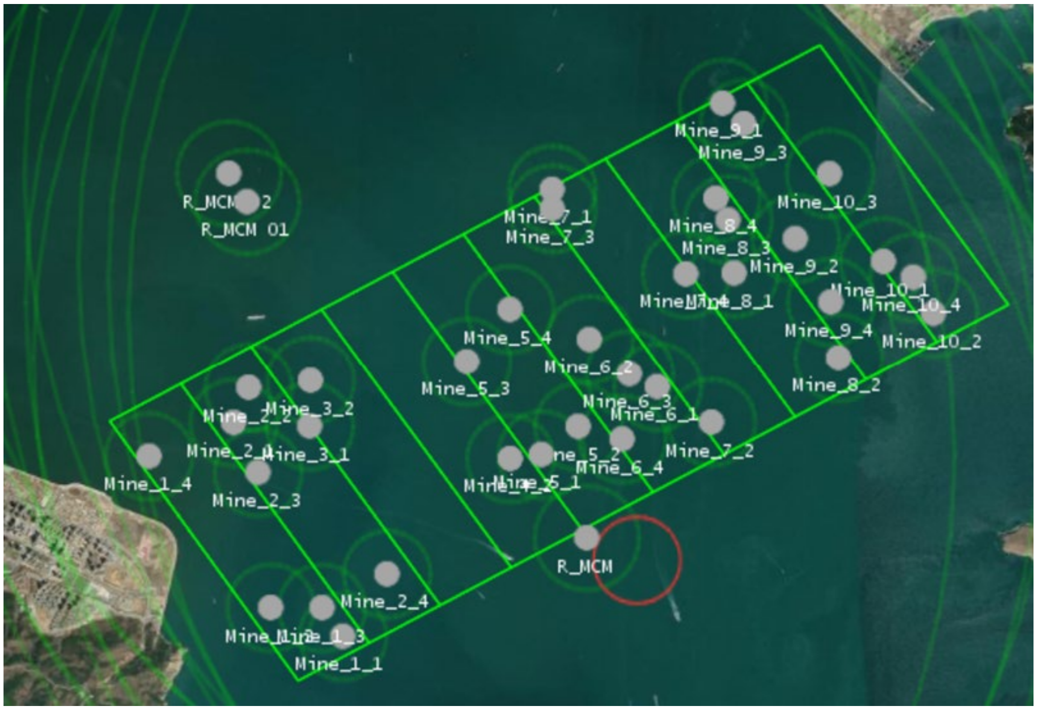


Figure 34. Q-Route Cleared through Mobile Field

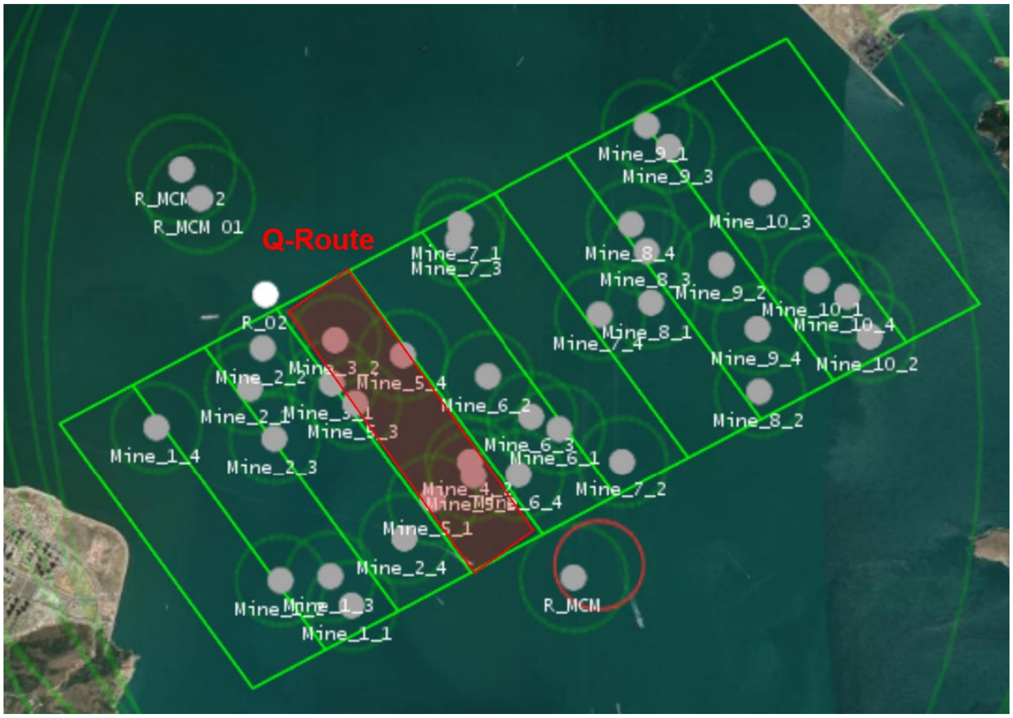


Figure 35. Mobile Minefield after Mine Movement

4. Analysis of Results

The analysis of simulation results across scenarios with static and mobile mines provides insight into the operational challenges posed by increasing mine densities and the dynamic nature of threats. A comparison of the two scenarios highlights several key implications for naval strategy and future mine development.

Even at the lowest density, mobile mines presented a substantial threat, with an average of 3.5 vessels killed and 218 minutes of delay, higher than the highest density of static mines, as shown in Table 15. At four mobile mines per sector, nearly all vessels were routinely killed (average 9.8) and the delays skyrocketed to an average of 574 minutes.

Table 15. Summary of Simulation Results

	Static				Mobile			
Mine Density (mine/sector)	Average Enemy Platforms Killed	Average Enemy Platforms Survived	Average Mines Neutralized by Enemy MCM	Average Induced Enemy Delay Time (mins)	Average Enemy Platforms Killed	Average Enemy Platforms Survived	Average Mines Neutralized by Enemy MCM	Average Induced Enemy Delay Time (mins)
1	1.2	8.8	1.2	154	3.5	6.5	1.8	218
2	1.7	8.3	2.6	236.1	5.6	4.4	5.1	373.5
3	2.3	7.7	4.3	338.5	9.3	0.7	8.3	515.8
4	3.4	6.6	5.8	400.6	9.8	0.2	9.8	573.8

The drastic increase in effectiveness depicted in Figures 36 and 37 show the enhanced complexity and danger posed by mobile mines, which can adapt to countermeasure tactics and pursue targets aggressively, leading to higher casualty rates and drastically longer breakout times. Per the analysis completed, a mobile minefield would be more complicated to clear than a static minefield. Of note, the number of mines neutralized by MCM also increased for the mobile scenario, this is due to the mines moving into the previously cleared Q-route that was swept by subsequent MCM platforms.

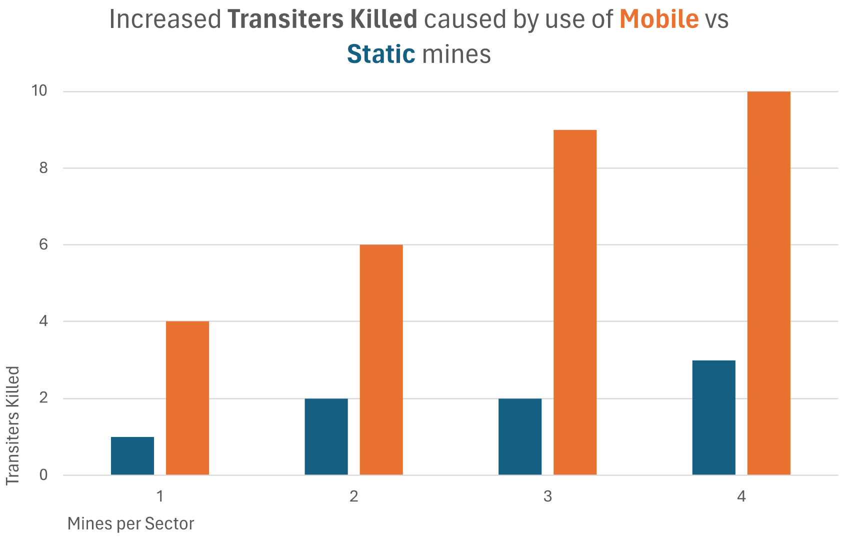


Figure 36. Mines per Sector versus Transiters Killed

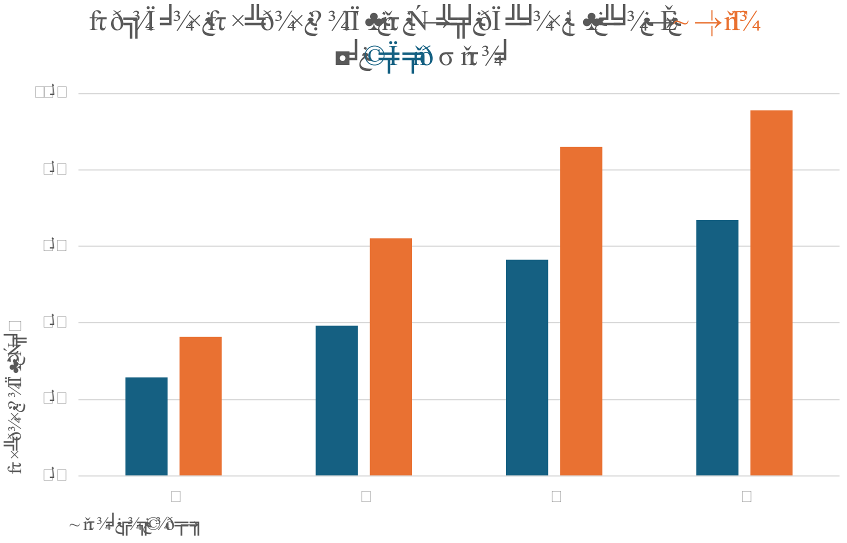


Figure 37. Mines per Sector versus Induced Delay

This comprehensive analysis, summarized by Figures 36 and 37, reveals that mobile mines amplify the adversary’s risk and operational challenges significantly at all density levels and present a disproportionately higher threat level over a longer period of time. Based on this analysis, to achieve the same effectiveness as four static mines per sector, only one or two mobile mines are required. In other words, mobile mines are nearly four times more effective at denying and twice as effective at delaying an enemy force from executing their breakout plan. These insights are significant for naval forces as they adapt strategies and technologies to better incorporate sophisticated underwater mines in varied operational environments. The simulation results serve as a vital data point for ongoing and future developments in naval warfare tactics and technology enhancements in the undersea domain.

B. FEASIBILITY ANALYSIS

The feasibility of the mobile minefield system can be assessed by examining the technology readiness level (TRL) of the subsystems and then the overall system TRL according to the guidelines set by the U.S. Government Accountability Office (GAO) in the Technology Readiness Assessment Guide (2020). The major subsystems individually had TRLs ranging from 8–9 because the technology behind them has been proven successfully in multiple systems as explained in Table 16. The subsystems that were rated TRL 8 were marked as such because of the limited information available concerning operational, test, and evaluation reports, most likely due to the classification level of such reports and the public's limited access to them. The subsystems individually have high TRLs, but the overall mobile mine system has never been designed, integrated, or tested before, so the system was assessed to be TRL 2 based on the information and analyses contained within this report. Further details on the TRL assigned for the subsystems and supporting services of the mobile mines are detailed in Table 16.

Table 16. Technology Readiness Analysis of Mobile Mine Subsystems and Supporting Services. Adapted from GAO (2020, 66–67).

Subsystems	TRL	Description
Sensor	8	Multi-influence sensors are not new technology and are used in different variants, with the chosen sensors having demonstrated effectiveness. However, it is not rated at TRL 9 due to limited information on actual full systems operating.
Payload	9	The payload subsystem is a mature technology that has been implemented in other torpedo/mine systems for many decades.

Subsystems	TRL	Description
Buoyancy Control	9	The buoyancy control system design is not a new technology and has been implemented in different unmanned underwater vehicles (UUVs).
Energy	9	The energy source chosen for the mobile mines are lithium-ion batteries, which are highly developed and optimized for system reliability, and are used in different electronic devices and systems.
Communications	9	Communication systems are mature technology that has been implemented for military systems for many decades. The Identification of Friend or Foe (IFF) system is also another system that is well-adopted among different navies (Bowden 1985).
Command and Control (C2)	9	The C2 systems are a mature technology that has been implemented for military systems for many decades.
Navigation	9	The navigation systems are mature technology that have been implemented for military systems for many decades.
Propulsion	9	Both propulsion methods of propeller and rocket fuel propulsion are separately mature technology that have been implemented for military systems for many decades, especially in torpedoes and UUVs.
Exterior and Control Surfaces	9	The exterior and control surfaces are not new technology and has been implemented for guided torpedoes for many decades.
Delivery	8	Based on enCAPsulated TORpedo (CAPTOR), Submarine Launched Mobile Mine (SLMM), and QuickStrike mobile mines, the delivery methods are mature and has proven a high level of reliability for the mobile mine's adoption (Norman 1983).
Automation Algorithm	8	Automation of the sea mines independently is not too complex and had been demonstrated in many different unmanned vehicles (Gage 1995).

C. SYSTEM LIFE CYCLE COST ESTIMATE

The cost estimate contained in this section is based on the system parameters established in this report and uses cost modeling techniques. As the system definition and design matures, the cost model also matures to be a closer representation of the costs that could be expected in building a similar system. For this report, the cost estimate serves to determine which factors drive the cost to make decisions about the system design.

1. System Cost Model Suite Description

The cost estimate was completed using the System Cost Model Suite online tool that was created by Ray Madachy at the Naval Postgraduate School (Madachy n.d.-b). The System Cost Model Suite is composed of three different types of models on separate tabs for the systems engineering, software, and hardware. Brief descriptions of the tabs will come in the next paragraphs, followed by the breakdown of the analysis using the System Cost Modeling Suite (Madachy n.d.-b).

The Systems Engineering tab utilizes the Constructive Systems Engineering Cost Model (COSYSMO) identifies areas that will be factors in the respective cost model. The sections outline the effects on the overall system's engineering cost, which is calculated based on the system's size, cost drivers, maintenance, and system labor rates (Valerdi 2008).

The Software tab is composed of the modeling methodology called Constructive Cost Model (COCOMO II), which has variability in the software size, software scale drivers, cost drives, personnel, platforms, project, maintenance, and software labor rates (Clark and Madachy2015).

The Hardware tab is composed of a modeling methodology named Advanced Missions Cost Model (AMCM) which uses variables of quantity, dry weight, mission type, initial operating capability (IOC) year, block number, and difficulty of the respective system that is being built (Jones 2015).

Finally, the Summary tab is composed of a summation of the Systems Engineering, Software, and Hardware tabs, providing a total for systems engineering acquisition, software development, hardware development and production, maintenance, and the total cost.

2. Systems Engineering Costs

In the COSYSMO, system size had to be established first by identifying all the system requirements, interfaces, algorithms, and operational scenarios and determining how many of each of those would be classified as easy, nominal, or difficult (Valerdi 2008). An example of this process is to use a high-level requirement of “mines shall have communication means to positively identify friendly forces” from the Design Requirements of the Functional Requirements section of Chapter IV; due to the technology and rigor that would be required to achieve this system requirement, this requirement was marked as a difficult requirement. In this way, it was determined that there were eight easy requirements with well-established technology already used on other mines, seven nominal requirements that use existing features but with upgrades or moderate engineering challenges, and six difficult requirements that are either newer technology or would need to be integrated in a unique way.

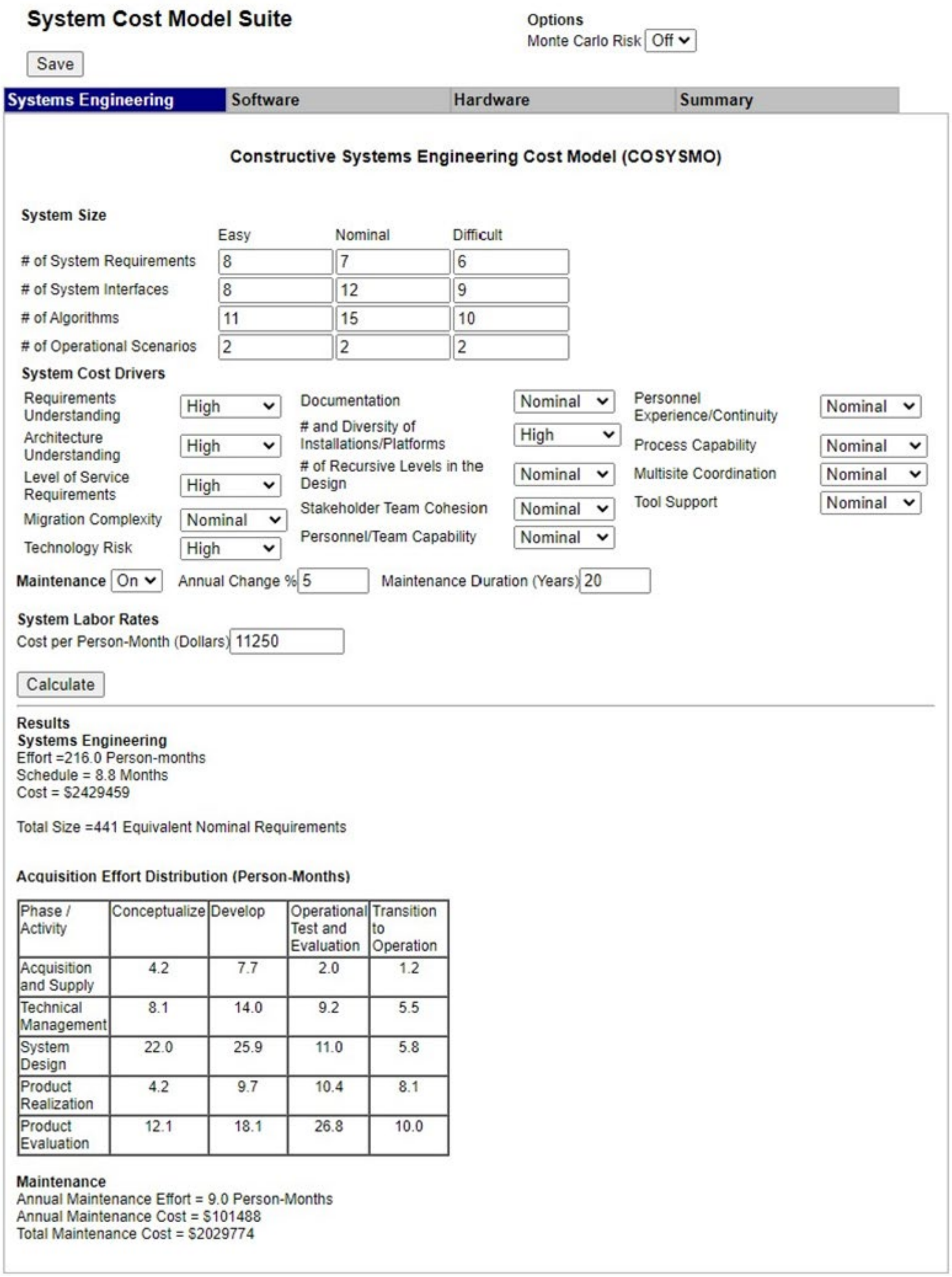
Using the established component and subsystems list and a list of external interfaces such as between mines within the field or to friendly and hostile ships, a count of the interfaces could be conducted which resulted in eight easy interfaces, 12 nominal, and nine difficult interfaces. The functional block diagram helped estimate how many algorithms would be needed for all the major functions. Each end function was assigned a rating with 11 easy, 15 nominal, and 10 difficult algorithms. The last size driver was the operational scenarios, for which there was already a list created with six scenarios that were already defined with two easy, two nominal, and two difficult scenarios.

System cost drivers are classified as very low, low, nominal, high, and very high (Valerdi 2008). An example of a system cost driver would be the requirements understanding for this application. We assessed this as high due to the requirements being understood by the team. This process was completed for the rest of the system drivers using heuristics and comparisons to existing mine technology being used by the U.S. Navy. Since the design of the mobile mine system is still in the early stages, most of the system cost drivers were set as nominal by default. The exceptions to this rule were the requirements understanding, architecture understanding, level of service requirements, technology risk, and the number and diversity of installations/platforms which were all set to be high.

Maintenance was determined to be part of this calculation based on wanting to understand the cost estimate across the system life cycle. An annual change of 5% was assumed, based on the number of mines that would need to be assessed and have configuration changes made to them. It was assumed that the life of the system would be for 20 years.

The cost estimation assumes the labor rate is $11,250 based on an average salary of $135,000 for a person working in the systems engineering field (Glassdoor 2024).

Figure 38 shows the input to the cost estimation model.



System Cost Model Suite

Options
Monte Carlo Risk Off

Constructive Systems Engineering Cost Model (COSYSMO)

System Size

	Easy	Nominal	Difficult
# of System Requirements	8	7	6
# of System Interfaces	8	12	9
# of Algorithms	11	15	10
# of Operational Scenarios	2	2	2

System Cost Drivers

Requirements Understanding	High	Documentation	Nominal	Personnel Experience/Continuity	Nominal
Architecture Understanding	High	# and Diversity of Installations/Platforms	High	Process Capability	Nominal
Level of Service Requirements	High	# of Recursive Levels in the Design	Nominal	Multisite Coordination	Nominal
Migration Complexity	Nominal	Stakeholder Team Cohesion	Nominal	Tool Support	Nominal
Technology Risk	High	Personnel/Team Capability	Nominal		

Maintenance On Annual Change % 5 Maintenance Duration (Years) 20

System Labor Rates
Cost per Person-Month (Dollars) 11250

Results
Systems Engineering
Effort =216.0 Person-months
Schedule = 8.8 Months
Cost = $2429459

Total Size =441 Equivalent Nominal Requirements

Acquisition Effort Distribution (Person-Months)

Phase / Activity	Conceptualize	Develop	Operational Test and Evaluation	Transition to Operation
Acquisition and Supply	4.2	7.7	2.0	1.2
Technical Management	8.1	14.0	9.2	5.5
System Design	22.0	25.9	11.0	5.8
Product Realization	4.2	9.7	10.4	8.1
Product Evaluation	12.1	18.1	26.8	10.0

Maintenance
Annual Maintenance Effort = 9.0 Person-Months
Annual Maintenance Cost = $101488
Total Maintenance Cost = $2029774

Figure 38. Screenshot of the Systems Engineering Cost Inputs and Results

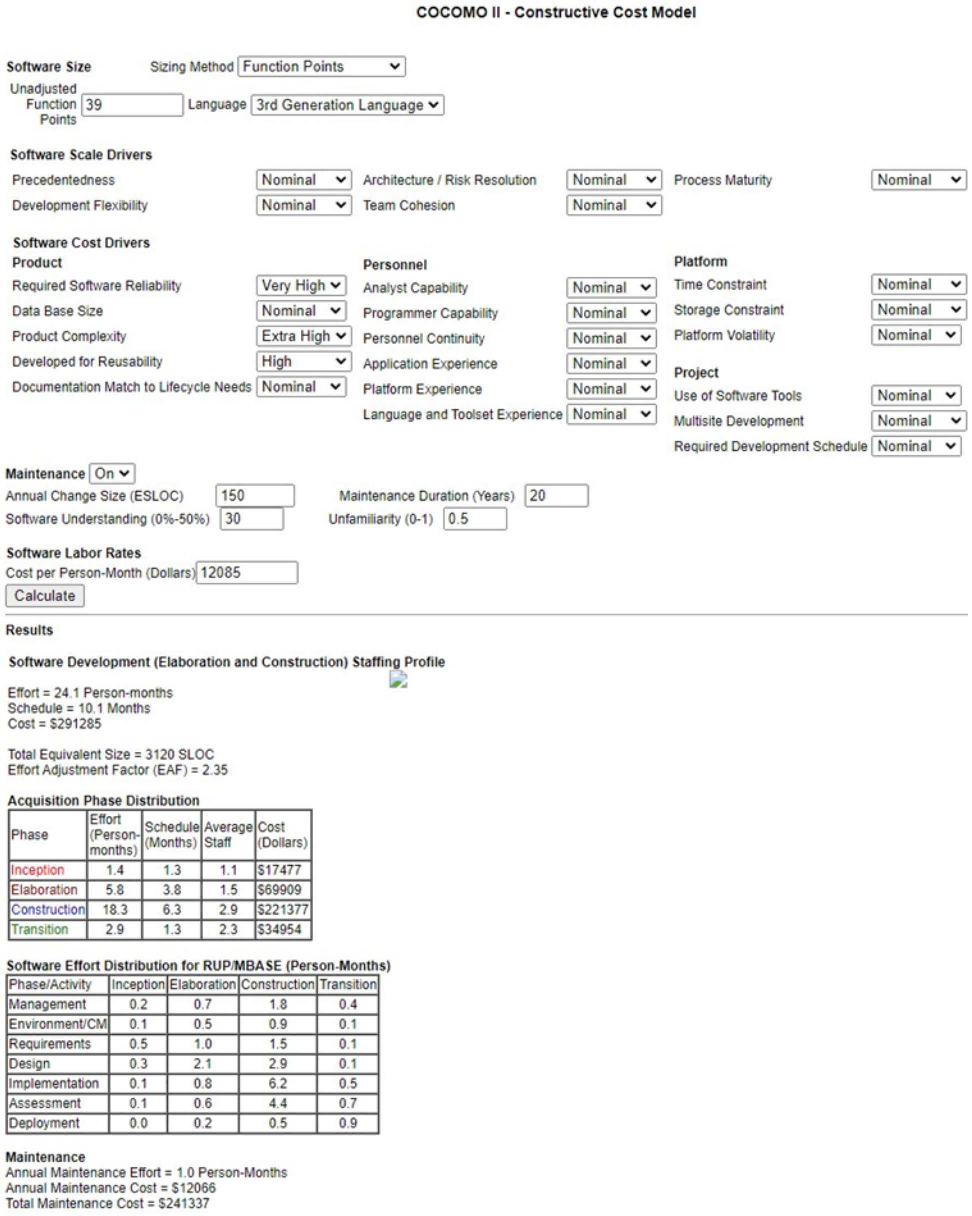
Based on the analysis of the system size, cost drivers, the maintenance, and the system labor rates, the results of this calculation for systems engineering was determined to be an effort of 216 person-months with an 8.8-month project duration. These inputs give a total system engineering cost of $2,429,459. The annual maintenance cost estimate was $112,765 and the total lifetime maintenance cost was $2,029,774.

3. Software Costs

Function points were used to determine the software size. "Function points are determined based on the amount of functionality in the respective project and the factors that determine the project" (Clark and Madachy 2015, 26–29). Using the established list of components and subsystems, an estimate of all the external inputs, external outputs, external inquiries, internal files, and external interfaces led to a count of 39 function points. Of the options given for a programming language, 3rd generation language was chosen because that option is platform independent and provides the most flexibility to use any language that falls into the category of 3rd generation (Burgeois n.d.).

Software scale drivers and software cost are measured on an ordinal scale of very low, low, nominal, high, and very high. Required software reliability was determined to be very high because of the risk to human life. The database size and documentation match to life cycle needs are set to nominal since those factors are unknown. The product complexity is extra high because of the multiple resource scheduling and performance-critical embedded systems. Finally, the design for reusability factor is high because of the requirement for the software to be reused across the program.

The maintenance of software was also turned on for the mine project due to the need for an analysis of the software life cycle. Because the estimated equivalent size was 3120 source lines of code, the amount of estimated annual change was selected to be 150 equivalent source lines of code (ESLOC) over the duration of 20 years, with a medium level of software understanding at 30%, and a nominal level of unfamiliarity at 0.5. The labor rate for the software engineer was determined similarly to the systems engineer with a value of $12,085 per person-month based on the average salary for software engineers in the U.S. being $145,000 (Glassdoor 2024). Figure 39 shows the input parameters entered into the COCOMO II section of the System Cost Model Suite.


COCOMO II - Constructive Cost Model

Software Size
Sizing Method: Function Points
Unadjusted Function Points: 39
Language: 3rd Generation Language

Software Scale Drivers
Precedentedness: Nominal
Development Flexibility: Nominal
Architecture / Risk Resolution: Nominal
Team Cohesion: Nominal
Process Maturity: Nominal

Software Cost Drivers

Product
Required Software Reliability: Very High
Data Base Size: Nominal
Product Complexity: Extra High
Developed for Reusability: High
Documentation Match to Lifecycle Needs: Nominal

Personnel
Analyst Capability: Nominal
Programmer Capability: Nominal
Personnel Continuity: Nominal
Application Experience: Nominal
Platform Experience: Nominal
Language and Toolset Experience: Nominal

Platform
Time Constraint: Nominal
Storage Constraint: Nominal
Platform Volatility: Nominal

Project
Use of Software Tools: Nominal
Multisite Development: Nominal
Required Development Schedule: Nominal

Maintenance: On
Annual Change Size (ESLOC): 150
Maintenance Duration (Years): 20
Software Understanding (0%-50%): 30
Unfamiliarity (0-1): 0.5

Software Labor Rates
Cost per Person-Month (Dollars): 12085

Results

Software Development (Elaboration and Construction) Staffing Profile

Effort = 24.1 Person-months
Schedule = 10.1 Months
Cost = $291285

Total Equivalent Size = 3120 SLOC
Effort Adjustment Factor (EAF) = 2.35

Acquisition Phase Distribution

Phase	Effort (Person-months)	Schedule (Months)	Average Staff	Cost (Dollars)
Inception	1.4	1.3	1.1	$17477
Elaboration	5.8	3.8	1.5	$69909
Construction	18.3	6.3	2.9	$221377
Transition	2.9	1.3	2.3	$34954

Software Effort Distribution for RUP/MBASE (Person-Months)

Phase/Activity	Inception	Elaboration	Construction	Transition
Management	0.2	0.7	1.8	0.4
Environment/CM	0.1	0.5	0.9	0.1
Requirements	0.5	1.0	1.5	0.1
Design	0.3	2.1	2.9	0.1
Implementation	0.1	0.8	6.2	0.5
Assessment	0.1	0.6	4.4	0.7
Deployment	0.0	0.2	0.5	0.9

Maintenance
Annual Maintenance Effort = 1.0 Person-Months
Annual Maintenance Cost = $12066
Total Maintenance Cost = $241337

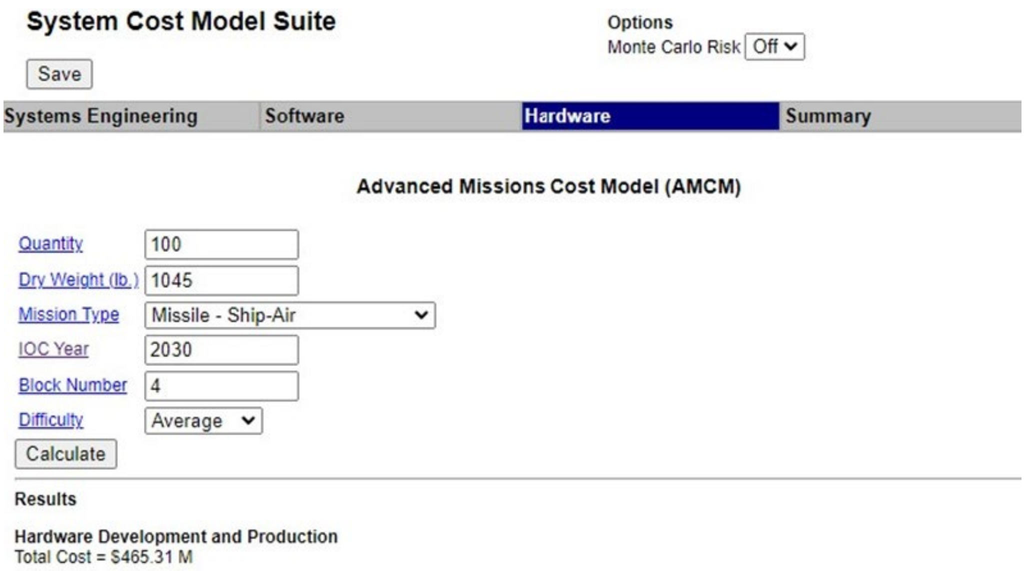
Figure 39. Screenshot of the Software Costs from the System Cost Model Suite

The effort result for the software is 24.1 person-months and 10.1 months project duration. At about three personnel on the software team, that cost becomes $291,285 for the creation of the software and an annual maintenance cost of $12,066 with a total maintenance cost of $241,337.

4. Hardware Costs

The Hardware tab of the System Cost Model Suite uses the AMCM developed by NASA to estimate life cycle costs of missions (Jones 2015) as the basis for the input variables. A quantity of 100 mines was estimated as the first order quantity, which had a dry weight of 1045 lbs. This number was calculated by taking the estimated payload and only including the weight of the empty "vehicle." The mission type that would be performed was selected as "Missile-Ship-Air." The missile provided a similar technological capability to the mobile mining system. An IOC year of 2030 was assumed based on the delivery of the first mine. Block number 4 was selected based on the number of iterations that it took for the past designs for mines in the early development of this technology (general purpose munitions that are already used in current mines, MK 63/4/5 along with the QuickStrike modifications, and MK 67 SLMM being the previous iterations). Finally, an average difficulty was assumed for developing this system.

It is important to note that this cost model does not account for maintenance costs for hardware. The inputs described were entered into the System Cost Model Suite as shown in Figure 40. Using the tool to calculate the value for the hardware development and production results in an estimated cost of $465.31 million.



System Cost Model Suite

Options
Monte Carlo Risk: Off

Advanced Missions Cost Model (AMCM)

Quantity: 100
Dry Weight (lb.): 1045
Mission Type: Missile - Ship-Air
IOC Year: 2030
Block Number: 4
Difficulty: Average

Results

Hardware Development and Production
Total Cost = $465.31 M

Figure 40. Screenshot of the Hardware Cost Parameters and Results from the System Cost Model Suite

5. Total Life Cycle Costs

Table 17 shows the total estimated cost of the 100-mine system will be $470.8 million. This number can be broken down into the acquisition cost of $468 million, with an annual maintenance cost (systems engineering and software) of $113,554 and a total maintenance cost of $2.27 million over the life cycle of the system.

Table 17. Summary of Cost Estimate from System Cost Model Suite

Description	Production & Acquisition Cost	Annual Maintenance Cost	Total Maintenance Cost	Total Life Cycle Cost
Systems Engineering	$2.4 million	$101,000	$2.0 million	$4.5 million
Software	$291,000	$12,000	$241,000	$533,000
Hardware	$465.3 million	Not Estimated	Not Estimated	$465.3 million
TOTAL	$468.0 million	$114,000	$2.3 million	$470.3 million

D. RISK ANALYSIS

Risk analysis for mobile sea mines is performed to ensure maritime safety. Given the potential devastating consequences of sea mine incidents, a comprehensive risk analysis is imperative. To achieve this, a Failure Modes, Effects, and Criticality Analysis (FMECA) approach will be employed. The FMECA assessment, as outlined in MIL-STD-882E is a systematic methodology that identifies potential failure modes of systems or components, assesses the effects, and evaluates the criticality based on factors such as probability of occurrence, severity of consequences, and detectability (Department of Defense [DOD] 2023). As part of the FMECA all subsystems' risk levels were categorized based on the assessment matrix shown in Table 18. This assessment matrix and approach is defined by MIL-STD-882E (11-13).

Table 18. Risk Assessment Matrix.
Adapted from DOD (2023).

	Severity Category			
Probability Level	Catastrophic	Critical	Marginal	Negligible
Frequent	High	High	Serious	Medium
Probable	High	High	Serious	Medium
Occasional	High	Serious	Medium	Low
Remote	Serious	Medium	Medium	Low
Improbable	Medium	Medium	Medium	Low

This approach enables the identification of critical failure modes, assessment of the potential impacts on maritime operations and infrastructure, and the development of mitigation strategies to enhance sea mine resilience and minimize any operational risk. This analysis provides the program manager and project personnel with an effective visual for communicating the program's risk and severity. Table 19 describes the FMECA assessment of the mobile mines.

Table 19. FMECA of Mobile Mine System

S/N	Functional System (Nomenclature)	Components and Functional Description	Failure Modes and Causes	Failure Outcome	Severity Category	Probability of Occurrence (Based on Probability of Failure)	Risk Assessment
1	Mechanical	Mechanical subsystem of a mobile sea mine, components like the aerial attenuator, sub-surface attenuator, horizontal fin, and vertical fin work together to control the mine's depth, stability, and orientation in the water. The attenuators adjust buoyancy, while the fins stabilize the mine and control its movement, ensuring effective operation in underwater environments.	Aerial attenuator failure, characterized by loss of buoyancy control, can result from corrosion, mechanical damage, or internal malfunctions. Similarly, sub-surface attenuator failure may occur due to fouling, leakage, or structural damage, leading to depth control issues. Horizontal and vertical fin failures, caused by mechanical damage, corrosion, or malfunctioning control mechanisms, can compromise stability and control during lateral and vertical movement.	Unable to maintain buoyancy control and position. May lead to loss of mine (sinking to bottom of sea) or detection of mine (floating on the surface).	Marginal	Occasional	Medium
2	Propulsion	The propulsion system of a mobile sea mine comprises two essential subsystems: the engine and propeller propulsion. This power is then transmitted to one or more propellers attached to the engine's output shaft. The propellers are meticulously designed to transform the rotational motion from the engine into thrust, propelling the sea mine through the water. Efficient coordination between the engine and propeller propulsion subsystems ensures effective underwater navigation, enabling the sea mine to fulfill its designated mission objectives with precision and reliability.	Failure modes include engine malfunction due to component wear, corrosion, or mechanical damage, resulting in reduced power output or complete engine failure. Propeller-related failures may arise from blade damage, fouling, or misalignment, leading to decreased thrust efficiency or loss of propulsion. Causes for these failures may stem from environmental factors such as marine fouling or harsh operating conditions, design flaws, or manufacturing defects	Engine failures results in the mine becoming stranded or unable to reach its intended destination. Loss of propulsion due to propeller-related issues can render the mine unable to maintain its position or navigate as intended, potentially leading to drift or deviation from its intended course	Critical	Occasional	Serious

S/N	Functional System (Nomenclature)	Components and Functional Description	Failure Modes and Causes	Failure Outcome	Severity Category	Probability of Occurrence (Based on Probability of Failure)	Risk Assessment
3	Comms	The comms system of the sea mine is required for maintaining connectivity and situational awareness. The acoustic transceiver and processor facilitate underwater communication with nearby vessels or assets, while the radio frequency (RF) transceiver and processor enable communication with surface vessels or aircraft over longer distances. Additionally, the GPS receiver provides precise positioning data, aiding navigation and mission execution.	The comms system failure modes and associated causes includes acoustic transceiver malfunction due to water ingress or sensor damage, RF transceiver failure resulting from electromagnetic interference or component degradation, and GPS receiver errors stemming from signal obstruction or hardware faults. Causes could also involve environmental factors such as extreme temperatures, mechanical stresses, or exposure to corrosive elements.	Failures in the communications system could lead to a loss of data transmission capabilities, compromised command and control functions, or reduced situational awareness.	Marginal	Occasional	Medium
4	C2	The C2 system of a mobile sea mine consists of two key subsystems: the Central Processing Unit (CPU) and the Data Memory Disk. The CPU serves as the system's core, executing commands, processing data, and coordinating operations. It interprets incoming data, executes predefined algorithms, and manages tasks across subsystems. Meanwhile, the Data Memory Disk subsystem provides storage for critical operational data and mission plans, ensuring quick access to real-time information and archival storage for historical records.	Failure modes include CPU malfunctions, such as processor overheating, hardware failure, or software errors leading to system crashes. Data Memory Disk failures could arise from storage media corruption, read/write errors, or physical damage. Causes of these failures may stem from component degradation over time, environmental factors like temperature and humidity, electromagnetic interference, or manufacturing defects.	CPU failure results in a loss of command processing capability, leading to the inability to execute critical functions. This renders the mine unresponsive to external commands. Similarly, a failure in the data memory disk could lead to the loss or corruption of vital mission data, including navigational waypoints, target information, or operational parameters. Such data loss impairs decision-making processes and hinders situational awareness.	Critical	Occasional	Serious

S/N	Functional System (Nomenclature)	Components and Functional Description	Failure Modes and Causes	Failure Outcome	Severity Category	Probability of Occurrence (Based on Probability of Failure)	Risk Assessment
5	Navigation	The navigation system provides accurate positioning, orientation, and movement tracking. It comprises an altimeter for altitude measurement, a flow rate sensor for monitoring water flow, an Inertial Measurement Unit (IMU) with sensors like accelerometers and gyroscopes for motion and orientation sensing, an IMU processor for sensor data fusion, and a GPS processor and receiver for satellite-based positioning. Together, these subsystems provide real-time data on the mine's location, velocity, and attitude, enabling precise navigation.	Failures due to sensor malfunctions, such as sensor drift or calibration errors in the altimeter, flow rate sensor, or IMU sensors. Additionally, failures in signal processing components, such as the IMU processor or GPS processor, could lead to inaccurate data fusion or loss of satellite signal reception, resulting in navigation errors. Environmental factors like electromagnetic interference or physical damage from water pressure or impact may also contribute to system failures.	Sensor malfunctions or signal processing errors may lead to inaccurate positioning, navigation, and velocity estimation. The mine may deviate from its intended course or fail to navigate safely through its environment, rendering it ineffective.	Marginal	Occasional	Medium
6	Power	The power system of a mobile sea mine, equipped with Li-ion batteries, serves as the primary electrical energy source for various onboard subsystems and components. These batteries store and provide power to essential systems such as propulsion, communication, control units, and sensors, ensuring the mine's operation throughout its lifespan. Managed by battery management systems, these batteries maintain optimal performance and safety features, including overcharge and over-discharge protection.	Failures include battery cell degradation, overcharging, over-discharging, short circuits, and mechanical damage. Cell degradation can occur due to factors like aging, frequent charging cycles, leading to reduced capacity and voltage output. Overcharging and over-discharging may occur due to malfunctioning charging systems or improper battery management, causing stress on the cells and reducing lifespan. Short circuits, caused by physical damage or manufacturing defects, can lead to sudden power loss. Mechanical damage from shock, vibration, or impact can also compromise battery integrity.	In cases of battery cell degradation, the outcome may include reduced battery capacity and voltage output, leading to decreased operational duration and compromised performance of the sea mine.	Critical	Occasional	Serious

S/N	Functional System (Nomenclature)	Components and Functional Description	Failure Modes and Causes	Failure Outcome	Severity Category	Probability of Occurrence (Based on Probability of Failure)	Risk Assessment
7	Weapon	The weapon system of a mobile sea mine comprises passive and active acoustic sensors, a magnetic field sensor, an electric field sensor, a trigger processor, a trigger assembly, and a warhead. These subsystems collectively detect, identify, and engage targets. Passive and active acoustic sensors detect underwater signals, while the magnetic field sensor identifies metallic objects, and the electric field sensor detects changes in the electric field. The trigger processor analyses sensor data to determine target presence, prompting the trigger assembly to initiate detonation of the warhead upon confirmation.	Failures in the passive and active acoustic sensors could result from sensor degradation, signal interference, or physical damage due to environmental factors or enemy action. Similarly, the magnetic field sensor and electric field sensor may fail due to component wear, electromagnetic interference, or exposure to harsh conditions. Failures in the trigger processor may occur due to software errors, hardware malfunctions, or power supply issues. The trigger assembly could malfunction due to mechanical faults, corrosion, or improper handling. Warhead failures may stem from manufacturing defects, aging explosives, or improper detonation sequencing.	Failures in the sensors may lead to reduced detection capabilities, compromising the mine's ability to identify and engage targets effectively. Malfunctions in the trigger processor or assembly could result in the failure to detonate the warhead when needed, rendering the mine inert or reducing its effectiveness. In the worst-case scenario, a complete system failure could result in the mine being unable to perform its intended function, leading to a loss of mission capability and potentially allowing hostile targets to evade detection or counter the mine's effects. Additionally, if a failure results in an unintended detonation of the warhead, it could cause collateral damage or harm to friendly forces or civilians in the area.	Catastrophic	Occasional	High

For the risks assessed to be high and serious, risk mitigation measures should be taken to manage these risks effectively. Examples of such measures like enhanced design features, improved deployment protocols, and heightened monitoring and maintenance procedures. Through these risk management practices, operators can mitigate high and serious risks during the operation and deployment of mobile mines.

E. SUMMARY

The simulations and additional analyses for the mobile mine concepts brought together information that would be presented to a stakeholder on the mobile mine and on the system's necessary risks, technology readiness levels, and cost associated with the concept. The simulations resulted in testing the theory that a high density of mines provided a significant decrease to enemy force, proving that the mobile mine concept provides a significant increase in mission achievability over static mining. The technology readiness level analysis provided an assessment on the feasibility of this technology coming to fruition due to all the technology being a high TRL, it provides assurance on a system that will be able to perform even though the components have not been integrated in this configuration previously. It is important to note for the stakeholder that additional work would need to be done on the configuration of the system to get it to a higher TRL. The cost estimate provides the stakeholder with an understanding of the monetary value that would be associated with the cost to make the technology, put together as a system, a viable product that could be procured. Finally, the analysis of risks from the FMECA study provides the stakeholder notification up front of the risks that will need to be mitigated and the planning that should be done to ensure the deployment of the mines is done correctly.

VI. CONCLUSION AND RECOMMENDATIONS

This chapter summarizes the project team's analysis of proposed mobile mine designs. It explores both the physical design concepts and the operational effectiveness of their mobility based on simulations and models. The chapter also provides recommendations for further research in this area.

A. SUMMARY OF ANALYSIS

1. Physical Architecture Analysis

Deriving the system requirements from stakeholders, operations, and the operating environment, a list of functional requirements was generated and the requirements further corresponded to the components and subsystems of the proposed mobile mine design. To ascertain the finer details for key aspects of design—munition sizing, energy and power requirement, and buoyancy—further analyses were done. The team was successful in generating and specifying a conceptual design of a mobile mine capable of being delivered from various platforms (i.e., aerial, surface, and subsurface) well before the forward edge of the battle area (FEBA; up to 50 nm), travel to the deployment site independently, and operate autonomously for up to 90 days while withstanding undersea currents of up to 3 knots. The mobile mine is also capable of repositioning itself using propulsion systems when it senses mine countermeasure (MCM) activities, existence of a Q-route, or when another mobile mine is destroyed.

2. Simulation Results Analysis

In analyzing the simulation results from Chapter V, the study demonstrates the potential effectiveness of mobile mines, should they be developed and included in the naval weapons inventory. In general, static mines present a fixed initial threat that decreases over time, whereas one of the major benefits achieved by employing mobile mines is that this threat level remains relatively constant throughout the scenario.

Compared to a static minefield, the introduction of mobile mines brought about a distinct increase in operational challenges and threat levels. From the outset, even the lowest density of mobile mines presented a severe challenge, with 3.5 vessels on average being neutralized and inducing significant delays of approximately 218 minutes compared to 1.2 vessels and 154 minutes in the static scenario, which corresponds to a 192% and 42% increase, respectively. One of the most significant findings from the analysis, however, was that it only required one mobile mine per sector to inflict the same attrition as four static mines per sector. As the density of mobile mines increased, the threat intensified dramatically, leading to nearly complete annihilation of adversary forces (average of 9.8 out of 10 vessels neutralized) and extensive delays induced, peaking at an average of 574 minutes at the highest density compared to 3.4 vessels and 400 minutes for the same configuration of static mines, in other words a 188% increase in lethality and a 44% increase in induced delay. Across all sector densities, mobile mines were on average 228% more lethal and caused 49% longer induced delays than their static counterparts. This stark escalation underlines the dynamic and formidable nature of mobile mines, which, unlike static mines, can adapt their strategies in real time to counteract naval maneuvers and countermeasure tactics effectively. Of note, although the mobile mines consistently proved to be more effective than their static counterparts, due to the scripted nature of simulated adversary actions, the team assesses that the results for attrition are likely optimistic and the delay estimates likely pessimistic since MCM efforts would take significantly longer than simulated and sequential transiters likely would not proceed until a certain level of confidence in the aforementioned MCM efforts has been achieved.

These simulation results suggest that if mobile mines were developed and incorporated into the naval weapons inventory, they could significantly enhance naval operational capabilities by creating more adaptable and formidable defense mechanisms. This analysis serves as a key insight for naval operational planners and technologists, highlighting the need to further explore mobile mine technologies and develop strategies that can leverage their unique capabilities.

B. RECOMMENDED FUTURE RESEARCH

1. Continued Mobile Mines Study

a. Additional Modeling and Simulation

Due to limitations in the Modeling and Simulation Toolkit (MAST) software specifically regarding state changes and interaction between units, neither the mobile mine behavior nor the enemy MCM behavior could be fully modeled. These limitations had the effect that the mobile mine behavior could not be refined or optimized. A purpose-built simulation that is not limited by preexisting asset classes would be more flexible and allow for a complete assessment of the mobile mine behavior performance. This simulation would allow the logic to be optimized and tuned to specific tactical scenarios. This model could also be used to then create the mobile mine asset class in MAST for latter operational analysis.

b. Mobile Mine Prototype

The feasibility analysis found that all the individual systems of the mobile mine design exist with a high technology readiness level (TRL). However, the integration of these systems in the form factor of the mine is novel. A prototype mobile mine that could demonstrate the integration of the systems and the basic mobility performance of a group of mines would reveal possible integration and performance challenges of the current design. These prototypes could be used to identify emergent behaviors that are not accounted for in the simulations and iterate on the design to solve performance or integration issues and raise the overall TRL of the mobile mine system. The results of the prototype testing could then be used to further inform future modeling and simulation efforts.

c. Command and Control

The assessment of the mobile mine solution was done primarily considering no communications between the mines or with any controlling unit. However, significant additional value could be added by the capability to communicate with the mines. This capability should never be required for operation but the additional functions that could be realized include the ability to redeploy or move the minefield, reprogramming the minefield, battle damage assessment (BDA), and other intelligence collection. Current communication systems would require a friendly manned surface or subsurface vessel to be in the vicinity of the minefield. The development of a remote relay system that would allow friendly assets to control the minefield from a safe distance could take the form of a system like a sonobuoy or gateway buoy. Another solution could be an unmanned underwater vehicle (UUV) that travels through the minefield transmitting instructions, collecting information, and then returning to a host platform for analysis.

d. MAST Simulation

Building on the foundations laid in previous simulations and research, including those documented by Deken et al. (2021), the future studies of mobile mines within MAST should incorporate several enhancements to increase realism and provide more detailed data analysis. The following recommendations aim to refine the simulation capabilities and extend the scope of scenarios explored.

- **Variations in Mine Depth:** Future simulations should introduce variable mine depths as a core parameter. Adjusting mine placement depth will allow for a comprehensive analysis of mine effectiveness, responsiveness, and detectability. This variation can help assess how depth influences the strategic placement of mines and their interaction with different naval platforms.

- **Advanced Sensor Technologies:** Incorporating a broader range of sensor options that reflect the latest technological advances in mine and mine detection could enhance the simulation’s relevance. By simulating various sensor types, researchers can analyze their performance under different combat conditions. This change could help validate current detection systems and identify improvement areas. Such simulations could refine mines’ tactical applications, boosting their effectiveness in real-world scenarios. Understanding these dynamics aids in developing more effective countermeasures and strategies, improving naval operational readiness and safety.

- **Weather Effects Integration:** Adding weather effects into the simulation parameters will provide insights into how environmental factors influence mine efficacy and detection. This addition will help simulate more realistic naval operations and evaluate the robustness of mine technologies under diverse weather conditions.
- **Inclusion of Commercial and Private Vessels:** To further enhance the realism of the simulation environment, future studies should include commercial and private vessel agents. This inclusion will allow for the analysis of mines' behavior in more complex traffic scenarios and their potential impacts on non-military maritime activities.
- **Inclusion of Mixed Minefields:** The cost-effectiveness of legacy static mines should still be considered a viable solution for minefield deployment. The performance benefits of mobile mines could be coupled with the low cost of static mines to create a more inexpensive but still resilient mixed minefield. This should be assessed against the performance of the mobile minefield with cost as part of the assessment criteria.
- **Inclusion of Other MCM Platforms:** The performance of the mobile mines was assessed using traditional surface MCM vessels because this reflects the current capabilities of the People's Liberation Army Navy (PLAN) and what is believed to be the worst-case scenario for the minefield. With the increased use of UUV mine hunting platforms and the significant operational differences that they create in the way MCM is conducted, the mobile minefield should be assessed against this emerging threat.

Implementing these suggestions will enhance the accuracy and comprehensiveness of the simulation environment. Additionally, it will increase the strategic value of MAST by providing deeper insights into the operational dynamics of naval mines under varied and realistic conditions. These improvements will support the development of more effective mine warfare strategies and technologies, catering to the evolving needs of modern naval defense.

2. Surface Mine Delivery

The mobile mine system was designed to be platform agnostic to provide the greatest operational flexibility by not restricting delivery to any particular platform. However, due to a lack of supporting systems, surface delivery from existing platforms is not trivial. Current U.S. surface platforms would have to launch the mines via crane operation, which is slow and cumbersome. Amphibious class ships could possibly launch mobile mines via the well-deck, but no current procedures exist. A rapid surface mine delivery system needs to be developed to make surface vessel mine delivery a viable alternative for seeding an operational minefield. Possible solutions could take the form of a modular universal mine rail system or a containerized mine delivery and support system.

3. Mine Recovery

Currently mine recovery is performed by explosive ordinance divers (EOD) and an MCM ship or by a mobile diving and salvage unit (MDSU). The mobile mine was designed in such a way to facilitate surface recovery by floating to the surface in permissible water space. This aids recovery in that it does not require the use of divers or mine hunting sound navigation and ranging (SONAR) but would still likely require either an MCM ship or a MDSU to recover the mine from the water. With the sundown of the AVENGER class MCM ships, the U.S. Navy will soon only have the few MDSUs as mine recovery units. Systems and procedures need to be developed to allow common surface platforms to be able to recover the floating mines from the water. An example of a similar system is the net used by the MH-60 to recover exercise torpedoes.

4. Recommended MAST Expansion

To significantly enhance the functionality and utility of MAST, we recommend the following key expansions.

- **Collaborative Capability:** Introduce a feature allowing users to share simulation environments and agent builds in real-time. This feature could be facilitated by enabling environment-specific passwords for selective user access; implementing a global user menu, akin to an email address list, for straightforward access among authorized users; and establishing admin-controlled user groups that can collaborate on projects in real-time via a cloud server, with access managed through preset usernames and passwords.

- **Real-Time Software Updates:** Ensure MAST supports seamless integration of real-time updates, including firmware, plugins, and software upgrades. These updates should be designed to integrate smoothly without causing disruptions or malfunctions, maintaining MAST's reliability and cutting-edge status.
- **Enhanced Mapping Integration:** Expand MAST's capability to include compatibility with external mapping services like Google Earth. This integration would allow users to download or share up-to-date, real-time maps directly within the MAST environment, enhancing the geographical accuracy of simulations.
- **Internal Data Analysis Package:** Incorporate a robust data analysis package within MAST to enable comprehensive internal data analysis. This functionality would eliminate the need for data export to other software for analysis, simplifying the workflow and enhancing MAST's standalone capabilities.

These proposed expansions aim to transform MAST into a more dynamic, collaborative, and efficient tool, suitable for the complex demands of contemporary defense simulations and strategic analysis.

C. CONCLUSION

In conclusion, this report has presented a comprehensive analysis of the proposed mobile mine design including functional analysis (design, delivery, durability, doctrine, and disposal), non-functional analysis (reliability, maintainability, supportability, compatibility), risk analysis, and cost estimation. The team explored both the physical design concepts and their operational effectiveness through simulations and models. The results demonstrate the potential of mobile mines to significantly enhance maritime warfare capabilities. Their adaptability and autonomous operation provide resilience to traditional MCM tactics; therefore, the mobile minefield can effectively increase the number of enemy ships destroyed and extensively delay the enemy's movement.

The team recommends further research and investment in the mobile minefield concept and technology for its operational enhancement to naval mine warfare. Expanding the functionalities of the MAST simulation software will allow for more detailed and realistic assessments of mobile mine performance. Additionally, exploring alternative modeling approaches and incorporating considerations for command and control systems will provide a more holistic understanding of mobile mine effectiveness. Finally, investigating efficient surface delivery and recovery methods is crucial for the practical implementation of mobile mine technology. These combined efforts will pave the way for the development of robust mobile mine warfare strategies and technologies, bolstering naval capabilities in the face of evolving maritime threats.

APPENDIX A. ENERGY AND POWER SYSTEM ANALYSIS

The size, weight, and power specifications of a system is an important aspect that influences the requirements of many supporting subsystems and external systems. Given a blank slate to begin designing the mobile mine system with little information available increases the challenge to provide an optimized design. Nevertheless, this appendix provides the thought process and estimations done to specify the energy and power system of the mobile mine.

A. OBJECTIVE OF ANALYSIS

The analysis objective is to provide the system design with engineering estimates on the energy and power system based on assumptions made on the weight, propulsion, and the power consumption of key components.

B. ASSUMPTIONS OF ANALYSIS

1. Platform Agnostic

Given the variety of delivery methods from air/land/sea/underwater. One of the constraints considered is to ensure that the mine can fit in the most restrictive form of delivery. In this case, the mine should fit into a torpedo tube as it is the most restrictive form of delivery. Consequently, for the power analysis, a munition that has a maximum length of 250 inches and a diameter of 21 inches (Bureau of Ordnance 1944) will be examined. The length is derived from the maximum effective length of a bow tube, while the diameter is the standard diameter of torpedoes. The dimensions are similar to the Mark 48 Torpedo, which has a length of 228 inches.

2. Warhead

The warhead design for the mobile mine will be a high explosive shaped charge. We used directed sea mines/torpedoes still within the U.S. Navy's service to provide a sensible range: a) Mark 50 torpedo (100 lb warhead) meant for fast deep-diving submarines; b) Mark 54 torpedo (96.8 lb warhead) meant for slow conventional submarines; c) Mark 48 torpedo (647 lb warhead) meant for nuclear-powered submarines and high performance surface ships; d) Mark 60 CAPTOR naval mine (97 lbs) meant for submarines; and e) Mark 67 Submarine Launched Mobile Mine (510-lb warhead). The weight of the warheads ranges from 96.8 to 647 lbs. As such, it was assumed that the warhead weight would be 330 lbs of explosives content, and it was assumed that they would have a density of 62.4 to 124.8 $\mathrm{lb/ft^3}$ (Olinger 2005).

3. Effective Range of Detection

This will be limited by the type of sensors we use. Based on the focus on increasing operational endurance, the mobile mine will use a combination of passive acoustic and electromagnetic sensors. Based a study by Lowes and Neasham (2024), at a depth of 8 meters, the new Passive Acoustic Detection and Localization (PADAL) system could detect vessel activity in a 1.08 nm radius with a power consumption of 0.19 W. While there was difficulty in finding extensive information on the range and power consumption of electromagnetic sensors, nevertheless, based on a report on the PLAN mining capabilities (Erickson, Murray, and Goldstein 2009), the effective range of electromagnetic influence mines was reported to be around 1312 feet.

4. Total Weight of System

Based on weight estimation based on proportion of warhead weight to the overall system weight, the Mark 67 Submarine Launched Mobile Mine (SLMM), which had a total weight of 1,662 lbs and warhead weight of 510 lbs was used as a close reference. As such, it was estimated that the total system weight for the mobile mine is 1075 lbs.

$$\frac{330lb}{KMM\ weight(lb)} = \frac{510lb}{1{,}662lb} \rightarrow MM\ weight\ (lb) = 1075$$

C. SYSTEM POWER REQUIREMENT

The system power requirements are summarized in Table 20.

Table 20. System Power Requirements

Key System Component	Description
Wireless Signal Transmitter/Receiver	MIT Low-Power Underwater Acoustic Communication System: 1.8 W to transmit data at 500 bps over 984 feet (Gent 2023)
Navigational Sensors (Self-Position/ Velocity/Angular Rate/Heading/Flow Rate)	Approximately 30 W of power rating
Passive Detection Sensor (Magnetic Field/Acoustic/Electric Field)	Acoustic Sensor approximately 0.19 W Magnetic Sensor approximately 200 mW (Li et al. 2023)
IFF Receiver	IFF Receiver (similar to Acoustic Sensor)
Buoyancy Control Module	Maximum Operating Pressure is 3046 psi; Mass Flow rate of 12.45 to 20.01 lb/min requires around 369 W to 594 W of power.

Based on the assumption that our system weighs around 1075 lbs as well as the researched approximate power requirements of the various systems, it would be safe to assume that majority of the power requirements would be due to the buoyancy control module and the propulsion control module. This is echoed by Carelli (2019, 33), who claims that "the endurance (of a UUV) is dependent on the size of the battery, the power required for propulsion, and the power required for the payload." Therefore, we conduct the power requirements analysis based on the requirements for propulsion.

It was further assumed that the non-propulsion and non-buoyancy related operations will take up to 30% of total power. Given that the mobile mine might be required to surface or reposition itself on the seabed multiple times, the buoyancy operations would require around 20% of the total power consumption. This leaves 50% of the total power for propulsion.

It was assumed that the mobile mine can travel at least 3 knots during redeployment using the propeller propulsion system. An approximate required thrust was given by:

$$Thrust = \frac{\rho}{2} \times C_d \times S \times U^2 \approx 18.20 \text{ lb-f}$$

Where,

Density of sea water, ρ = 63.68 lb/ft^3

Drag coefficient, C_d = 0.15 to 0.3 (most conservative term of 0.3 will be used)

Frontal surface area, S = π× 〖10.5”〗 ^2 ≈ 346.36 sq-inches

Speed (U) = 3 knots

Therefore, the thrusters/propellers used will be required to provide at least 18.20 lb-f of thrust. A suitable commercial thruster, T500 from Blue Robotics (Jehangir 2022), was able to achieve a maximum performance of 35.5 lb-f of thrust with only a power consumption of 1 kW.

D. BATTERY AND ENDURANCE ANALYSIS

Assuming that the total distance for deployment and redeployment is 50 nautical miles. At a speed of 3 knots, the propulsion system would require approximately ≈ 16.7 kWh of electrical energy. Assuming this contributes 50% of the total power as assumed earlier, the battery capacity required would be approximately 33.4 kWh. The power available for the sensors would be 10.02 kWh, given the power requirements of the sensors and navigational equipment, a reasonable estimate of the power required would be 50 W.

$$\frac{50\ nm}{3\ nm/hr} \times 1kWh \approx 16.7\ kWh$$

Given that a lithium/water battery has a power density of 0.907 kWh/lb and 42.48 kWh/ft^3 (PolyPlus n.d.), every lb of battery takes up around 0.02135 ft^3 of volume. It was estimated that around 36.82 lbs of batteries will be required for the mobile mine and that will last the system for approximately 8.35 days. This endurance could be increased by 0.77 days for every additional lb of battery. For a mobile mine system that has 90 days of endurance, approximately 143.3 lbs of batteries will be required (taking up only 3.06 ft^3 of volume). Looking at the volumetric requirements of battery, with the total system having a maximum volume of 50.11 ft^3, there is plenty of space for additional batteries to be included to extend the system endurance. However, this will be a trade space between volume of the system and buoyancy control effort that will be further elaborated in Appendix B.

APPENDIX B. BUOYANCY CONTROL DESIGN AND ANALYSIS

Based on earlier assumptions and estimates on energy and power system analysis, a trade space between buoyancy control effort and system volume was identified. As such to propose a suitable buoyancy control design, a buoyancy analysis must be done for the mobile mine. To reduce power consumption, a design goal of making the system slightly positively buoyant was set, and floating and sinking the mobile mine can be controlled by manipulating the buoyancy of the mobile mine to achieve ± 22 lbs of buoyancy.

Based on the maximum possible volume and weight estimate, the system was found to be positively buoyant and will need to reduce buoyancy by around 2116 lbs.

Density of surface seawater $\rho \approx 63.68\ \mathrm{lb/ft^3}$

Volume of system$\nabla \approx 50.11\ \mathrm{ft^3}$ (based on 21 inches diameter and 250 inches maximum length)

Buoyancy (lb) $= \nabla\rho - M = 63.68\ \mathrm{lb/ft^3} \times 50.11\ \mathrm{ft^3} - 1075 = 2116$

Given that the highest buoyancy that needs to be achieved is 22 lbs, the estimated new volume of the system can be derived as approximately 17.23 $\mathrm{ft^3}$, resulting in a reduction of system length to around 86 inches. To effectively control the buoyancy of the system, around 0.706 $\mathrm{ft^3}$ of volume will be required for the buoyancy control subsystem to ingest sea water to reduce buoyancy to sink the mobile mine. This can be done easily using an internal container and piston (akin to a syringe) system that uses an electronic motor to draw the piston in or push it out.

A volumetric analysis of the system was done to estimate if the smaller system volume was viable. The analysis, as summarized in Table 21, showed promise that there is sufficient space for the system to contain all its components. Further studies in the mobile mine can get better estimates of the components and conduct balancing analysis to create a prototype of the system that does not overexert the control surfaces and propulsion systems.

Table 21. Summary of Weight and Volume from Volumetric Analysis of the Mobile Mine System

Item	**Weight (lbs)**	**Volume (ft^3)**
Total	1075	17.23
Batteries (PolyPlus n.d.)	143.3	3.06
Buoyancy Control "Ballast Tank"	-	0.706
Warhead (Density = 124.8 $\mathrm{lb}/\mathrm{ft}^3$; Olinger 2005)	330.7	2.650
Allowance for all other equipment	601	10.81

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