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ASSIGNING UNMANNED UNDERSEA VEHICLES (UUVs) TO MINE DETECTION OPERATIONS

by

J. Enrique Reyes Diaz

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Thesis Advisor: Robert F. Dell
Second Reader: Don Brutzman

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In an era when mines are inexpensive and easily accessible, present mine detection and area reconnaissance capabilities are insufficient to enable unencumbered maneuver in the littoral regions. Unmanned undersea vehicles (UUVs) possess potential to provide tactical commanders with full understanding of the mine threat without risk to ships or personnel and without exposing intentions. By integrating an assortment of emerging capabilities, a system comprised of a variety of UUVs could address this mine threat. This thesis develops and implements the Mine Reconnaissance System Assessment (MiRSA) model, a mixed integer-linear program, to assign a mix of UUVs to search areas within a suspected minefield. Using unclassified UUV performance estimates, this thesis compares combinations of two Long-term Mine Reconnaissance System (LMRS) vehicles, six Remote Environmental Monitoring Units (REMUS) vehicles, and a notional Manta vehicle. For a 262 square nautical mile area in the Straits of Hormuz, MiRSA finds the two LMRS vehicles can complete a 95% confidence level search in 91 hours, the Manta vehicle can complete the search in 130 hours, and the two LMRS vehicles with Manta employed optimally together require only 52 hours. For an exhaustive search, times rise sharply: Manta operating alone requires 1,004 hours and optimal employment of the two LMRS, six REMUS, and Manta vehicles finish the search in 384 hours.

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**ASSIGNING UNMANNED UNDERSEA VEHICLES (UUVs)
TO MINE DETECTION OPERATIONS**

J. Enrique Reyes Diaz
Lieutenant, United States Navy
B.S.E, University of Michigan, December 1991

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Author: J. Enrique Reyes Diaz

Approved by: Robert F. Dell, Thesis Advisor

Don Brutzman, Second Reader

(OR BW for OR)
Richard E. Rosenthal, Chairman
Department of Operations Research

ABSTRACT

In an era when mines are inexpensive and easily accessible, present mine detection and area reconnaissance capabilities are insufficient to enable unencumbered maneuver in the littoral regions. Unmanned undersea vehicles (UUVs) possess potential to provide tactical commanders with full understanding of the mine threat without risk to ships or personnel and without exposing intentions. By integrating an assortment of emerging capabilities, a system comprised of a variety of UUVs could address this mine threat. This thesis develops and implements the Mine Reconnaissance System Assessment (MiRSA) model, a mixed integer-linear program, to assign a mix of UUVs to search areas within a suspected minefield. Using unclassified UUV performance estimates, this thesis compares combinations of two Long-term Mine Reconnaissance System (LMRS) vehicles, six Remote Environmental Monitoring Units (REMUS) vehicles, and a notional Manta vehicle. For a 262 square nautical mile area in the Straits of Hormuz, MiRSA finds the two LMRS vehicles can complete a 95% confidence level search in 91 hours, the Manta vehicle can complete the search in 130 hours, and the two LMRS vehicles with Manta employed optimally together require only 52 hours. For an exhaustive search, times rise sharply: Manta operating alone requires 1,004 hours and optimal employment of the two LMRS, six REMUS, and Manta vehicles finish the search in 384 hours.

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LIST OF ACRONYMS

ESA	Elemental Search Area
ETOTITL	Estimated Time on Target In The Lap
GAMS	General Algebraic Modeling System
LMRS	Long-term Mine Reconnaissance System
Manta	Advanced Capabilities Unmanned Undersea Vehicle Concept
MCM	Mine Countermeasures
MCM 1	Mine Countermeasures class (USS AVENGER lead ship)
MHC 51	Coastal Mine-hunting class (USS OSPREY lead ship)
MiRSA	Mine Reconnaissance System Assessment
REMUS	Remote Environmental Monitoring Units
SMA	Suspected Minefield Area
SMAMT	Suspected Minefield Area Mission Time
SZ	Search Zone
SZCT	Search Zone Completion Time
UUV	Unmanned Undersea Vehicle

EXECUTIVE SUMMARY

In an era when mines are inexpensive and easily accessible, present mine detection and area reconnaissance capabilities are insufficient to enable unencumbered maneuver in the littoral regions. Unmanned undersea vehicles (UUVs) possess potential to provide tactical commanders with full understanding of the mine threat without risk to ships or personnel and without exposing intentions. By integrating an assortment of emerging capabilities, a system comprised of a variety of UUVs could address this mine threat.

Recent UUV employment studies focus primarily on developing a specific UUV architecture (i.e., selection of sensors, power sources, communication systems, and navigation systems). These studies use simulation-based tools to evaluate the performance of UUV architectures, to help identify preferred UUV architectures, and to specify performance characteristics. The analysis in this thesis differs from previous efforts by using optimization to assign a variety of UUVs working together to conduct mine detection operations.

This thesis develops and implements the Mine Reconnaissance System Assessment (MiRSA) model. MiRSA is a mixed integer-linear program that assigns UUVs to search areas within a suspected minefield. Using unclassified UUV architectures, MiRSA evaluates combinations of two Long-term Mine Reconnaissance System (LMRS) vehicles, six Remote Environmental Monitoring Units (REMUS) vehicles, and a notional Manta vehicle searching 262 square nautical miles in the Straits of Hormuz.

MiRSA finds two LMRS vehicles can complete a 95% confidence level search of the Straits of Hormuz in 91 hours and the Manta vehicle requires 130 hours. If two vehicle architectures are available, the two LMRS vehicles with Manta employed together require only 52 hours. When only the LRMS or the Manta is to be operated with the REMUS vehicles, MiRSA finds the LMRS and REMUS combined system requires 78 hours and the Manta and REMUS combined system requires 100 hours. Employing two LMRS vehicles, six REMUS vehicles, and Manta together finish the search in 47 hours.

For an exhaustive search, mission times rise sharply. Two LMRS vehicles require 794 hours while the Manta vehicle requires 1,004 hours. The two LMRS vehicles with Manta employed together require only 436 hours. Employing two LMRS vehicles with REMUS requires 644 hours, the Manta vehicle with REMUS requires 780 hours, and all three UUV architectures finish the search in 384 hours.

The value of a mixed integer-linear programming approach is twofold. The MiRSA model provides a tool for rapidly assessing the benefit of employing combinations of UUV architectures. In addition, for a specific scenario and UUV characteristics, MiRSA model results provide tactical commanders with a decision-aid for assigning UUVs to mine detection operations.

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Lastly, many thanks to my family, dear friends and the Good Lord. You've suffered with me in difficult times and we celebrate our triumphs together.

DISCLAIMER STATEMENT

Unmanned undersea vehicle performance parameters included in this thesis are estimates derived from unclassified sources.

I. INTRODUCTION

In an era when mines are inexpensive and easily accessible, present mine detection and area reconnaissance capabilities are insufficient to enable unencumbered maneuver in the littoral regions. Unmanned undersea vehicles (UUVs) possess potential to provide tactical commanders with full understanding of the mine threat without risk to ships or personnel and without exposing intentions. By integrating an assortment of emerging capabilities, a system comprised of a variety of UUVs could address this mine threat. Using unclassified UUV performance estimates, this thesis develops and implements the Mine Reconnaissance System Assessment (MiRSA) model, a mixed integer-linear program, to assign a mix of UUVs to search areas within a suspected minefield. This thesis compares combinations of two Long-term Mine Reconnaissance System (LMRS) vehicles, six Remote Environmental Monitoring Units (REMUS) vehicles, and a notional Manta vehicle searching a 262 square nautical mile area in the Straits of Hormuz.

A. BACKGROUND

Now that the cold war has ended, the absence of a competing superpower and the emerging threat from smaller second and third world countries present the U.S. Navy with the challenge of shifting strategy from dominance of the open ocean to mastery of the littorals (Bovio 1999). Although the nature of the enemy has changed, the ability to project power ashore with overwhelming tempo, momentum, and sustainable forces from the sea remains a central aim of the Navy and Marine Corps. Operational Maneuver from the Sea (U.S. Marine Corps 1996) and Ship-to-Objective Maneuver (Blaisol 1997) reflect this evolution of amphibious warfare and power projection in littoral waters.

Developing nations, unable to maintain a large naval force, use mines as a low cost, effective counter to western power projection. During the Gulf War Conflict, in a period of three hours and merely ten nautical miles apart, the USS TRIPOLI (LPH-10) and the USS PRINCETON (CG-59) struck mines in the northern Arabian Gulf. The USS TRIPOLI sustained a 16-foot by 20-foot hole in her starboard side below the waterline (Figure 1). USS PRINCETON, able to maintain only half power, suffering from a cracked superstructure and a jammed port rudder, limped back to port under tow from the USS BEAUFORT (Naval Historical Center 1991). An Associated Press article states "Mines that Iraq planted in the sea during the Persian Gulf War nearly split the cruiser USS Princeton in half and held an American amphibious assault force at bay. Iraq, the

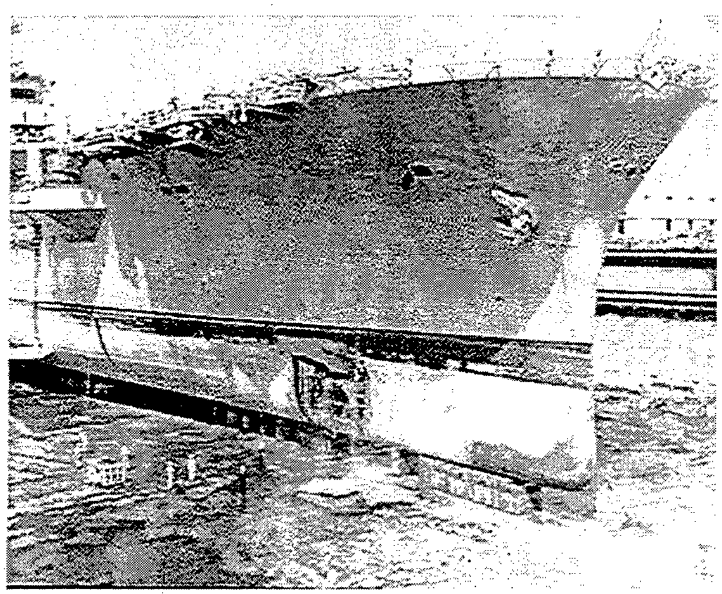

Figure 1. Mine Damage to USS Tripoli (LPH-10)

In Operation Desert Storm, the USS Tripoli struck a mine resulting in 16 x 20 foot hole. Easily attainable, capable of being deployed from the air, surface vessels, or from submarines, mines can be employed effectively to deny access through key sea-lanes and severely hamper operational maneuver. With growing doctrinal emphases on littoral operations, new approaches to mine countermeasures are needed to prevent this from happening in the future. [Source: U.S. Naval Institute Press 1991]

Pentagon learned, was better at laying mines than the U.S. Navy was at clearing them (Associated Press 1998)."

The full spectrum of mine countermeasure (MCM) operations involves detection, classification, localization, and neutralization of mines. "Present and near-term mine detection and area reconnaissance capabilities are insufficient to assure the absence of mines and therefore to enable unencumbered maneuver (Pollitt 1998)." As the workhorses of the Navy's current surface mine-hunting capabilities, the Avenger (MCM 1) and Osprey (MHC 51) class ships are equipped with mine-hunting sonar and remotely operated mine neutralization systems (Figure 2). In addition, Avenger class vessels also possess mechanical sweep equipment, and magnetic and acoustic influence sweeping equipment, that must be towed at a "safe" distance behind the ship in hopes of

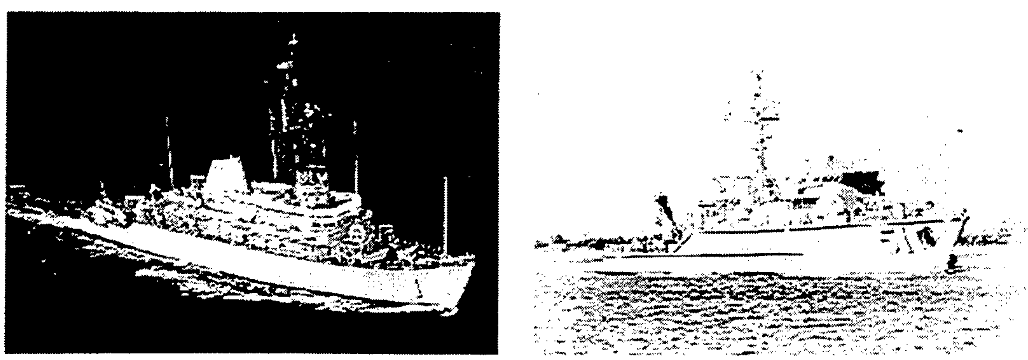

Figure 2. Avenger and Osprey Class Mine Countermeasure Vessels

Mine countermeasure (MCM) operations include detection, classification, localization, and neutralization of mines. Equipped with mine-hunting sonar and the remotely operated mine-hunting system, the Avenger (MCM 1) class [Source: U.S. Naval Institute Press 1987] and the Osprey (MHC 51) class [Source: U.S. Naval Institute Press 1991] mine-hunting vessels are the U. S. Navy's premiere mine hunters. Battlegroup commanders must wait for these costly vessels to arrive in theater before MCM operations can proceed. Additionally, MCM operations must be conducted within the suspected minefield area placing these ships and their crews at risk. The U.S. Navy proposes placing UUVs aboard non-MCM platforms to provide the flexibility for on-the-spot and on-demand MCM capabilities.

actuating mines. With this capability, these ships bear the brunt of the MCM effort. This effort requires them to pass through suspected minefield areas, placing them at risk. Furthermore, overt MCM operations in shallow waters alert the enemy of intentions, enabling them to prepare for the arrival of assaulting forces.

The U.S. Naval Mine Warfare Plan states "Mine reconnaissance is the Navy's highest mine warfare objective as well as the top unmanned undersea vehicle priority. Knowledge of the full dimension of the mine threat without exposing the reconnaissance platforms and the intentions of the tactical commander is vital to littoral warfare (Mine Warfare Command 1996)." Currently, studies sponsored by the Office of Naval Research, Mine Warfare Command and Naval Undersea Warfare Center investigate the transfer of technology in UUVs to mine-hunting capabilities. The Navy plans to build its first mine-hunting UUV in the form of the Long-term Mine Reconnaissance System (LMRS) with production to begin in 2003 (Castelli 1999).

B. THESIS OUTLINE

Chapter II reviews some previous studies on the development of UUVs for use in mine-hunting operations. Chapter III discusses the partitioning of a suspected minefield area into search zones and introduces the use of elemental search area assignment of UUVs. Chapter IV presents the MiRSA mixed integer-linear program for assigning UUVs to elemental search areas. Chapter V details MiRSA model input calculations and discusses MiRSA model results. Chapter VI provides conclusions.

II. LITERATURE REVIEW

Recent unmanned undersea vehicle (UUV) employment studies focus primarily on developing a specific UUV architecture (i.e. selection of sensors, power sources, communication systems, and navigation systems). These studies use simulation-based tools to evaluate the performance of UUVs, to identify preferred UUV architectures, and to specify performance characteristics. Below we review some of these studies.

A. MINE COUNTERMEASURES ACCELERATED CAPABILITIES

In a joint multi-laboratory study, Johns Hopkins University Applied Physics Laboratory and the Navy Surface Warfare Center/Coastal Systems Station propose employing clandestine surveillance UUVs along with bottom emplaced sensors in areas of interest. The Mine Countermeasures Accelerated Capabilities Initiative System Study "...constructs an integrated system by identifying requirements, projecting future capabilities, and noting shortfalls (Johns Hopkins University Applied Physics Laboratory and Naval Surface Warfare Center/Coastal Systems Station 1996)."

This study reports the UUV surveillance role is achievable with current and projected near-term UUV capabilities. However, this study also finds that the development of reconnaissance UUVs poses considerable technical challenges. Limitations in power sources, computer aided detection, classification, and identification algorithms, and navigation systems complicate development of a capable reconnaissance UUV. Despite these limitations, the study concludes that use of clandestine UUVs can reduce the length of overt MCM efforts, and thereby reduce enemy reaction time to an amphibious landing. (Johns Hopkins University Applied Physics Laboratory and Naval Surface Warfare Center/Coastal Systems Station 1996)

This study employs an object-oriented, Monte Carlo based, event driven simulation to evaluate vehicle design performance. The simulation mimics the movement of MCM assets and amphibious forces as well as the interaction between MCM ships and mines using probabilistic detection and actuation widths. Furthermore, simulation of the interaction between amphibious assault craft and remaining mines determines losses. (Johns Hopkins University Applied Physics Laboratory and Naval Surface Warfare Center/Coastal Systems Station 1996)

B. LMRS COST AND OPERATIONAL EFFECTIVENESS ANALYSIS

Johns Hopkins University Applied Physics Laboratory's cost and operational effectiveness analysis of the LMRS evaluates the cost-effectiveness of alternative submarine-launched UUV configurations for conducting clandestine mine reconnaissance, narrows the field of potential alternative architectures, and identifies necessary performance parameters. (Benedict 1996)

From a selection of over 150 different UUVs, the study recommends seven alternative solutions. On the basis of the study's recommendation, Oversight Board co-chairs agree that the LMRS should possess the following characteristics:

"1. 21-inch diameter by 240-inch long autonomous UUV,
2. Torpedo-tube-launched and recovered,
3. Radio frequency and/or acoustic communications capable,
4. Replaceable energy source (safe to conduct aboard a submarine),

5. Forward-looking and side-looking classification sonar,
6. Single-sortie reach of 75-125 nautical miles,
7. Total area coverage of 400-650 square nautical miles/mission, and
8. Area coverage rate of 35-50 square nautical miles/day (Benedict 1996)."

The study's primarily focuses on varied sensor types, energy systems, tethered versus untethered systems, storage, and launch and recovery methods. Additionally, the study includes several secondary considerations including trade-offs among maximum and minimum operating depths, navigation capabilities, noise signature, speed, and communication systems. (Benedict 1996)

Analysis of alternatives involves three levels of modeling: mission level analysis, analysis of individual UUV architectures, and acoustic performance analysis. Mission level analysis employs a Monte Carlo simulation to evaluate various individual UUV architectures. The model simulates a particular UUV's ability to select mine-free transit lanes in seventeen representative tactical situations. Among the tactical situations, the simulation includes the Persian Gulf, Gulf of Oman, and the Straits of Hormuz. The model also considers the effect of varied levels of clutter (non-mine objects) in evaluating UUV performance. (Benedict 1996)

Benedict (1996) also reports their use of spreadsheets to help evaluate specific UUV design measures of effectiveness that are independent of clutter levels. Evaluation of vehicle sortie reach, total area coverage and area coverage rate possible with varied power source limitations, electrical loads, sensor performance, and navigation and communication capabilities help to eliminate some UUV architectures.

Sensor performance analysis employs physics-based acoustic raytrace models to assess the signal-to-noise ratio versus range of sensor systems in particular environments. Signal-to-noise ratio data relates probabilities of detection based upon receiver-operator-characteristic curves. The results from these models provide the necessary sensor performance parameters for the unit and mission level analysis. (Benedict 1996)

C. SUMMARY

Recent studies explore the benefit of developing mine-hunting UUVs and provide the unclassified performance estimates for use in the MiRSA model. This thesis differs from previous efforts by considering a variety of UUV architectures and using optimization to assign them to mine detection operations.

III. SEARCHING A SUSPECTED MINEFIELD USING UNMANNED UNDERSEA VEHICLES

Although the Avenger and Osprey class ships are capable of conducting mine countermeasure operations in depths as shallow as 30 feet, such operations near shore expose them to shore batteries. In future concepts of operations, UUVs could be employed in advance of a planned amphibious operation to conduct intelligence, surveillance, and reconnaissance operations in areas very near shore (in depths as shallow as 10 feet). Designed to be platform independent and capable of being launched and operated by any ship in theater, UUVs may provide commanders with an on-demand, ship-borne mine-hunting capability. However, UUVs are still in the development stages as designers seek to exploit current and future technologies in the areas of navigation, endurance, communication systems, computer-aided detection, and computer-aided classification systems. The discussion below describes the issue of how a system of UUVs may be employed to search a suspected minefield.

A. TECHNOLOGY TRADE-OFFS AND CAPABILITIES INTEGRATION

Development of UUVs will enable clandestine intelligence, surveillance, reconnaissance, mapping, mine searching, identification, and neutralization of coastal waters. Because there is a wide diversity of mine types and there are UUV technology limitations, it is unlikely that a single class of UUVs will be able to perform all mine countermeasure missions (Pollitt 1998). By integrating an assortment of capabilities, a system comprised of a variety of general-purpose, mine-hunting, and expendable mine neutralizing UUVs is better suited to the diversity of ocean environments and mine types encountered in littoral regions. The Remote Environmental Monitoring Units (REMUS)

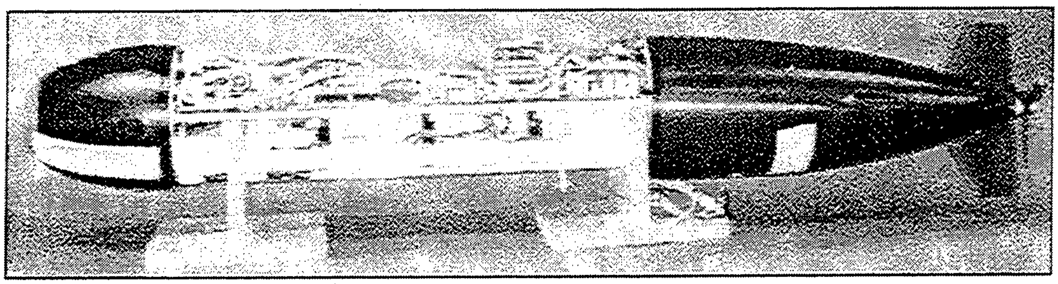

Figure 3. Remote Environmental Monitoring Units (REMUS) UUV

Only 52 inches long and body diameter of 7.5 inches, the REMUS weighs 68 pounds and may be trimmed for operations in fresh or salt water. Its small size, light weight, and reconfigurable design make it possible to be launched from small vessels with little support. Currently, REMUS is a developmental tool of the Oceanographic Systems Lab of the Woods Hole Oceanographic Institution, funded by National Oceanographic and Atmospheric Administration and National Undersea Research Program. However, it can easily be adapted to perform the MCM mission. [Source: Woods Hole Oceanographic Institution 1999]

vehicle is one of several UUVs under development that might be adapted for mine-hunting operations (Figure 3). Equipped with a high-resolution sonar sensor, the REMUS vehicle is capable of taking near photographic-quality images of the ocean floor.

B. SEARCH ZONES (SZ) AND ELEMENTAL SEARCH AREA (ESA) ASSIGNMENT

When clearing a *suspected minefield area* (SMA), conceptual *search zones* (SZs) running parallel to the shoreline partition the area into contiguous parcels of ocean that possess similar characteristics such as depth, bottom type, acoustic environment, and the type of mines expected (Figure 4). An *elemental search area* (ESA) for a UUV is the maximum area it can search to a specified confidence level before having to return to its host platform to recharge its batteries. The *search level*, defined as the percentage of area physically surveyed by the UUV's sensors, determines the confidence level as defined in

(Pollitt 1999a). Assuming a uniform [0,100] mine distribution and using the methods described in Pollitt (1999a), the *confidence level* is the cumulative probability that no more than two mines exist in the SMA if no mines are detected. The *width of the ESA* (esawidth) varies according to the UUV, search zone, confidence level, and host platform standoff distance.

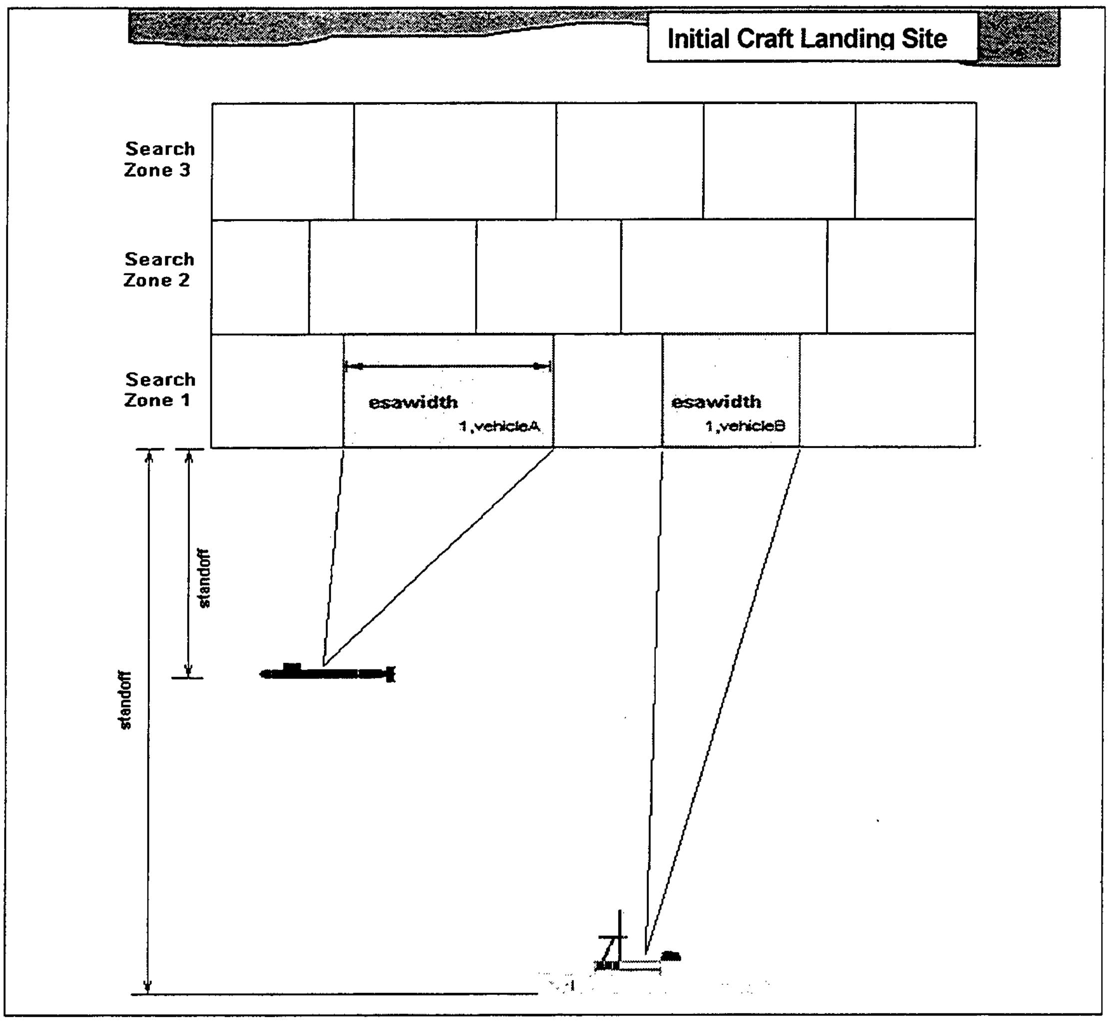

Figure 4. Partitioning of Suspected Minefield Areas (SMAs) into Search Zones

Partitioning a suspected minefield area into parallel search zones (SZs) divides the ocean into parcels that possess similar oceanographic characteristics such as depth, bottom type, and other acoustic properties. Unmanned undersea vehicles (UUVs) conduct searches within these SZs to a specified probability that no more than two mines remain undetected. An elemental search area (ESA), a rectangle above, is the maximum area a UUV can search to a specified probability before having to return to its host platform to recharge its batteries. The width of an ESA (esawidth) varies according to the UUV, search zone, and host platform standoff distance.

Within these ESAs, UUVs conduct a *ladder search* with sufficient *search lane separation* and sensor width overlap to ensure a specified confidence level. A UUV conducts a ladder search by traversing parallel tracks or *search lanes* to form a ladder-like pattern. Each search lane is a single pass within the ESA. The search lane separation defines the spacing between each search lane (Figure 5). For this study, 95 percent is a good initial assessment for confidence level (Pollitt 1999a). The sum of the ESA widths for all assigned UUVs must span the entire width of the SZ. Because searches typically follow a "march-to-the-beach" fashion, UUVs assigned searches in multiple SZs conduct their searches from the seaward SZs first and progress toward the initial craft landing site as each SZ search is completed.

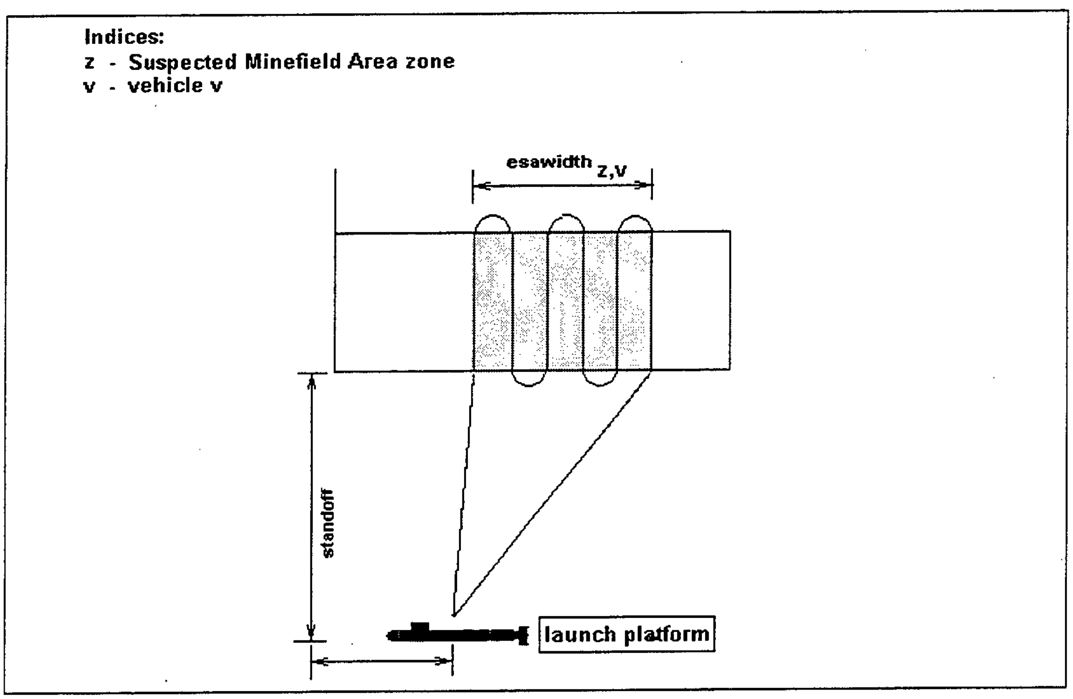

Figure 5. Elemental Search Area (ESA)

UUV searches divide the search zone (SZ) into ESAs. The endurance of the UUV, sensor performance within the SZ, and the standoff distance of the host ship from the ESA determine ESA width. Within the ESA, UUVs conduct a ladder search to a specified probability that no more than two mines exist in the suspected minefield area given that none are detected. Each vertical pass within the ESA is a search lane and the horizontal spacing between search lanes is the search lane separation.

C. SUSPECTED MINEFIELD AREA MISSION TIME (SMAMT)

The *ESA time* is defined as the time required for a UUV to complete its search within an assigned ESA. For each UUV, the sum of the ESA times for all assigned ESAs in previous and current SZs determine the time needed to complete its searches through the current SZ. The longest time among all UUVs is the *SZ completion time* (SZCT). The *SMA mission time* (SMAMT) is the time required to search the entire SMA. Times for launching, recovering, transiting, and recharging UUVs determine the *full ESA times.* Some scenarios exist when full ESA times may be discounted. For example, UUVs assigned to the last ESA in a SZ need not consider the return transit provided appropriate communications are available.

D. SUMMARY

This chapter introduces the conceptual division of an SMA into ESAs. The size of an ESA depends on the UUV, the standoff distance of the host platform, the search zone, and the desired confidence level. The next chapter contains the MiRSA model for assigning UUVs to ESAs.

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IV. MINE RECONNAISSANCE SYSTEM ASSESSMENT (MiRSA) MODEL

The Mine Reconnaissance System Assessment (MiRSA) model, a mixed integer-linear program, assigns UUVs to search areas for mine-hunting. There are two versions of MiRSA. The first assumes that each ESA has fixed area for a given UUV within a specific SZ. The second allows each ESA to have variable width. This thesis develops both versions because it is uncertain that UUV technology will allow precise navigation of ESAs with variable widths.

A. FIXED-SIZE ELEMENTAL SEARCH AREA (ESA) MiRSA MODEL

1. Problem Definition

Given a fixed number of host platforms available near shore, each with a variety of UUVs, an SMA of fixed length and width is to be surveyed in the least amount of time. MiRSA determines the number of fixed-size ESAs assigned to each UUV. The ESA width corresponds to a specified search level and a desired confidence level. The search level is the percentage of area physically surveyed by the UUV's sensors and it determines the confidence level. The confidence level is the probability that no more than two mines exist in the area searched if no mines are detected.

2. Assumptions

The ESA width for a given UUV and SZ is constant. Asserting a long standoff distance compared to ESA widths ensures that transit distances remain fairly uniform for a specific vehicle throughout a given SZ. Other simplifying assumptions include constant UUV performance for a given SZ and allowed simultaneous UUV launches. MiRSA therefore, does not consider how UUV performance varies over the course of a day in response to weather, sea-state, and tidal changes. MiRSA also ignores the small additional time associated with scheduling UUV launches and recoveries when simultaneous launches and recoveries of multiple UUVs are not possible. This additional time would be small in comparison to the overall time required to search the entire SMA.

3. Indices

z, z' SZ of an SMA partitioned according to similar geographic characteristics such as bottom depth, bottom type, salinity, and distance from shore

v vehicle serial number, defining the type of UUV and host ship

4. Data

$esast_{z,v}$ ESA setup time (time required to launch, transit to and from the SZ, recovery, and recharge) [hours]

$etotitl_{z,v}$ the search time for UUV v in SZ z in one ESA [hours]

$sesast_{z,v}$ shortened ESA setup time (does not include battery recharge time and recovery time) for last ESA of vehicle v to zone z or for vehicles equipped with real time communications systems [hours]

$esawidth_{z,v}$ width of ESA searched in SZ z by vehicle v [yards]

$szwidth_z$ width of SZ z [yards]

5. Variables

SMAMT total mission time from launch of first vehicle to search completion [hours]

$SZCT_z$ cumulative mission time required to search SZ z and all lower numbered SZs [hours]

$ESAS_{z,v}$ number of complete ESAs performed by vehicle v within SZ z

$SESA_{z,v}$ 1 if vehicle v completes a shortened ESA in SZ z and 0 otherwise

6. Formulation

minimize $SMAMT$

subject to:

$$SMAMT \geq SZCT_z \qquad \forall z \quad (4.1)$$

$$\begin{aligned} SZCT_z \geq \sum_{z'<z}(esast_{z',v} + etotitl_{z',v})(ESAS_{z',v} + SESA_{z',v}) \\ + (esast_{z,v} + etotitl_{z,v})(ESAS_{z,v}) \\ + (sesast_{z,v} + etotitl_{z,v})(SESA_{z,v}) \end{aligned} \qquad \forall z,v \quad (4.2)$$

$$\sum_v esawidth_{z,v}(ESAS_{z,v} + SESA_{z,v}) \geq szwidth_z \qquad \forall z \quad (4.3)$$

$$SMAMT \geq 0 \qquad (4.4)$$

$$SZCT_z \geq 0 \qquad \forall z \quad (4.5)$$

$$ESAS_{z,v} \geq 0 \text{ and Integer} \qquad \forall z,v \quad (4.6)$$

$$SESA_{z,v} \in \{0,1\} \qquad \forall z,v \quad (4.7)$$

Equation (4.1) and the objective function ensure time to search the entire SMA is the maximum time required to search any SZ. In equation (4.2), for each UUV, the time needed to complete searches in any SZ includes the UUV's time in lower numbered zones. Equation (4.3) ensures complete area coverage of each SZ. Equations (4.4) to (4.7) respectively declare variables as non-negative, non-negative integer and binary.

B. VARIABLE-SIZE ELEMENTAL SEARCH AREA (ESA) MiRSA MODEL

1. Additional Variables

This version of MiRSA uses the same variables as the fixed-size ESA MiRSA model and the following additional variable:

$CESAS_{z,v}$ number of ESAs assigned to vehicle v in SZ z.

2. Formulation

minimize $\quad SMAMT$

subject to:

$$SMAMT \geq SZCT_z \qquad \forall z \quad (4.8)$$

$$\begin{aligned} SZCT_z \geq & \sum_{z'<z} [(esast_{z',v})(ESAS_{z',v} + SESA_{z',v}) \\ & + (etotitl_{z'v})(CESA_{z',v})] \qquad \forall z,v \quad (4.9) \\ & \quad + (esast_{z,v})(ESAS_{z,v}) + (etotitl_{z,v})(CESAS_{z,v}) \\ & \quad + (sesast_{z,v})(SESA_{z,v}) \end{aligned}$$

$$\sum_v esawidth_{z,v}(CESAS_{z,v}) \geq szwidth_z \qquad \forall z \quad (4.10)$$

$$CESAS_{z,v} \leq ESAS_{z,v} + SESA_{z,v} \qquad \forall z,v \quad (4.11)$$

$$SMAMT \geq 0 \qquad (4.12)$$

$$SZCT_z \geq 0 \qquad \forall z \quad (4.13)$$

$$CESAS_{z,v} \geq 0 \qquad \forall z,v \quad (4.14)$$

$$ESAS_{z,v} \geq 0 \text{ and Integer} \qquad \forall z,v \quad (4.15)$$

$$SESA_{z,v} \in \{0,1\} \qquad \forall z,v \quad (4.16)$$

Equation (4.8) is the same as equation (4.1). Equation (4.9) is the same as equation (4.2) except search times vary for the variable-size ESA widths. Equation (4.10) ensures area coverage of the entire SZ. Equation (4.11) ensures the number of $CESAS_{z,v}$ assigned does not exceed the number of fixed-size ESAs assigned. Equations (4.12) to (4.16) respectively declare variables as non-negative, non-negative integer and binary.

V. ELEMENTAL SEARCH AREA CALCULATIONS AND MiRSA RESULTS

This chapter applies the concept of dividing an SMA into SZs and ESAs for a hypothetical tactical situation in the Straits of Hormuz. It describes the preliminary calculation of ESA parameters needed to implement MiRSA, discusses specific UUV characteristics, and details the varied combinations of UUVs investigated. Finally, it reports both fixed-size and variable-size ESA MiRSA model results for the hypothetical situation.

A. SUSPECTED MINEFIELD AREA (SMA) DEFINITION

A Straits of Hormuz tactical situation builds upon earlier studies evaluating individual UUV architecture performance in the Straits of Hormuz. A Defense Mapping Agency chart of the Gulf of Oman-Persian Gulf (Defense Mapping Agency and Hydrographic/Topographic Center 1995) serves as a guide for defining the SMA.

The SMA incorporates the observed traffic separation scheme for incoming and outgoing ships and extends towards the Iranian coastline. An SMA with twice the width of the transit lanes allows for greater flexibility in transiting the straits. The entire SMA spans 262 square nautical miles (nm). Four search zones (SZs) partition the SMA. SZs one and two are 12.5 nm by 3.25 nm and define the southern entrance to the straits. SZ three is 20.2 nm by 5 nm and captures the bend in the transit lanes. The fourth SZ is 16 nm by 5 nm. Defining the SZs is arbitrary for the straits because the water depth is consistently greater than 200 feet. A submarine stationed 12 nm south of the entrance of the straits serves as the launch platform for the UUVs (Figure 6).

B. ELEMENTAL SEARCH AREA (ESA) CALCULATIONS

MiRSA uses ESA width ($esawidth_{z,v}$), ESA setup time ($esast_{z,v}$), shorter SESA setup time ($sesast_{z,v}$), and search time ($etotitl_{z,v}$) as input. A spreadsheet generates the necessary input values based on the desired search level (P), sensor width ($A_{z,v}$), detection probability ($B_{z,v}$), battery availability time, transit distance, and search and transit speed for each UUV and SZ. During operation, UUVs equipped with GPS conduct GPS fix events. GPS duty cycle time is the amount of time in minutes spent obtaining GPS fixes for each hour of operation.

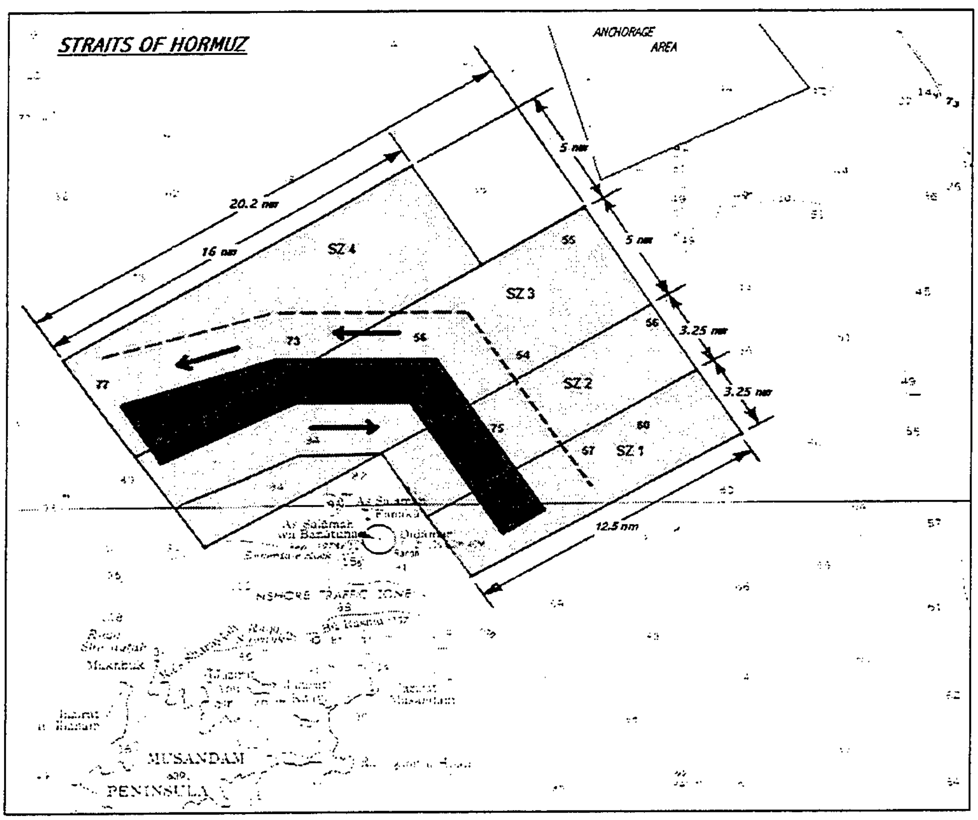

Figure 6. Straits of Hormuz Suspected Minefield Area (SMA)

The Straits of Hormuz serves as the suspected minefield area. Arrows depict the traffic separation scheme for ships entering and leaving the Persian Gulf. Partitioning divides the SMA into four search zones (SZs). SZ 1 and SZ 2 are 12.5 nm by 3.25 nm. SZ 3 describes the bend in the transit zone and is 20.2 nm by 5 nm. SZ 4 is 16 nm by 5 nm. The depth of the water is consistently greater than 200 feet. A submarine stationed 12 nm south of the entrance of the straits (not shown above) serves as the launch platform for the UUVs.

General input characterizing search (Table 1) includes the number of vehicles, the search level, transit speed, search speeds, and battery information. The spreadsheet uses these input values to determine preliminary ESA inputs.

Search Level (P)	63.00%
Confidence Level	94.93%
Number of passes per sensor / path (J)	1
Number of sensors / path (N)	1

Transit Speed (kts)	6
Search Speed (kts)	4
Standoff Distance (nm)	12

Battery Available Time (hrs)	33.87
Launch Time (hrs)	0.25
GPS Duty Cycle Time (min/hr of ETOTITL)	10
Recovery Time (hrs)	0.5
Battery Recharge Time (hrs)	10

LMRS

Table 1. UUV General Input

General information characterizing a search includes search level, confidence level, the number of sensors assigned per path, and the frequency with which an individual sensor passes over a given path. During operation, UUVs equipped with GPS conduct GPS fix events. GPS duty cycle time is the amount of time in minutes spent obtaining GPS fixes for each hour of operation. Launch and recovery, GPS duty cycle, and transit must all be deducted from battery available time determining the time available for search.

Equation (5.1) determines the necessary search lane separation ($d_{z,v}$) in yards to achieve the desired search level (Pollitt 1999b):

Sensor Parameters

$d_{z,v}$	necessary search lane separation to achieve a desired search level [yards]
J	number of passes performed by a given sensor over a given path
$N_{z,v}$	number of sensors dedicated to search a given path
$A_{z,v}$	search width of vehicle v in SZ z [yards]

$B_{z,v}$ detection probability of vehicle v in SZ z

$e_{z,v}$ standard deviation of navigational error [yards]

$Y_{z,v}$ MCM efficiency obtained from the graph depicted in Figure 7 (Mine Warfare Command 1986) by the ratio of search width and standard deviation of navigational error ($A_{z,v}/e_{z,v}$) and detection probability ($B_{z,v}$)

P the desired search level

$$d_{z,v} = -J \cdot N_{z,v} \cdot A_{z,v} \cdot B_{z,v} \cdot Y_{z,v} / \ln(1-P) \tag{5.1}$$

Equation (5.2) determines the transit length in nautical miles of each turn ($turn_{z,v}$) between search lanes (Pollitt 1999b). The division by 2025.37 converts units from yards to nautical miles. Table 2 shows the spreadsheet for UUV sensor characteristic input and resulting search lane separation and turn length output.

Turn Parameters

$turn_{z,v}$ transit length of each turn [nm]

$d_{z,v}$ necessary search lane separation to achieve a desired search level [yards]

$$turn_{z,v} = d_{z,v} \cdot \pi / 2 \cdot (1/2025.37) \tag{5.2}$$

Battery endurance limits search time. For each vehicle and SZ, the time required to launch, transit to and from the ESA, and to conduct GPS fixes are constant and reduce the battery time available for search. The *estimated time on target in the lap* ($etotitl_{z,v}$) is

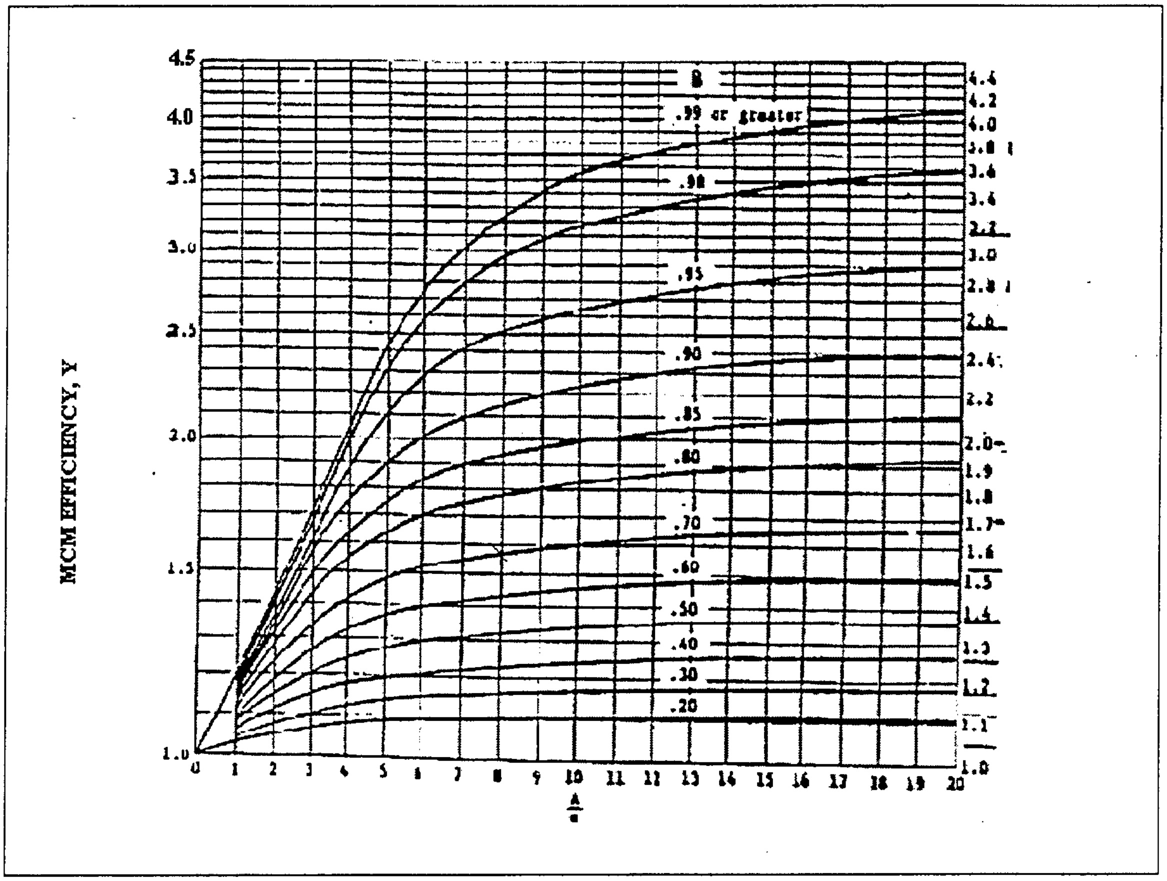

Figure 7. MCM Search Efficiency

MCM Efficiency (Y) characterizes the effectiveness of search efforts based on search width (A), detection probability (B), and standard deviation of navigational error (e). High detection probabilities and search widths with low standard deviations of navigational error result in highly efficient searches. On the contrary, low B and A with high e characterize low efficiency searches. [Source: Mine Warfare Command 1986]

defined as the time in hours dedicated to conducting a ladder search. Equation (5.3) provides $aetotitl_{z,v}$, the time available for $etotitl_{z,v}$.

Search Zone	Search Width (A) (yds)	Detection Probability (B)	Std Deviation of Nav. Error (e) (yds)	A/e	MCM Efficiency (Y)
1	1167	0.85	25.00	46.68	2.00
2	1167	0.85	25.00	46.68	2.00
3	1167	0.85	25.00	46.68	2.00
4	1167	0.85	25.00	46.68	2.00

Search Zone	Lane Separation (d) (yds)	Turn Length (nm)
1	1995.36883	1.54753
2	1995.36883	1.54753
3	1995.36883	1.54753
4	1995.36883	1.54753

Table 2. UUV Sensor Characteristics

The table above shows the spreadsheet for UUV sensor characteristic input and resulting search lane separation and turn length output. Suspected minefield area geometry and estimates of vehicle sensor performance are entered into equation (5.1) to determine the necessary search lane separation for a desired search level.

ETOTITL Parameters

$aetotitl_{z,v}$	available search time [hours]
battery avail time$_v$	battery endurance of UUV v [hours]
GPScycle$_v$	GPS fix duration per hour of operation for UUV v [minutes]
launch time$_v$	time required for launching UUV v [hours]
recovery time$_v$	time required for recovering UUV v [hours]
transit distance$_z$	transit distance from launch point to SZ z [nm]
tspd$_v$	transit speed of UUV v [nm/hr]

$$\begin{aligned} aetotitl_{z,v} = {} & \text{battery avail time}_v * (1 - \text{GPScycle}_v / 60) \\ & - \text{launch time}_v - \text{recovery time}_v \\ & - (2 * \text{transit distance}_z)/\text{tspd}_v \end{aligned} \tag{5.3}$$

Equation (5.4) determines the number of search lanes ($lanes_{z,v}$) in the ladder search for a given SZ search lane length ($szlength_z$), search speed ($sspd_v$), and $aetotitl_{z,v}$.

Search Lane Parameters

$lanes_{z,v}$	number of search lanes (a continuous value) in an ESA performed by vehicle v in zone z
$aetotitl_{z,v}$	available search time [hours]
$sspd_v$	search speed of vehicle v [nm/hr]
$szlength_z$	length of a single search lane in ladder search [nm]
$turn_{z,v}$	transit length of each turn [nm]

$$lanes_{z,v} = aetotitl_{z,v} \cdot sspd_v / (szlength_z + turn_{z,v}) \qquad (5.4)$$

Limiting the number of search lanes to an even number ensures the vehicle exits the ESA on the side it entered. The product of search lane separation and the number of even search lanes determine the ESA width in yards, for a given UUV in a SZ. Equation (5.5) describes this relationship.

ESA Search Width Parameters

$esawidth_{z,v}$	width of an ESA [yards]
$d_{z,v}$	necessary search lane separation to achieve a desired search level [yards]
$lanes_{z,v}$	number of search lanes (an even integer) in an ESA performed by vehicle v in zone z

$$esawidth_{z,v} = d_{z,v} * lanes_{z,v} \tag{5.5}$$

The ESA setup time accounts for the vehicle's launch, recovery, transit to and from the SZ, and battery recharge. The amount of time required only for launch and the transit to the SZ determines the SESA setup time. (Table 3)

Search Zone	Transit Distance to Search Zone (nm)	Zone Lane Length (nm)	Zone width (nm)	Transit Time with Launch and Recovery (hrs)	Single Leg Transit Time with Launch only (hrs)	Available ETOTITL (hrs)	GPS Cycle Time (hrs)	GPS Adj. ETOTITL (hrs)	Battery Ltd. Num. Of Lanes	Even no. of Lanes?	Act. Number of Lanes	ESA width (nm)	ESA Width (yds)	ETOTITL (hrs)	ESA Setup Time (*esast*) (hrs)	SESA Setup Time (*sesast*) (hrs)	ESA Time (hrs)
1	12.00	3.25	12.50	4.75	2.25	29.12	4.85	24.27	20.00	TRUE	20	19.70	39907.38	28.45	14.75	2.25	43.20
2	15.25	3.25	12.50	5.83	2.79	28.04	4.67	23.36	19.00	FALSE	18	17.73	35916.64	25.87	15.83	2.79	41.71
3	18.50	5.00	20.20	6.92	3.33	26.95	4.49	22.46	13.00	FALSE	12	11.82	23944.43	23.75	16.92	3.33	40.66
4	23.50	5.00	16.00	8.58	4.17	25.29	4.21	21.07	12.00	TRUE	12	11.82	23944.43	23.47	18.58	4.17	42.05

Table 3. Summary of Elemental Search Area (ESA) Width Calculations

The "ESA width" is derived from the required search lane separation (See Table 2) and the "Act. Number of Lanes" possible with the "GPS Adj. ETOTITL". An even number of search lanes in an ESA ensures the vehicle exits the ESA on the side it entered. "ESA Setup Time" accounts for launch, transit to and from the search zone (SZ), recovery, and battery recharge. The "SESA Setup Time" is the launch and transit time only. "GPS Cycle Time" allows for GPS fix events during the "Available ETOTITL". The "GPS Adj. ETOTITL" is the available time the vehicle can search within the ESA. "ETOTITL" is the time needed to search the ESA for the specified number of search lanes. For example, in Search Zone 1, an LMRS vehicle possesses 33.87 hours of available power (See Table 1). After 4.75 hours spent for launch and transiting to and from the SZ, and 4.85 hours conducting GPS fix events, the time available to search is (33.87-4.75-4.85) 24.27 hours. 24.27 hours supports a ladder search with 20 search lanes (28.45 hours with GPS Cycles). The resulting ESA width for 20 search lanes with the required search lane separation is 19.70 nautical miles or 39,907.38 yards. The "ESA Setup Time (*esast*)" is 14.75 hours. The "SESA Setup Time (*sesast*)" is 2.25 hours. "ESA Time" is 43.20 hours from launch to launch.

Table 4 summarizes the ESA widths, ESA setup times, SESA setup times, and actual search times calculated for a 63% search level in the Straits of Hormuz.

Search Level	63.00%	Confidence Level	94.93%

Vehicle ESA DATA Summary

LMRS

	ESA width (nm)	ESA Width (yds)	ESA Setup Time (*esast*) (hrs)	ETOTITL (hrs)	SESA Setup Time (*sesast*) (hrs)	ESA Time (hrs)
1	19.70	39907.38	14.75	28.45	2.25	43.20
2	17.73	35916.64	15.83	25.87	2.79	41.71
3	11.82	23944.43	16.92	23.75	3.33	40.66
4	11.82	23944.43	18.58	23.47	4.17	42.05

REMUS

	ESA width (nm)	ESA Width (yds)	ESA Setup Time (*esast*) (hrs)	ETOTITL (hrs)	SESA Setup Time (*sesast*) (hrs)	ESA Time (hrs)
1	2.75	5576.05	12.25	2.89	4.25	15.14
2	2.75	5576.05	14.42	2.89	5.33	17.30
3	0.00	0.00	16.58	0.00	6.42	0.00
4	0.00	0.00	19.92	0.00	8.08	0.00

MANTA

	ESA width (nm)	ESA Width (yds)	ESA Setup Time (*esast*) (hrs)	ETOTITL (hrs)	SESA Setup Time (*sesast*) (hrs)	ESA Time (hrs)
1	32.27	65349.61	11.15	40.28	1.45	51.43
2	32.27	65349.61	11.80	40.17	1.78	51.97
3	22.34	45242.04	12.45	37.54	2.10	49.99
4	22.34	45242.04	13.45	37.38	2.60	50.83

Table 4. Summary of Unmanned Undersea Vehicle Elemental Search Area (ESA) Widths

For the 63% search level, a spreadsheet calculates "ESA width", "ESA Setup Time (*esast*)", "SESA Setup Time (*sesast*)", and "ETOTITL" (MiRSA inputs) for each vehicle and for each SZ in the Straits of Hormuz. These ESA values depend on the geometry of the search zone, UUV sensor characteristics, battery endurance, and transit distance. For example, in Search Zone 1, the "ESA width" for six REMUS vehicles is 2.75 nm or 5,576.05 yards. Transiting to and from the ESA and recharging batteries requires 12.25 hours. Time dedicated to conducting a search is 2.89 hours. The time between launches of a REMUS vehicle is 15.14 hours. A short time ESA requires 4.25 hours for setup plus 2.89 hours for an ESA search. Because the REMUS vehicles lack the endurance to reach and search distant zones, REMUS' "ETOTITL" and "ESA width" are zero in Search Zones 3 and 4.

C. VEHICLE CHARACTERISTICS

Benedict (1996) describes the LMRS system as consisting of two independent autonomous vehicles. Each vehicle is a 21-inch by 240-inch, torpedo-tube-launched UUV. It comes equipped with a replaceable or rechargeable energy section capable of approximately 34 operational hours without replenishment. Battery replacement or recharge time is approximately 10 hours. The sensor suite includes a forward-looking search sonar system having a sensor width of 1167 yards and an associated probability of detecting bottom mines of 85%. Equipped with GPS navigation and periodic radio frequency communications, the LMRS can communicate search area survey findings to tactical commanders at regular intervals. Estimated GPS cycles require approximately 10 minutes for every hour of operation. The LMRS vehicle requires approximately 10 minutes to launch. Recovery of the LMRS requires about 30 minutes.

The Remote Environmental Monitoring Units (REMUS) is a relatively inexpensive UUV. Modeling a system of six vehicles operating as a single entity widens the search lane separation while still maintaining a reasonably high search level. The vehicle is 7.5 inches by 52 inches long and weighs only 68 pounds. Because of its small size and simplicity of design, launch and recovery is simple. However, its compactness presents limitations in energy and search capability with only 14 hours available battery time, a mere 400-yard search width, and associated 70% probability of detection from its side-looking high-resolution sonar suite. The REMUS possesses no GPS or communications systems capability. Launch time takes 15 minutes with essentially no time required for recovery. The battery recharges in approximately four hours. (Woods Hole Oceanographic Institution 1999)

Finally, this study includes a notional Manta vehicle. The Manta's performance characteristics represent desired capabilities beyond the year 2015. The Manta performs as a single vehicle with an estimated battery endurance of up to 45 hours. The Manta's sonar capabilities include an 85% probability of detection for a sensor width of 1400 yards. Like the LMRS, the Manta will likely possess GPS and radio frequency communications. The GPS cycles require about 10 minutes for each hour of operation. The times necessary for launch and recovery of the Manta are 15 minutes and 10 minutes respectively.

D. SYSTEM COMPOSITION

This analysis compares combinations of two LMRS vehicles, six REMUS vehicles, and one MANTA vehicle. Optimized SMAMT measures a combination's effectiveness. This study excludes comparison of a system of six REMUS vehicles operating alone because REMUS does not possess the endurance to conduct searches of appreciable size in distant SZs. The following list contains the combinations of vehicle architectures in this study.

Combined Vehicle Systems

1. Full System of two LMRS vehicles, six REMUS vehicles, and one MANTA,
2. Two LMRS vehicles,
3. One MANTA vehicle,
4. Two LMRS vehicles supported by six REMUS vehicles,
5. One MANTA vehicle supported by six REMUS vehicles, and
6. Two LMRS vehicles and one MANTA vehicle.

E. MiRSA MODEL STATISTICS

A Pentium III 450 MHz personal computer with 64MB of RAM executes the MiRSA model using the General Algebraic Modeling System (GAMS) (Brooke et al. 1997) and the XA: Profession Linear Programming System Solver (Sunset Software

Technology 1993). The most complex MiRSA model with the full system of composite architectures consists of only 61 equations, 21 continuous variables, and 32 binary variables. All the model runs achieve an optimal solution in less than one minute except the 100% search level, which achieves a solution in under five minutes.

F. FIXED-SIZE ELEMENTAL SEARCH AREA (ESA) MiRSA RESULTS

Fixed-size ESA MiRSA executions for the Straits of Hormuz for search levels of 63%, and 70-95% (at five percent increments) result in the SMAMTs listed in Table 5. A plot of SMAMTs versus desired search level produces curves useful in comparing different combinations of vehicles (Figure 8).

At all search levels, the full system requires the least SMAMT. Specifically, at a 63% search level, the full system completes a search of the SMA in approximately 71 hours. This result is expected because it employs all the available assets. By contrast, the Manta requires the most time, completing its searches in 193 hours.

% Search Level	% Confidence Level	FULL	LMRS	MANTA	LMRS + MANTA	LMRS + REMUS	MANTA + REMUS
63%	95.00%	70.84	111.51	193.38	70.84	108.97	141.40
70%	97.00%	69.72	112.78	194.41	69.72	110.13	142.13
75%	98.50%	91.68	151.83	246.02	91.68	111.47	193.38
80%	99.20%	89.84	155.04	293.53	89.84	118.90	241.76
85%	99.60%	91.12	196.88	297.71	113.00	153.15	241.23
90%	99.90%	110.21	234.26	299.21	152.10	155.79	246.23
95%	99.99%	121.63	241.20	344.06	153.63	238.47	246.52

* All suspected minefield area mission times listed in hours.

Table 5. Fixed-Size Elemental Search Area (ESA) MiRSA Suspected Minefield Area Mission Times (SMAMTs)

Fixed-size elemental search area MiRSA results for the Straits of Hormuz with search levels assuming values of 63%, and 70-95% at five percent increments. At a 63% search level, the full system completes searching the entire SMA in 70.84 hours. The LMRS and Manta system performs equally well, completing its search in the same amount of time. At a 95% search level, differentiation between the different combinations is more noticeable.

The composite system including two LMRS vehicles and the Manta vehicle provides SMAMTs equivalent to the full system at all search levels less than 85% and a 26% increase at the 95% search level. At search levels of 80% and lower, the LMRS' and Manta's sufficiently wide ESAs enable timely search completion of the SMA. The addition of the REMUS vehicles at these lower search levels provides no additional

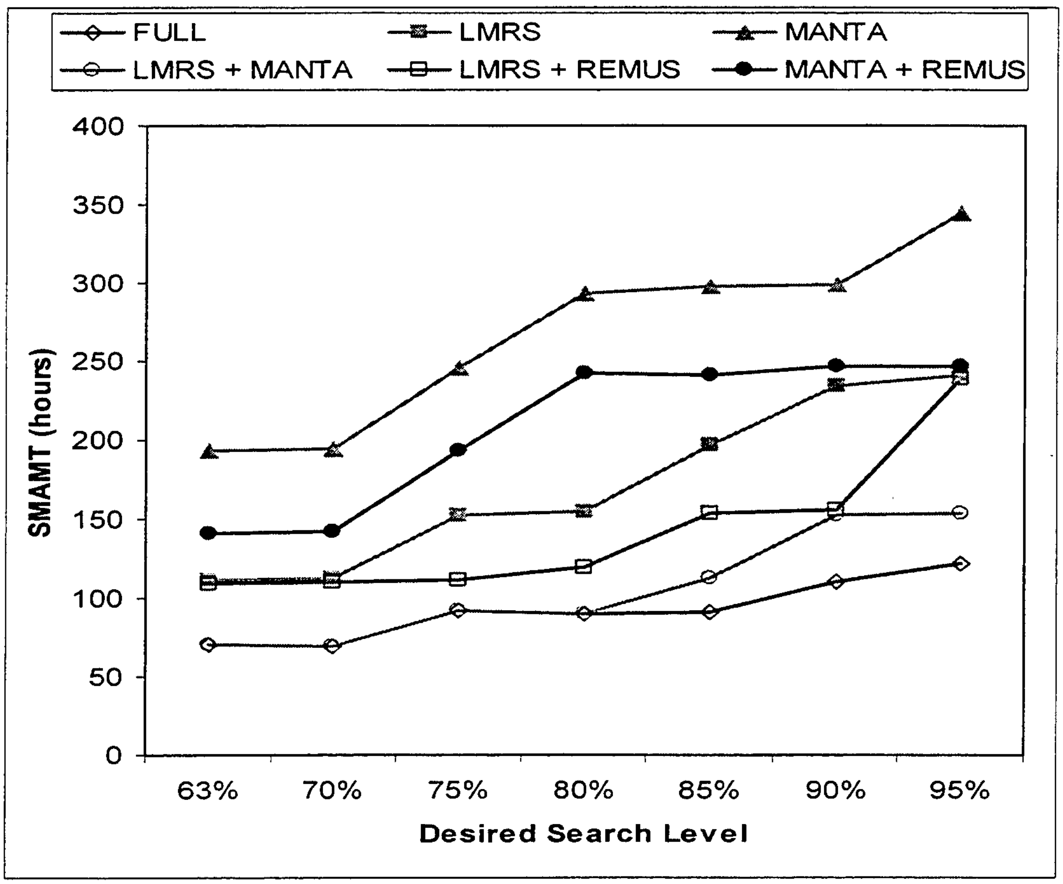

Figure 8. Fixed-Size Elemental Search Area (ESA) MiRSA Optimized Suspected Minefield Area Mission Time (SMAMT) Curves

With the fixed-size elemental search area implementation of MiRSA, the LMRS and Manta combined system performs as well as the full system for search levels below 85%. However, REMUS reduces mission times when operating with the LMRS at moderate (75-90 %) search levels, and when operating with Manta at any search level.

benefit. At search levels greater than 80%, narrower search lane separation reduces the ESA widths of the LMRS and Manta vehicles such that REMUS searches provide a significant benefit.

Low search levels (63-70 %) possess sufficiently large ESA widths so the LMRS can survey the entire SMA without the need for REMUS. At the 95% search level, the composite LMRS and REMUS system demonstrates performance equivalent to LMRS. REMUS' contribution when working with the Manta significantly reduces optimized SMAMTs at all search levels.

G. VARIABLE-SIZE ELEMENTAL SEARCH AREA (ESA) MiRSA RESULTS

Variable-size ESA MiRSA executions for the Straits of Hormuz at 63%, and 70-100% at five percent increments result in the SMAMTs listed in Table 6. A plot of SMAMTs versus desired search level produces curves useful in comparing different combinations of vehicles (Figure 9).

% Search Level	% Confidence Level	FULL	LMRS	MANTA	LMRS + MANTA	LMRS + REMUS	MANTA + REMUS
63%	94.93%	46.53	90.69	129.89	51.82	77.98	99.22
70%	97.30%	53.20	98.99	143.32	57.02	88.99	110.82
75%	98.44%	60.07	118.63	167.54	65.62	96.19	133.29
80%	99.20%	65.82	131.18	195.72	71.91	103.48	157.72
85%	99.66%	75.55	160.37	213.72	87.80	130.65	173.16
90%	99.90%	84.92	184.14	239.66	98.69	149.31	190.64
95%	99.99%	103.73	222.39	297.69	124.48	182.28	239.01
100%	100.00%	384.06	794.43	1003.97	436.10	644.05	780.41

Table 6. Variable-size Elemental Search Area (ESA) MiRSA Suspected Minefield Area Mission Times (SMAMTs)

Implementation of the variable-size ESA version of MiRSA for varying search levels results in the SMAMTs listed above. The full system comprised of two LMRS vehicles, six REMUS vehicles, and one Manta at a 63% search level (~95% confidence level) requires only 46.53 hours to search the 262 square nautical miles of the Straits of Hormuz and 384.06 hours for an exhaustive search. Manta operating alone requires 129.89 hours at a 63% search level and 1,003.97 hours for an exhaustive search.

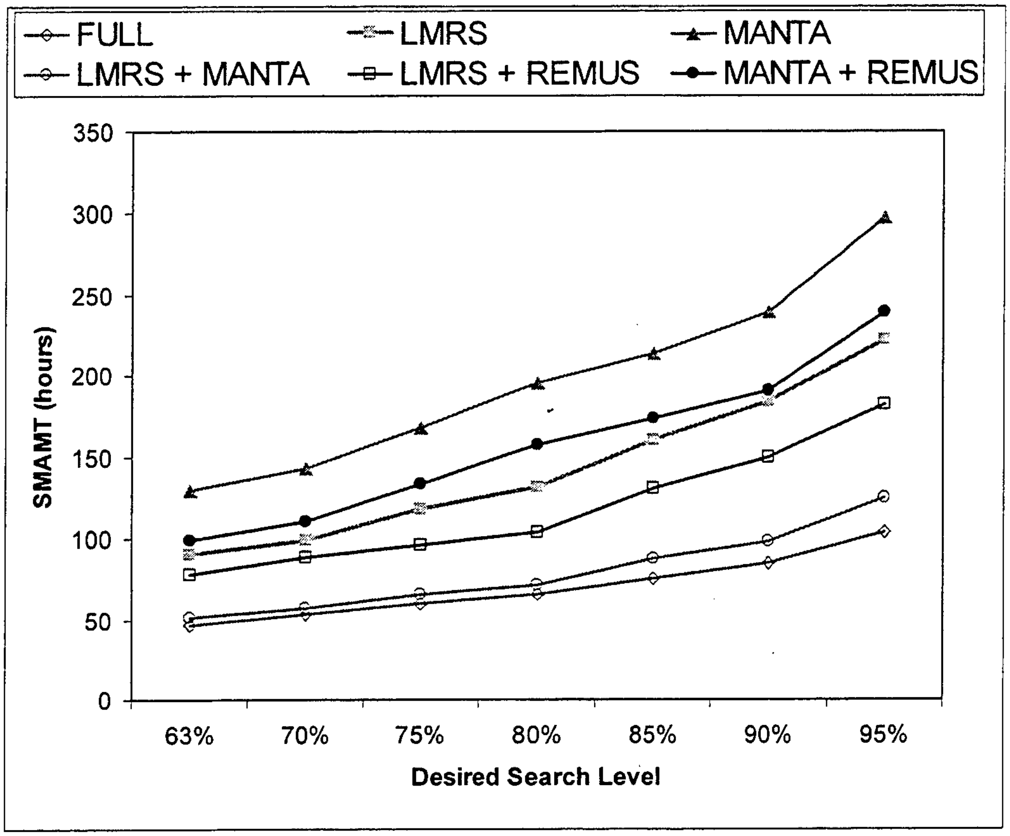

Figure 9. Variable-size Elemental Search Area (ESA) MiRSA Optimized Suspected Minefield Area Mission Time (SMAMT) Curves

SMAMT results for composite systems remain consistent with results from the fixed-size ESA MiRSA model. Variable-size ESAs reduce the amount of excess area searched for each SZ. Because significantly more time is required at the 100% search level (Table 6), the 100% search level results are not shown above.

The result remains consistent with the fixed-size ESA MiRSA model. However, implementing variable-size ESAs reduces the amount of excess area searched for each SZ.

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VI. CONCLUSIONS

The value of a mixed integer-linear programming approach is twofold. The MiRSA model provides a tool for rapidly assessing the benefit of employing combinations of varying UUV architectures. In addition, for a specific scenario and available UUV architectures, MiRSA model results provide tactical commanders with a decision-aid for assigning UUVs to mine detection operations. The MiRSA model's simplifying assumptions include constant UUV performance for a given SZ and allowed simultaneous UUV launches. The additional time associated with launch and recovery of multiple UUVs are small in comparison to the overall time required to search the entire SMA. Lastly, by assuming fairly uniform ESA widths for each UUV and each SZ, the MiRSA model executes in under five minutes for all scenarios considered.

MiRSA finds two LMRS vehicles can complete a 95% confidence level search of the Straits of Hormuz in 91 hours and the Manta vehicle requires nearly 130 hours. If two vehicle architectures are available, the two LMRS vehicles with Manta employed together require only 52 hours. When only the LRMS or the Manta is to be operated with the REMUS vehicles, MiRSA finds the LMRS and REMUS combined system requires 78 hours while the Manta and REMUS combined system requires 100 hours. Employing two LMRS vehicles, six REMUS vehicles, and Manta together finish the search in 47 hours.

Exhaustive search requires no gaps between search lanes and a sharp increase in search time. Two LMRS vehicles require 794 hours to conduct an exhaustive search; the Manta vehicle requires 1,004 hours. The two LMRS vehicles with Manta employed together require only 436 hours. Employing two LMRS vehicles with REMUS requires

644 hours, employing the Manta vehicle with REMUS requires 780 hours, all three UUV architectures, employed together, finish the search in 384 hours.

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