Decision Algorithms for Unmanned Underwater Vehicles during Offensive Operations

by

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B.S., Operations Research
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Submitted to the Department of Civil and Environmental Engineering
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Abstract

The field of research involving autonomous vehicles has expanded greatly over the past decade. This thesis addresses the case of a system of Unmanned Underwater Vehicles (UUVs) operating in littoral areas in an offensive capacity. A series of complementary algorithms were designed to collect information about an enemy vessel, and subsequently use this information to both select and move to a preferred intercept location that maximizes the opportunity to both re-acquire and destroy an enemy vessel. Additionally, within the context of a specifically designed simulation, key parameter changes were analyzed to determine their effectiveness to improve the system’s performance as measured by four measures of effectiveness. A methodology was also designed to optimize the location of the engaging UUVs to maximize their effectiveness, and capitalize on the enemy movement within the operational area. Results are presented for both original locations and optimized locations, and initial findings provide insight into the effectiveness of the designed algorithms and statistical inference of these key parameter changes.

Technical Supervisor: Margaret F. Nervegna
Title: Charles Stark Draper Laboratory

Thesis Supervisor: Professor Cynthia Barnhart
Title: Civil and Environmental Engineering
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Tyler B. Smith, MAJ, US Army, May 12, 2006
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Chapter 1

Introduction

This thesis develops decision algorithms to facilitate unmanned undersea vehicles (UUVs) operating in an offensive capacity. More precisely, this thesis develops and implements decision algorithms that will enable a specially structured team of UUVs to detect, intercept, engage and ultimately destroy hostile contacts in littoral or shallow water areas. This chapter discusses the problem, the motivation, and the importance of UUVs operating in an offensive capacity. The conclusion of this chapter presents a summary of the contributions and an outline of the thesis.

An unmanned undersea vehicle is defined as a self-propelled submersible whose operation is either fully autonomous (pre-programmed or real-time adaptive mission control) or under minimal supervisory control and is un-tethered except for wireless communication links. [1] This research will focus on algorithms that are applicable to offensive operations for UUVs under minimal supervisory control, and un-tethered. Additionally, within the context of these algorithms, a realistic simulation testbed must be designed and built to measure algorithm success and analyze the contribution of key parameters toward improving system performance.
1.1 Problem Motivation

The future of modern warfare is for light mobile troops to operate independently in littoral areas. With the US military spiraling its capabilities toward sea-based warfare during the first quarter of the 21st century and other western forces readying themselves for littoral warfare, there is increasing need for a suite of weapons systems that can simultaneously defend both sea-based assets and amphibious forces. [21] While it is true that many recent naval missions such as sanction enforcement, interdiction operations, and support to ground forces ashore, suggest a shift from blue water to littoral operations, in fact most naval activity during the Cold War took place in littoral areas. [20] While strategic mobility and operational maneuver are still inherent strengths for naval forces, care must be exercised when operating within the range of land, and magnifies the importance of operating in and controlling littoral areas of operation.

Autonomous Operations (AO), one of twelve future naval capabilities, is the capability to perform militarily useful missions using unmanned vehicles in dynamic and unstructured environments with greatly reduced need for human intervention. The United States Navy explores multiple types of UUV mission profiles, but for the purposes of this thesis, offensive weapon engagements are explored. [1] Key benefits and missions in which UUVs show high promise are:

1. **Sensor Deployment**: UUVs have the ability to emplace sensors in an excellent position in both the vertical and horizontal dimensions.

2. **Autonomy**: The ability of an UUV to operate independently for extended periods creates a force multiplier that allows manned systems to extend their reach and focus on more difficult tasks. Reduced costs are also a result when sensors and weapons are operated from smaller platforms like UUVs.

3. **Risk**: Because UUVs are unmanned, there is a reduced threat to personnel from a harsh sea or enemy combatants.
4. **Deployability:** UUVs can be designed as flyaway packages or pre-positioned in forward areas. They can be launched from a wide variety of platforms including ships, submarines, aircraft, and shore facilities. Also, they do not have to be recovered from the same craft from which they were launched. Recoveries may be delayed or abandoned because of the extendability created by a UUV's low cost.

5. **Environmental Adaptability:** UUVs can operate in a diverse range of environments including deep to shallow water, foul weather and seas, and tropical or arctic conditions [1].

Due to the complicated nature of these missions and the environments in which they are carried out, there exists a continued need to develop and implement decision systems that can handle untested situations and environments.[5] Although technology and industrial capacity exist, UUV autonomy has yet to reach a level of confidence where they would be permitted to execute complex missions, especially missions involving hostile engagements.

### 1.2 Problem Statement

The specific problem addressed through this thesis is the development of efficient decision algorithms to allow a system of UUVs to act in an offensive capacity. Initially, it is assumed that a threat vessel is operating in its own harbor, and a system of friendly UUVs has been deployed to locate and engage the threat vessel. However, the system must acquire the target, receive permission to engage, and subsequently engage only after receiving appropriate approval. Therefore, a series of complementary algorithms must be developed that can acquire the enemy vessel, detect key information about the threat, and determine a methodology to select and move to a preferred location to intercept the threat vessel.

In the end, a simulation must be developed to test the decision algorithms, and provide a methodology by which key UUV technological enhancements can be examined.
1.3 Contributions and Organization of Thesis

The contributions of this thesis are:

1. **Enemy Information.** The work in this thesis develops an approach to use shipping lane information to accurately estimate information regarding location and speed of potential targets. The fundamental idea is to assume the enemy vessel is traveling down the center of the lane, and use bearing information gathered from a detector to calculate an estimated location for the target, and subsequently infer its operating speed. Additional benefits of this approach include the ability to gather information about the threat vessel without requiring complex detector movements that are both difficult to automate, and require the use of limited energy stores.

2. **Intercept locations.** The fundamental approach in this research again uses information regarding the shipping lanes in a harbor and specifies a preferred intercept location. Rather than attempting to intercept the threat vessel based on predicted location and time, this research uses the shipping lane concept to intercept the threat at a location that minimizes the area of the shipping lane at the intercept point. This point both increases the opportunity for reacquisition of the target, and minimizes the operational area for the threat to avoid the impending attack by the UUV.

3. **UUV location.** The research develops and implements a novel concept for placement of UUVs. Through the use of environmental information, the friendly UUVs are positioned in optimal locations that provide a robust opportunity for reacquisition and improves probability of successful engagements.

The remaining portions of this thesis are organized as follows. Chapter 2 explores the current state of technology and tactics for UUVs operating in the military environment.

Chapters 3 and 4 explore the selected area of operations and the base vehicles that are used in the underlying simulation designed to test the algorithms and gain inference on statistical improvements to the system.
Chapter 5 outlines the design of the algorithms and discusses the overall structure of the simulation. The algorithms are discussed in detail, and are presented in a general format to permit their application in any operational area that is similar to the littoral area selected for this simulation.

Chapter 6 explores the experimental design used to compare the parameter changes, examines the statistical methods selected to numerically compare the varying simulation cases, and presents the initial results of the simulation.

Chapter 7 examines the developed methodology to optimize the location of the UUVs charged with killing the threat vessel, and subsequently presents the new results of the experimental design with the new placement of these “killer” UUVs.

Chapter 8 offers a summary of the research and provides recommendations for future work that could benefit the future of UUVs operating in the offensive role.
Chapter 2

UUV Role in Naval Operations

"Throughout history we have seen that the technology that has given us the best return often was looked at skeptically at the beginning."

Rear Adm. Paul F. Sullivan
Director - Submarine Warfare Division

Among the world's naval forces, the U.S. Navy and Marine Corps are second to none, and at present they have no close competitor. However, the current national security environment places increased demands on the Navy and Marine Corps for increased presence in a larger number of strategically important geographic locations. Additionally, the need exists for a more rapid and flexible response to emerging crises, and for new capabilities to enable decisive victory over determined adversaries employing asymmetric means; defined as a weaker combatant uses nontraditional weapons and strategy in order to obtain a fighting advantage over a stronger opponent.

As the post-Cold War era has evolved, it has become increasingly clear that many legacy military systems have limited utility in meeting many emerging challenges. As part of the ongoing transformation of the U.S. military services, the future Navy and Marine Corps requirements mandate a marked transformation. The environment of the world today reflects increased uncertainty about origins of threats, possible locations of attacks, and the means by which they might be delivered. The term asymmetric threat is now familiar in military
operations, and terrorist actions are a frequent occurrence and constant threat. For naval forces, the classical terms “blue water” threat and “major threat axis” no longer hold the significance they once did; the threat environment has moved from the “blue water” to “brown water,” or littoral regions, placing emphasis on power projection, force protection, and global expeditionary operations in littoral areas.

Along with this change in emphasis, new capabilities will be required of naval forces in the areas of “transitre time intelligence, surveillance, and reconnaissance (ISR); oceanographic bathymetric surveys; battlespace preparation; battlespace awareness; mine warfare; antisubmarine warfare (ASW); special operations and strike support; surface warfare (including interdiction); littoral ASW with emphasis on diesel submarines; and base and port security.”[2] In turn, the kinds of missions listed above place a premium on integrated, persistent ISR; command, control, and communications (C3); and distributed, real-time knowledge. The increasing needs arising from the new threats may be alleviated, to a growing extent, by exploiting the benefits of technological advances.[3]

One key technology that has emerged over the last two decades is the unmanned vehicle which can perform military functions that are often too dangerous or impossible for manned vehicles. These unmanned vehicles are capable of operating on land, sea or air and have demonstrated an operational ability to act as a force multiplier in almost all military operations. Several current systems set the precedent, including the Tomahawk, which is an armed unmanned aerial vehicle (UAV); the ADCAP torpedo; the Improved Submarine Launched Mobile Mine (ISLMM), and the CAPTOR mine.[2]

With these systems in place, the United States Navy has placed significant emphasis on the development of UUVs to meet their future operational needs. Speed, covertness, and long standoff could allow a UUV to be an effective weapon or weapon platform in a variety of mission scenarios. All else being equal, unmanned vehicles with a high degree of autonomy can potentially reduce training, support rapid change in tactics (i.e., capitalize more rapidly on the digital battlefield), enable reductions in force personnel, and help reduce the logistics footprint, to name a few advantages. The bottom line is that autonomous vehicles will play
a major role in the transformed force.

2.1 UUV Development in US Navy

In June 2002, the United States Navy introduced “Sea Power 21” to guide the US Navy toward a “broadened strategy in which naval forces are fully integrated into global joint operations against regional and trans-national dangers.”[2] This document gives Naval operators, technical advisers and future acquisition personnel general guidance about the future Naval vision, and ensures a common picture of growth and focus for the many disparate stakeholders.

Beginning in 1994, the United States Naval Undersea warfare community developed a “UUV Master Plan” to guide the future capabilities and integration of Unmanned Undersea Vehicles into the Navy arsenal and execution of its core competencies. This plan has subsequently had two revisions in 2000, and most recently in November, 2004, which followed the “Sea Power 21” framework to ensure on-going UUV development was nested within this overarching framework.

The Navy-approved UUV Master Plan provides a thorough and explicit road map for the development of UUVs, addressing their evolving capabilities, their tactical and strategic concept of operations, and they many technology and engineering issues; including underwater communications, improved sensors, improved navigation, high energy density sources, and improved launch-and-recovery systems.[1]

The “UUV Master Plan” crafted with input from Navy users, stakeholders, Navy laboratories, academia, and industry to develop prioritized missions where UUV technology can play a discernible role[1]. The priorities are as follows:

1. **Intelligence, Surveillance and Reconnaissance (ISR):** This mission focuses naval resources to gain information about current or future threats through direct or indirect observation. This does not normally include direct action.

2. **Mine Countermeasures (MCM):** This capability is to find or create operating areas
that are clear of sea mines without requiring manned platforms to enter threatening areas.

3. Anti-Submarine Warfare (ASW): This capability focuses on preventing a threat from operating its Submarine force to hinder, threaten or interdict friendly operations.

4. Inspection/Identification: This capability focuses on the ability to reconnoiter areas of concern rapidly for threatening objects or vehicles, and subsequently identify and possibly react to the threat.

5. Oceanography: This capability provides for the collection of hydrographic and oceanographic data in ocean environments. This supports real-time operations as well as intelligence preparation of the battlefield for future operations.

6. Communication/Navigation Network Nodes (CN3): This capability focuses on providing connectivity across multiple platforms, and enabling navigation and secure communications to meet any naval requirement.

7. Payload Delivery: This capability focuses on a clandestine method of delivering logistics to support mission objectives. An example could be clandestine resupply of CIA operatives operating in hostile areas.

8. Information Operations (IO): The objective of Information Operations is to "exploit, deceive, deter and disrupt our enemies"[1].

9. Time Critical Strike (TCS): This aspect focuses on delivering weapons to a target, using the stealth of the UUV to confuse the enemy and reduce their reaction time to the normal long-distance cruise missile.

These high priority missions were subsequently grouped under the four Sea Power 21 pillars[2]:

1. **Sea Shield**: Sea Shield is the concept focused on the protection of national interests by sea-based defense resources. Traditionally, the Navy has maintained vital sea lines
of communication, protected its own offensive forces, and provided strategic deter-
rence through nuclear-armed submarine patrols. Under Sea Shield, the Navy will also
project an umbrella of theater air defense ashore, assist in providing ballistic missile
defense for the U.S. homeland and for forces in theater, and extend the security of the
United States seaward by detecting and intercepting vessels of hostile intent.[3] The
aforementioned priorities associated with Sea Shield are:

(a) Mine Countermeasures
(b) Anti-Submarine Warfare
(c) Inspection/Identification

2. Sea Strike: Sea Strike is a broad concept for projecting precise and persistent offensive
power from the sea. According to this concept, networked, autonomous, organic, long-
dwell naval sensors, integrated with national and joint systems, will provide persistent
intelligence, surveillance, and reconnaissance (ISR), enabling the development of a
comprehensive understanding of an adversary's capabilities and vulnerabilities. Closely
integrated with these ISR assets will be the capability to strike time-sensitive and
moving targets so as to defeat any plausible enemy force.[3] The priorities associated
with Sea Strike are:

(a) Information Operations
(b) Time Critical Strike

3. Sea Base: As stated in “Sea Power 21,” “As enemy access to weapons of mass de-
struction grows, and the availability of overseas bases and ports declines, it is com-
pelling both militarily and politically to reduce the vulnerability of U.S. forces through
expanded use of secure, mobile, networked sea bases.”[2] Sea Basing will support ver-
satile and flexible power projection, enabling forces up to the size of a Marine Exped-
ditionary Brigade (MEB) to move to objectives deep inland. More than a family of
platforms afloat, Sea Basing will network platforms among the Expeditionary Strike
Group (ESG), the Carrier Strike Group (CSG), the Maritime Prepositioning Force (MPF), the Combat Logistics Force (CLF), and emerging high-speed sea lift technologies. It will enable Marine forces to commence sustainable operations and enable the flow of follow-on forces into theater and through the sea base, as well as expediting the reconstitution and redeployment of Marine forces for other missions.[3] The aforementioned priorities associated with Sea Base are:

(a) Payload Delivery

4. **ForceNet**: FORCEnet is the Chief of Naval Operations (CNOs) vision for enabling network-centric operations for the Navy. According to the CNO ADM Vern Clark, FORCEnet is the “operational construct and architectural framework for naval warfare in the information age, integrating warriors, sensors, command and control, platforms, and weapons into a networked, distributed combat force.”[2] While broader in concept than just communications networks, it includes “dynamic, multi-path and survivable networks” among the capabilities to be provided.[3] The aforementioned priorities associated with ForceNet are:

(a) Intelligence, Surveillance and Reconnaissance

(b) Communication/ Navigation Network Nodes

(c) Oceanography

It is within this framework that this thesis examines the UUV capability to perform offensive operations. This document explores decision algorithms that are enhancements to current tactics and fall within both the Sea Shield and ForceNET areas of emphasis. However, prior to in-depth discussion, it is imperative to understand the basic fundamentals of UUVs and explore the current state of technology within this growing community.
2.2 Current UUV Operations

The field of UUVs has grown over the past 20 years from rudimentary tethered vehicles that execute simple tasks such as ship inspection or oceanic search to today’s UUVs that can utilize advanced sensors to search for mines or undersea life. The preponderance of open source UUV development has taken place with civilian applications in mind, and the military development has often been geared to capitalize on these advances to improve their operations.

2.2.1 Civilian Operations

For more than two decades, unmanned systems have played a notable role in oceanographic research, deep water commercial applications, and military related missions. In the 1980s, researchers used a tethered UUV to explore the wreck of the Titanic, nearly 2.5 miles below the ocean surface.[21] More recently, UUVs have helped the oil and gas industries explore the seabed for new energy sources; and aided the military in destroying active underwater mines littering the Persian Gulf floor following the Gulf War. Interest in using UUVs in private industry is growing and internationally, at least a half-dozen firms have begun to commercialize UUV technology developed in university and military laboratories. Currently, several vehicles are available for sale on the world market, and some developers also offer UUV services to the oil, undersea mining, and submarine cable industries for detailed bottom mapping, surveying and geological exploration. In many applications, the UUV approach costs less than half that of a typical deep towed system covering the same area— and, these vehicles can, and have, explored places that towed systems cannot, such as under the Arctic Ice. Typically, the UUVs offered for commercial services have been relatively small – generally about 15 feet long and several thousand pounds – and they offer endurance on rechargeable batteries of nearly 20 hours at three to five knots. [21]
2.2.2 Military Operations

The first real autonomous underwater vehicle was the MK30 modified torpedo, used in ASW training to simulate a submarine’s signature. The MK30MOD1 initially became operational in 1975 with 63 units in fleet service, and the much more advanced MOD2 began evaluations in 1998 with the first units to be procured during 2005.[8] The 1994 UUV Program Plan led to the development of the Near-term Mine Reconnaissance System (NMRS), which was tested in 1998 from an oceanographic vessel, conducting deep and shallow water surveys for mine countermeasures purposes. Additional tests from LOS ANGELES class submarines were conducted in the same year. NMRS is fiber-optic controlled, carries a multi-beam search sonar and a side-scan classification sonar, and is launched and recovered via a torpedo tube. NMRS was plagued by a number of significant limitations: poor navigation accuracy, high false-contact rate, no bathymetry, and additionally it is not fully independent, being tether-limited. The next generation Long Range Mine Reconnaissance System (LMRS), in development by Boeing, features a 533mm diameter torpedo shape, and is fitted with a forward looking search sonar and a side-looking classification sonar for mine counter-measures purposes as well as the specially developed Littoral Precision Underwater Mapping Array (LPUMA).[21]. LMRS should boast a 40-hour endurance and a top speed of 7 knots, which implies the capability to search daily an area of 35-50 square miles at ranges up to 120 miles from the parent ship. LMRS and the submarine will communicate at short ranges with an acoustic data-link, while sporadic satellite communications will allow both long-range command and control and data exchange. [20]

While the large LMRS is still in the development phase, the US Navy already has a man portable UUV in operational use. The REMUS (Remote Environmental Monitoring Units) weighs less than 40 kilograms, with a diameter of 19 centimeters and a length of 1.4-2.1 meters. It is powered by Lithium batteries with a speed of 3 knots and an endurance of 22 hours (or 8 hours at 5 knots).[20] It was initially designed for oceanographic measurements, but soon the US Navy deployed it for the mine clearance effort of the Umm Qasr port in Iraq, opening the way to the British amphibious ship HMS SIR GALAHAD loaded with
humanitarian aids. They also conducted additional UUV operations further up the river at Az Zubayr and Karbala, Iraq. During Operation Iraqi Freedom, the Naval Special Clearance Team-One (NSCT-1) made extensive use of REMUS, exploiting its small size to operate it from rubber combat boats and piers, requiring minimum support.[21] In all, REMUS conducted ten missions in the waters off Umm Qasr, covering a total of 2.5 million square meters. It discovered and marked 97 man-made objects and shapes. In all three locations, a useful byproduct of this underwater work was the bathymetric data collected and shared with the Port and Maritime Registry, which will help in pending dredging operations. NSCT Ones mission proved that by using UUVs in actual field work in difficult wartime conditions, they were able to achieve a military objective, and also provide valuable environmental and oceanographic data that will be extremely important in the days to come.[8] REMUS operates down to a 100m depth, and can be fitted with a variety of advanced sensors including a side scan sonar for MCM tasks. “The US Navy procured 18 REMUS units, manufactured by Hydroid, and is planning to use them in a number of roles, including environmental survey, MCM and inspection. REMUS is planned for deployment from small boats, large UUVs and other vessels, including of course mine hunters.”[20] The success achieved during Operation

![UUV Operations in Iraq](image)

Iraqi Freedom also paved the way for export orders. The German Navy Test Center ordered one unit for evaluations in the fields of both MCM and Special Forces. The NATO Undersea Research Center (SACLANTCEN) based in La Spezia also ordered two REMUS in February
2004, that were initially tested in the Baltic Sea to evaluate their possibilities in traditional mine hunting as well in counter-terrorism in an harbor environment. During these trials REMUS was fitted with some of the latest enhancements (e.g., GPS, dual frequency very high-resolution side-scan sonar, acoustic communications between the vehicle and the parent ship). REMUS was also recently ordered by the Royal Netherlands Navy and the Singapore Navy (two units each).[20]

2.3 Current UUV Challenges

Commercial and military UUVs share most of the same technology requirements, but as often happens, the military ones are more rigorous. There are different areas of technology involved. Indeed, operating in the undersea realm poses a significant number of complicated engineering issues that must be overcome to adapt current UUV operations to meet the future goals of the US Navy. The major engineering issues can be placed within five sections:

1. **Energy**: Today's UUVs are battery-powered, and battery capacity remains the most fundamental limitation on range and endurance. Because the power required to propel an underwater vehicle is roughly proportional to its size, and energy capacity to its volume, the mission duration achievable at a given velocity can be shown to vary directly with ship size. Thus, without quantum breakthroughs in energy storage, it is difficult to imagine small UUVs that are able to perform theater-scale missions or long-duration trailing tasks.

2. **Communications**: One major aspect of UUV operations rests in their area of operations; that is, under the ocean surface. Underwater communications remain a difficult task to accomplish, especially when coupled with the size and energy requirements that plague the UUV community. Additionally, the underwater bandwidth capability currently available is quickly exhausted when one considers the large amount of information that would need to be sent from or to the UUV during information collection missions. Without viable communications, however, the using force would need to
wait until the UUV returns for mission information, which in many cases might be detrimental to the mission goals.

3. **Navigation:** Precision vehicle position sensing is an essential element of control and use of UUVs. It is impossible, for example, to precisely control a vehicle to within 1 meter when its position sensor is precise on to 50 meters. Almost all imaginable UUV tasks require the UUV to have a precise knowledge of its own location, whether it be locating underwater mines, or attempting to locate threat vessels;[21] not to mention the importance of position knowledge when operating in obstacle rich environments such as littoral regions.

4. **Sensors:** The underwater realm has led to the development of many technological advanced sensors such as side-looking sonar, electro-magnetic and electro-optic ISR sensors. However, these sensors are both energy hungry and massive in size. The UUV limitation on size and energy require that these sensors, or instruments with similar capability, be re-engineered to be much smaller and in low power configurations.

5. **Autonomy:** This capability includes the ability to transit long distances, detect, collect information and assess the situation, all of this without human-in-loop intervention. It includes key aspects such as mission planning, obstacle and dynamic threat avoidance, and adaptive route planning. The UUV must be able to collect and evaluate the data, giving different importance to the results, both as a mission product and as it impacts on vehicle operation for the remainder of the sortie. Autonomy is paramount, because in most of the projected missions/scenarios it is very difficult or even utterly impossible to maintain a continuous link with a human supervisor.

Within the framework of these future missions and discernible engineering challenges, this research explores methods in which UUVs can operate in a hostile coastal area, and specifically, demonstrates how decision algorithms can assist UUVs in using coastal specific aspects and terrain to their advantage; more precisely, the benefits of naval choke points and “shipping” lanes. This research will focus on developing methods to allow a relatively
small number of UUVs deploy to detect, acquire, and ultimately engage and destroy a threat vessel. However, to examine the potential benefit of decision algorithms for this system it is crucial to develop a viable test area of operations. This will be explored in the next chapter.
Chapter 3

Area of Operations

The purpose of this chapter is to explain the selection methodology for an area of operations to represent a realistic environment in which to test the algorithms developed in this research and presented formally in subsequent chapters.

3.1 Area of Operations

Many future naval combat operations are likely to be in the littorals in order to project combat power ashore and to provide an umbrella of defense for land-based forces. In the littorals, naval operations could be contested with mines, diesel submarines, small coastal defense boats, and antiship cruise missiles or long-range artillery. Thus, the military’s ability to control and freely operate within these critical areas represents a center of gravity for future military planners. Additionally, operations in these shallow harbor areas present a unique opportunity for military offensive operations. The littoral regions surrounding an enemy nation represent a key transportation node for a nation’s military, and UUVs represent a viable tool capable of disrupting an enemy nation’s maneuver ability within its own waters.

With these concepts in mind, it proved critical to develop a simulation environment that would accurately represent a realistic operating area for UUV operations in future combat operations, and thus serve as a realistic test bed for UUV simulations. Thus, in
conjunction with past work at Draper Laboratory, Narraganset Bay, Rhode Island was chosen as the representative model. This bay has significant terrain that facilitates complex routing algorithms, and can be easily used to represent both offensive and defensive scenarios.

![Area of Operations](image)

**Figure 3.1: Narraganset Bay Area of Operations**

More precisely, the area of operations assigned to this simulation is the portion of Narraganset harbor that falls North of 41°24′, East of −71°36′, West of −71°06′ and South of 41°54′, as shown in Figure 3.1. This area is approximately 2353 square kilometers, of which 579 square kilometers is considered operational water area.

### 3.1.1 Bathymetric data for the area of operations.

This simulation utilized database information from the National Ocean Service (NOS) hydrographic data base (NOSHDB), maintained by the National Geophysical Data Center (NGDS) in conjunction with NOS; it comprises the majority of NGDC's area survey holdings and provides extensive survey coverage of the coastal waters and Exclusive Economic Zone (EEZ) of the United States and its territories. The NOSHDB contains data digitized
from smooth sheets of hydrographic surveys completed between 1851 and 1965, and from survey data acquired digitally on NOS survey vessels since 1965. The data is presented by providing multiple [LAT, LONG] grids and a corresponding depth presented in meters.

3.1.2 Shipping Lanes

One critical element of autonomous vehicles is their requirement to move safely throughout the real world environment, and account for the various physical obstacles; not to mention the threats that could appear without notice. However, it is also possible for the UUV to use these same physical obstacles to their operational advantage, and attempt to minimize its own weakness against a stronger enemy force. One pseudo-physical structure that exists in the littoral environment is shipping lanes. When one refers to shipping lanes, the most common structure is the established open-ocean environment where commercial vessels move cargo from port to port; however, shipping lanes also exist within coastal and harbor areas. Harbor regions, specifically, have significant restrictions to shipping operations. These lanes are more often defined by the depth and width of the waters in the harbor, but can also be shaped by civilian recreation areas, wildlife protection areas, or other political constraints. These established lanes are typically well known and charted on naval charts. Shipping lanes, thus, stand as a good reference to where ocean going vessels will travel through littoral areas, and provide a natural boundary which UUVs can use to their advantage.

3.1.3 Narraganset Bay Specific Lanes

The Narraganset Bay coastal area presents an excellent model for the simulation because of the diverse terrain that lends itself to simulate the shipping lane concept. Although the simulated shipping lane information used for Narraganset Bay was developed to meet the research needs for this thesis, the routes developed represent a realistic example of any fictional coastal area. Each of the three routes begins at a modeled northern start point, and transits the harbor region moving from north to south, and ends when the lane reaches open water at the southern exit point of Narraganset Bay.
Figure 3.2: Narraganset Bay Shipping Lanes
For documentation purposes, the routes are labeled according to assumed historical usage (see Figure 3.2), with Route A being the center most route, Route B being the western most route, and Route C being the eastern route. Table 3.1 provides more detailed information regarding the specific shipping lanes used in this research.

<table>
<thead>
<tr>
<th>Start Point</th>
<th>Route A</th>
<th>Route B</th>
<th>Route C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lat/Long</td>
<td>41.805°</td>
<td>41.805°</td>
<td>41.805°</td>
</tr>
<tr>
<td></td>
<td>-71.394°</td>
<td>-71.394°</td>
<td>-71.394°</td>
</tr>
<tr>
<td>End Point</td>
<td>41.411°</td>
<td>41.411°</td>
<td>41.411°</td>
</tr>
<tr>
<td>Lat/Long</td>
<td>-71.375°</td>
<td>-71.411°</td>
<td>-71.216°</td>
</tr>
<tr>
<td>Total Waypoints</td>
<td>17</td>
<td>15</td>
<td>21</td>
</tr>
<tr>
<td>Distance</td>
<td>48.73 Km</td>
<td>47.24 Km</td>
<td>58.85 Km</td>
</tr>
</tbody>
</table>

Table 3.1: Narraganset Bay Shipping Lanes

The next step was to transform the chosen operational area and digital bathymetric data into a usable digital framework for use on the simulation.

### 3.2 Digital Map

This digital map methodology takes the grid interval parameter and builds a map that is equal to the dimensions of the operating area, with each square having sides with a length equal to the grid interval parameter. The approximately 300,000 bathymetric data points were then placed into their respective grid squares with the true bathymetric data taken from NGDS services. For simplicity purposes, the script designates each square as either GO or NO-GO terrain. As shown in Figure 3.2, a 1 represents GO water, and the 0 represents NO-GO water.

For the purposes of this research, the minimum depth for UUV operations was determined to be 25 feet of water and thus if one of the bathymetric readings inside each square was equal or deeper than 25 feet, then the entire square was determined to be GO terrain. This metric was chosen to give a realistic combination of stealth and usable operational area.

For comparison purposes only, the following figures show what the digitized map looks like at 1000m, 500m and 200m accuracy levels.
Table 3.2: Example of Discrete Map

Figure 3.3: Digitized Map with 1000m grid Interval

Figure 3.4: Digitized Map with 500m grid Interval
As Figures 3.3 through 3.5 demonstrate, a larger grid interval size (i.e. 1000 meters) provides a larger operational water area for the UUVs to operate within, but at a cost of accuracy in the fidelity of the true harbor region. The larger grid interval size, however, provides the inherent benefit of a smaller mathematical matrix needed to describe the area in digital format. For example, by using 100m grid interval the digital map requires 235,200 nodes, while the 1000 meter grid interval describes the same sized terrain with only 9408 discrete nodes. With the desire to combine computational efficiency with a realistic portrayal of the operational area, the decision was made to use 200 meters as the standard grid interval. This grid interval allows for high fidelity modeling of the operational area, see figure 3.5, while allowing future computations to examine only 58,800 nodes.
Chapter 4

Simulation Vehicles

To build a realistic simulation environment in which to test the developed algorithms, it was critical to simulate both enemy and friendly vehicles accurately. This chapter describes the foundational assumptions used to design and simulate these vehicles and the mathematical procedures to simulate the enemy vessels travel through the operational area.

4.1 Enemy Vehicles

Inherent to the simulation is the creation of a viable enemy force that accurately represents vessels that Allied forces may face in the future. For the purposes of this thesis, three different vessels are designated to transit through the operational area, and the subsequent peculiarities of each of these ships is modeled in the simulation; these parameters are modeled by changing operating speed, route possibilities, and altering the probability of hit and probability of kill against these specific vessels.

4.1.1 Foundational Assumptions

The underlying assumption in this problem is that threat vessels will be encountered during the course of the simulation and that their ultimate goal is to transit the bay in a north-south direction and head out to open ocean. One key assumption is that the threat vessels will
remain within the previously established shipping lanes during their transit of the littoral region.

4.1.2 Three Types of Simulated Vehicles

In an attempt to accurately represent the broad range of missions the team of UUVs could be tasked to complete, and thus it is crucial to model several types of enemy vessels. Each of the three simulated vehicles retains specific characteristics that affect the route transited and the speed traveled down the route.

Definitions of key characteristics

1. Max Speed: This is the maximum speed that the ship can hope to attain under normal combat configuration and manning.

2. Cruise Speed: This is the speed that provides the maximum time endurance for the vessel (i.e. they can go this speed for the longest period of time.) This is the speed that one would normally expect to see the vessel traveling at, as it provides the best combination of fuel usage, endurance, and travel time.

3. Draw: This is the depth the ship extends below the surface when loaded to capacity. This aspect of the ship limits its ability to travel through shallow water, and is the primary factor that affects the ships ability to transit specific waters in and around littoral areas.

4.1.3 Enemy Vehicle 1: Cargo Vessel

The specifications for the cargo vessel are shown in the Table 4.1, and are representative of a general cargo vessel. Modern armies deploy their combat forces via these typical commercial vessels, they re-supply their deployed forces on these ships, and/or their economy is founded on their ability to import/export key resources. Thus this ship is representative of a possible target for a naval commander charged with denying enemy usage of littoral areas, or as part of an on-going campaign to at
Table 4.1: Cargo Vessel Specifications

<table>
<thead>
<tr>
<th>Cargo Vessel</th>
<th>Displacement (tons)</th>
<th>Full Load</th>
<th>4,250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
<td>Length</td>
<td>182.9m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Beam</td>
<td>32.2m</td>
<td></td>
</tr>
<tr>
<td>Speed (knots)</td>
<td>Cruise</td>
<td>14.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Draft</td>
<td>12.00M (39.5 ft)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1: Cargo Vessel Specifications
4.1.4 Enemy Vehicle 2: Ocean Surveillance Vessel

![Ocean Surveillance Vessel](image)

Figure 4.2: Ocean Surveillance Vessel

<table>
<thead>
<tr>
<th>Ocean Surveillance Vessel</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement (tons)</td>
<td>Full Load</td>
</tr>
<tr>
<td>Full Load</td>
<td>2,301</td>
</tr>
<tr>
<td>Dimension</td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>68.3m</td>
</tr>
<tr>
<td>Beam</td>
<td>13.1m</td>
</tr>
<tr>
<td>Speed (knots)</td>
<td></td>
</tr>
<tr>
<td>Cruise</td>
<td>10.5</td>
</tr>
<tr>
<td>Maximum</td>
<td>15</td>
</tr>
<tr>
<td>Draft</td>
<td>4.6M (15ft)</td>
</tr>
</tbody>
</table>

Table 4.2: Ocean Surveillance Vessel Specifications

The ocean surveillance vessel is designed to represent a typical medium-sized vessel that could be used by enemy forces for a variety of tasks. Ships of this size are often used as part of larger naval task forces to conduct mine warfare, electronic reconnaissance or anti-submarine tasks. Possible engagements against this type of ship are most likely during the naval preparation of a harbor area for follow-on action, or clearing the area for a special forces insertions. The specifics of this type of ship are shown in Table 4.2.

4.1.5 Enemy Vehicle 3: Frigate

The frigate represents a typical enemy ship of war. It has the capability to move both in open ocean and shallow coastal areas. It is typically armed with extensive weapons that protect it from both air, sea and sub-surface threat vessels. Engagements against a ship of this type are most likely in an effort to destroy dangerous enemy ships before they are able
to move into open ocean and hinder friendly vessels freedom of maneuver outside the direct area of operations. The specifics of this type of ship are shown in Table 4.3.

### 4.2 Enemy Movement Assumptions

With three types of enemy ships designated within the simulation environment, the next step is to develop a method to present the enemy movement through the operational area. Using the foundational shipping lanes presented in Chapter 3, the simulation uses a randomized metric to portray realistic enemy movement against which the system of friendly UUVs will operate.
4.2.1 Route

One critical assumption of this thesis is the foundational use of shipping lanes for water transit of the threat vessels. In this simulated environment, three enemy vessels are starting at the northern starting locations. Each enemy vessel is attempting to move from its harbor start area into open waters to complete an unspecified mission. Each of the three vessels will transit through the battlespace. However, based on harbor characteristics, not every route is viable for each vessel. This is reflected by the following table:

<table>
<thead>
<tr>
<th></th>
<th>Lane A</th>
<th>Lane B</th>
<th>Lane C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship 1</td>
<td>GO</td>
<td>NO-GO</td>
<td>NO-GO</td>
</tr>
<tr>
<td>Ship 2</td>
<td>GO</td>
<td>GO</td>
<td>NO-GO</td>
</tr>
<tr>
<td>Ship 3</td>
<td>GO</td>
<td>GO</td>
<td>NO-GO</td>
</tr>
</tbody>
</table>

Table 4.4: Ship Lane Usage

In a harbor region, historical information can either be inferred or is actually tracked by authorities. The historical route usage in Narragansett Bay is assumed to be the following:

<table>
<thead>
<tr>
<th></th>
<th>Lane A</th>
<th>Lane B</th>
<th>Lane C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.66</td>
<td>0.22</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Table 4.5: Historical Lane Usage Proportion

Using these proportions, a random number generator selects the threat vessel type of ship (with equal probability for each of the three ships), and using the lane usage proportion, a specific route is assigned for the enemy vessel to transit. The following table shows the specific route probabilities for each of the three ships:

<table>
<thead>
<tr>
<th></th>
<th>Lane A</th>
<th>Lane B</th>
<th>Lane C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship 1</td>
<td>1.00</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ship 2</td>
<td>0.66</td>
<td>0.22</td>
<td>0.12</td>
</tr>
<tr>
<td>Ship 3</td>
<td>0.75</td>
<td>0.25</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.6: Ship Lane Probability
4.2.2 Waypoints

For each enemy ship its specific route of travel, the natural tendency is to remain in the center of the shipping lane to reduce the opportunity for incident. To model this, a normal curve was placed around the center of each waypoint on the selected route, with a standard deviation of 25% of the width of the lane at that specific waypoint. For each subsequent waypoint selection, a random number generator derived a projected waypoint for each of the pre-established turn points along the selected routes. The projected route then draws a straight line from the current turn point to the next turn point. It is assumed that the threat vessel will not turn except at these established waypoints.

4.2.3 Speed

Each of the three enemy vessels will travel at different speeds, based on the route they travel, and the characteristics of the vessel. From a tactical perspective, one would not expect the enemy vessel to travel at maximum speed in the harbor; this would waste valuable fuel, and make the route especially hazardous due to restricted terrain.

1. **Initial Speed:** At the beginning of the simulation, the enemy vessel is assigned a speed value that is drawn from a normal distribution of the specified cruise speed, with a standard deviation of 25% of the average speed.

<table>
<thead>
<tr>
<th></th>
<th>Initial Speed (knots)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship 1</td>
<td>14.5</td>
<td>3.625</td>
</tr>
<tr>
<td>Ship 2</td>
<td>10.5</td>
<td>2.625</td>
</tr>
<tr>
<td>Ship 3</td>
<td>20</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 4.7: Initial Speed Distribution

Additionally, of note, is that since the enemy vessel is starting its travel at the initial location, the time must reflect the need to accelerate to the required initial speed. Clearly, complicated models could be developed to measure and calculate the acceleration of each of the three types of enemy vessels. However, for simplicity, it is assumed
that the enemy vessel will reach its desired speed after 5 minutes with a constant acceleration from zero knots to the selected initial en route speed.

2. **En-route speed changes:** It is obviously possible that the enemy vessel can make speed changes at any time along the route. For this simulation, it is assumed that the vessel will not make speed changes except at turn points. That is, between turn points the enemy ship's velocity is constant. At turn points, the vessel will be assigned a new speed that is again based on a normal distribution around the current en-route speed with a standard deviation shown in the above table. At no point is the threat vessel allowed to move at a velocity that is below five knots or greater than the maximum speed for the type of ship being simulated. Five knots was chosen as the minimum speed as an estimate of the minimum value that any ship would choose to travel through the operational area.

### 4.2.4 Calculate the Exact Enemy Route

At this point in the simulation, the enemy ship has a set number of waypoints to comprise its actual path through the operational area, and a random number generator, using the above methodology, has assigned a speed for each of the legs of travel. The final step for use in this simulation is to take the waypoints and speeds and assign a [LAT,LONG] grid for every 1 minute of travel, beginning at the northern start point and ending at the pre-defined end point of the chosen shipping lane. It is important to note that during this process there was no interaction with the physical or digital map during these calculations. Each of the shipping lanes was designated as viable water space throughout the route. Because the structure of the enemy path is designed around the shipping lanes, it is guaranteed that the enemy vessel will not travel outside of viable water. Figure 4.4 shows a sample of multiple independent enemy movements through the simulation environment.
4.3 Friendly Mission Statement

For the purposes of this research, a notional mission statement was developed to explore the possibilities of using UUVs in the offensive role. Although much literature focuses on the ASW mission for the UUV, it is also viable that the UUVs could be used to engage larger surface vessels during the course of armed conflict or other naval engagement. Thus, it can be seen as a viable task for a naval commander to destroy ships in littoral regions to meet a desired end state in a complex geo-political framework. These effects could be destruction of specific ships to prevent the personnel or cargo on board from reaching their ultimate goal, or the destruction of any ship to affect the morale of the enemy forces, or simply engage targets to act as a distractor to enemy forces.

The friendly units are tasked with intercepting a possible known enemy vessel that has left the northern start point, and is heading for open water to an unknown location. The friendly vessels must acquire the threat vessel, and subsequently report acquisition to higher headquarters. Only after higher headquarters has analyzed the situation report and the UUVs have received permission to engage can the team of UUVs engage the vessel with intent to damage or destroy. To accomplish this task, three teams of two UUVs each will be deployed into the target area. The first two teams will be comprised of “hunter” UUVs
which will be tasked with the initial acquisition and reporting of threat information. The final team will be tasked with the actual interception and engagement of the threat vessel.

4.4 Friendly Vehicles

In the course of developing a viable simulation to evaluate the decision algorithms, it is essential to develop representative vehicles that can capture a combination of current or realistic future capabilities of UUV technology. The technological gap between current and possible future capabilities is indeed unknown, and thus it is not trivial to determine a viable representation of vehicles to examine the offensive role. As quickly as tactics and methodologies are developed, new technologies can mandate a change to operational schemes; the tactics and methodologies that UUVs use must be a reflection on their capabilities. For example, a UUV that has sensor capabilities of 2000 meters would tactically respond and react to enemy movement different than that of a UUV with a sensor range of only 750 meters. Although the future capabilities of UUVs will surely demonstrate enhancements from current operational vehicles, it is imperative to demonstrate some reasonable expectation of performance. Given the broad range of mission objectives that UUVs might be called upon to explore, it is a common belief that UUVs will evolve into “four distinct classes of UUVs. The four classes of UUVs would be defined by their size: large diameter vehicles of greater than 21 inches; vehicles of 21 inches (similar to the MK48 torpedo); vehicles of 12-3/4 inches (similar to the lightweight torpedo); and smaller UUVs.”[1] Therefore for this research, two separate UUV’s, each with distinct capabilities, are modeled; a killer UUV armed with torpedoes and a hunter UUV armed with advanced sensor arrays.

4.4.1 Foundational Assumptions

For the purposes of this simulation, assumptions must be established regarding friendly UUV capabilities; although current technology does not meet all described technical capabilities in this thesis it is believed that they represent a fair approximation of where technology could
be in the near future.

1. **Endurance:** One common difficulty in developing autonomous UUVs is the endurance of the platform. For the purposes of this research, it is assumed that each of the UUV’s possesses the required endurance to move to position and complete one iteration of the mission profile and return to a safe location for maintenance and/or refit. While it is indeed likely that after one mission execution, or in the middle of a mission cycle, a UUV would exhaust its endurance, we can assume that a hand-off of mission requirements can occur seamlessly with another single or team of UUVs that provide relief on station.

2. **Communications:** Underwater communications, both near and far, have been a constant challenge for both manned and unmanned vessels. For this research, it is assumed that all operational UUV’s have a method to communicate with home base when they are stationary; possibly through some floating low-observable antenna. It is also assumed that the UUVs are out of contact when they are mobile.

3. **Sensor Range:** The technology of sensors is ever advancing, and there are a variety of sensors available to accomplish the myriad of mission specific tasks. For this simulation, the assumption is that the UUVs are equipped with sonar type sensors that have a specified range. This range allows the UUV to have 360° acoustic visibility out to the range for each system. That is, they can “hear” any activity within their sensor range, and subsequently determine, from their location, the bearing at which the acoustic activity occurred.

4. **Weapons Systems:** Although there is no current open-source information regarding armed UUVs, it is logical to assume that in the future such configurations are possible. Additionally, there is a certain level of ambiguity when discussing types of weapons systems that could be employed against threat vessels, and whether or not these weapons systems could provide an adequate size to lethality ratio that make them practicable
for UUV operations. Despite the engineering challenges, for this research the assumption is that it is possible to arm UUVs with multiple individual weapons with a discrete weapons range. These weapons can be fired from a distance within their designated range, and once all available weapons have been fired, the UUV is no longer lethal.

Within the context of these assumptions, two discrete friendly UUVs were denoted to accomplish the critical tasks. The Hunter UUV and the Killer UUV were assigned specific tasks and these are presented as follows.

4.4.2 **Hunter UUV Mission Specifications**

The first UUV, the detector, will have the operational task of clandestine movement into the prescribed area of operations, and subsequent long-term monitoring of its assigned area of operations. It is assumed that this UUV is smaller in size to allow this clandestine movement, and its size is optimized for long endurance, as movement into the operational area can be a slow deliberate movement. This UUV will be armed with only sensors and communications equipment allowing it to acquire threat vessels, and subsequently pass this information to a higher headquarters for further guidance.

4.4.3 **Killer UUV Mission Specifications**

The second UUV, the killer, will have the operational task of on-order moving to the engagement area, locating the enemy vessel, and engaging the enemy vessel in order to make it combat ineffective or to destroy it. This UUV would be much larger than the first, aforementioned clandestine UUV, due to the ammunition requirements. Additionally, it is assumed that this larger UUV sacrifices long endurance for greater speed; that is, once an engagement occurs it must return to friendly forces for maintenance and/or energy replenishment. Thus UUV will be armed with a varying amount of lethal torpedoes and requisite sensor capabilities to acquire the threat and process the subsequent engagement.
Chapter 5

Simulation Design and Key Algorithms

The purpose of this chapter is to outline the flow of the simulation and describe the integration of key algorithms into the simulation. Additionally, the key algorithms will be discussed in detail, and the final results of the simulation will be explored in Chapter 6.

5.1 User-Defined Simulation Parameters

The simulation design allows for easy changes to be made to parameters that affect the fidelity of the simulation and the performance metrics of the UUVs. These user-defined parameters will set the stage for the follow-on experimental design and results presented in the next chapter.

**User Specified Parameters:**

1. Grid Interval: This parameter specifies the degree of resolution the user wishes to use during the simulation. Numerous scenario examples have shown that the best interval for both fidelity of information and speed of simulation runs occurs when the grid interval is placed at 200 meters. Thus, all discussion in this thesis occurs in a digital map with 200 meter grid fidelity.
2. Friendly UUV Capabilities

(a) Speed: This is the speed in knots of the friendly UUVs.

(b) Sensor Range: This is the range at which the sensor arrays are capable of acquiring a bearing to the threat vessel.

(c) Number of Torpedoes (only for “killer” UUVs): This is the number of torpedoes that the UUVs can launch against threat vessel.

(d) Weapon Range: This is the maximum range of any torpedo fired from any killer UUV. The success or failure of the subsequent engagement will be based on probability of hit and probability of kill tables. See Table 5.2 and Table 5.3.

(e) Initial Locations. This is the Lat-Long start grid coordinate for each of the six UUVs.

3. System Parameters

(a) Decision Time: This designates the “best guess” on how long a decision will take at higher headquarters (HQ). For the purposes of this simulation, the decision time is dead time, where no friendly actions take place, but the threat vessel continues to move toward its objective. Decision time is an important aspect of this simulation. It is highly unlikely for an advanced nation to give an autonomous vehicle the ability to intercept and engage a vessel without “human” intervention and approval. All of the discussion in this thesis assumes that the decision time is set at 5 minutes.

(b) Engage Time: This parameter is a user-defined engagement window, measured in minutes. This engagement window, used during the course of the simulation, is converted into a engagement distance based on the enemy’s calculated speed. Using this enemy specific distance, the intercept locations are determined based on a series of algorithms that will be discussed later in this chapter. All of the discussion in this thesis assumes that the engagement time window is set at
3 minutes, which is an estimate of the amount of time required to shoot two torpedoes.

5.2 Simulation Initialization

The simulation takes place in 1 minute discrete time intervals. For each one minute involved in the simulation prior to intercept, the following process occurs:

For every time interval, $i$, the simulation completes each of the following steps:

1. Read actual enemy location for the time interval, $i$.

2. Calculate Distance from all Friendly UUVs to Enemy Vessel

3. For each friendly UUV, if this distance is less than Sensor Range, then that specific UUV is detecting the threat.

4. For each time period where one or more friendly UUV is detecting, then record time and bearing of enemy vessel.

5. If a detection has occurred previously, and no current hunter UUVs are detecting, then the system estimates the enemy location and speed using the Enemy location and speed calculation algorithms that will be discussed in the next section.

At this stage in the individual simulation run, the overall system of UUVs attempts to estimate the enemy location and its velocity, and subsequently determine the probability of the enemy vessel traveling down each of the possible shipping lanes. These algorithms are presented in the following sections.

5.3 Determine Enemy Location and Speed

This series of two complementary algorithms uses the knowledge of the shipping lane environment and the friendly UUV location to make an approximation of the threat vessels’
location and speed. This step of the simulation represents both the initial acquisition and reporting stage of the simulation.

As discussed earlier, the dynamic situation presented in this model presents the presence of “hunter” UUVs and “killer” UUVs. The primary mission of the hunter UUVs is to detect, and gather critical information about the threat vessel, and subsequently pass that information to higher headquarters for further mission processing. As defined by this research, the minimum critical information the hunter UUVs must report are enemy location (Latitude/Longitude), and enemy velocity (knots). It is assumed that some metric of classification is also passed in order to allow the higher headquarters to determine the follow-on decision, and also for the “hunter” UUVs to make positive re-acquisition. This classification could be a photograph, acoustic signature or some as of yet undetermined classification method both the hunter and killer UUVs can use to determine the threat identity.

5.3.1 Sonar discussion

Modern naval warfare makes extensive use of sonar. The two types of sonar commonly referred to are Active sonar and Passive Sonar. Active sonar is extremely useful because it gives the exact position of an object. Active sonar works the same way as radars: a signal is emitted. The sound wave then travels in many directions from the emitting object. When it hits an object, the sound wave is then reflected in many other directions. Some of the energy will travel back to the emitting source.[21] The echo will enable the sonar system or technician to calculate, with many factors such as the frequency, the energy of the received signal, the depth, the water temperature, etc., the position of the reflecting object. Using active sonar is somewhat hazardous however, because it does not allow the sonar to identify the target, only the presence of a possible target, and any vessel around the emitting sonar will detect the emission. Having heard the signal, it is easy to identify the type of sonar (usually with its frequency) and its position (with the sound wave’s energy).[20, 21] Moreover, active sonar, similarly to radars, allow the user to detect objects at a certain range, but also enable other platforms to detect the active sonar at a far greater range. With this in mind,
it is not tactically viable for the UUV to utilize active sonar capabilities to range the enemy vessels.

Passive sonar has fewer drawbacks. Generally, it has a much greater range than active sonar, and allows an identification of the target. Because any motorized object makes some noise, it may be detected eventually. It simply depends on the amount of noise emitted and the amount of noise in the area, as well as the technology used. Once a signal is detected in a certain direction (which means that something makes sound in that direction), and since every engine makes a specific noise, it is possible to identify the object. Passive sonars are stealthy and very useful. However, they require high-tech components (band pass filters, receivers) and are costly. They are generally deployed on expensive ships in the form of arrays to enhance the detection. For the remainder of this discussion we assume that the “hunter” UUV will only use passive sonar capabilities.

However, with passive sonar being the only practical method for detecting the enemy vessel, the problem of determining the enemy ships’ location and speed is presented. “A fundamental property of bearings-only target motion analysis (TMA) is that the contact range is not observable prior to an own ship maneuver. The range becomes observable only after an appropriate own ship maneuver followed by a second leg of motion (a leg is defined as a time interval of constant platform velocity.)” [13] The mathematics behind bearings only sonar calculation have been used since the beginning days of submarine technology; given the broad range of situations that sonar experts encounter, however, it has proved extremely difficult to program autonomous operations into UUVs that can mirror the typical reaction that a manned vessel would make to solidify TMA data.

With these facts in mind, two distinct algorithms for calculating enemy information were developed. These algorithms assume that the “hunter” UUVs retain the on-board capability to calculate accurately both their own location and the bearing to a tentative threat vessel within the prescribed range of their sensor array.
5.3.2 Enemy Location and Speed Algorithms

During the course of this research it was deemed very difficult to calculate enemy information without making UUV ship movements designed to gain information about the enemy targets. Not wanting to assume this difficult aspect of UUV tactics away, a pair of viable alternatives were developed to make realistic approximations of target vessel location and speed without dwelling into complex own ship maneuver plans. These two methods assume that when the target vessel is within the sensor range of the friendly UUV, then the UUV is capable of detecting only the azimuth of the target vessel with respect to its own location. The two methods that will be discussed are:

1. Single-Ship Calculations

2. Multiple-Ship Calculation

For each of these Enemy Information algorithms, there are two common procedures that make these calculations possible.

1. Procedure POLYXPOLY: This procedure, a MATLAB function, POLYXPOLY, takes two sets of [LAT, LONG] points and calculates the [LAT, LONG] point(s) of intersection. The procedure connects the points in order presented to form a piecewise linear function. If the initial point is repeated as the final point, for example, then a polygon is formed. A more formal presentation of this function is shown below:

(a) Input.
   i. $S_1$, Set of at least two points, given in [LAT, LONG] format.
   ii. $S_2$, Set of at least two points, given in [LAT, LONG] format.

(b) Output
   i. $INT_1$, set of intersection points. If no intersection, then $INT_1$ is empty.

   NOTE: If both $S_1$ and $S_2$ are comprised of only two points and $S_1 \neq S_2$, then $INT_1$ is guaranteed to be at most a single point, else it is possible for there to be multiple points of intersection.
2. Procedure Bearing Extend: This procedure, a MATLAB function, DRECKON, takes a [LAT,LONG] grid coordinate, a bearing and a distance and outputs a single [LAT,LONG] grid coordinate. A more formal presentation is shown below:

(a) Input.
   i. \( S_1 \), Start Point presented in [LAT,LONG]
   ii. \( B \), bearing measured in degrees.
   iii. \( D \), Distance measured in meters

(b) Output
   i. \( E_1 \), extrapolated point presented in [LAT,LONG]

5.3.3 Single-Ship Bearing only Calculation without own-ship movement

This algorithm is invoked in the simulation after the friendly UUV has detected the presence of the enemy vessel for a minimum of two observations. It takes the threat azimuth from the UUV location and extends it to infinity, as shown in Figure 5.1. Subsequently, it calculates the point where this extended azimuth intersects with the center of known shipping lanes, and estimates this as the enemy position. After two or more estimates of location, the speed is determined by calculating the time needed to travel the estimated distance. A more formal presentation of this algorithm is shown below.

**Algorithm (Single-Ship Enemy Detect).** Let \( B(i) \) be the vector of bearings from a UUV to a target vessel, where \( I \) = set of time units where target is within sensor range of UUV and \( RTE \) equals the set of shipping lanes in the area of operations.

1. Input:

   (a) UUV Position: \([Lat_{uuv}, Long_{uuv}]\).

   (b) UUV Detection: \( B(i) \ \forall \ i \in I \).
2. Output:

(a) Enemy Estimated Location: \([ELAT_i, ELONG_i]\); Enemy location at time \(i\).
(b) Enemy Estimated Speed: \(ESpeed_i\); Enemy speed at time \(i\).

3. Procedure:

(a) \(if \ |I| \leq 1, \ end;\)
else
(b) \(\forall \ i \in I \ do\)
   i. DO BEARING EXTEND(\(S_I = \text{UUV Location}, B = B(i), D = 1000m\));
      OUTPUT:= \(E_i\)
   ii. \(\forall \ r \in R \ do\)
A. DO POLYXPOLY(S₁ = RTEᵣᵣ, S₂ = [UUV₁, E₁]); OUTPUT:= INTᵣᵣᵣ

B. IF INTᵣᵣᵣ ≠ empty
   ELATᵣᵣᵣ, ELONGᵣᵣᵣ = INTᵣᵣᵣ

C. end;
   end;

iii. end;

(c) Calculate estimated Speed of enemy vessel:
   i. For i = MIN[I] + 1 → MAX[I] do
   ii. DISTᵣᵣᵣᵣᵣ = DISTANCE((ELATᵣᵣᵣᵣᵣ, ELONGᵣᵣᵣᵣᵣ), (ELATᵣᵣᵣᵣᵣ₋₁, ELONGᵣᵣᵣᵣᵣ₋₁))
   iii. Speedᵣᵣᵣᵣᵣ = (DISTᵣᵣᵣᵣᵣ, meters)/(60 min/hr) (nm/1852 meters)

(d) Estimate Enemy Information
   i. [ELATᵣᵣᵣᵣᵣᵣ, ELONGᵣᵣᵣᵣᵣᵣ] where i = MAX[I], Estimated Enemy Location
   ∑ᵣᵣᵣᵣᵣᵣ Speedᵣᵣᵣᵣᵣᵣ / (|I|−1) , Estimated Enemy Speed

By taking the average speed using all observations, we minimize the error of a single reading.
At this point, the algorithm has calculated the enemy estimated position at the time of the last observation, and has also estimated the speed the vessel has traveled.

5.3.4 Multiple-UUV Bearings only Calculation without own-ship movement

For the purposes of this discussion we assume that the enemy vessel is being detected by two or more sensors capable of accurately determining bearing-only calculations, and that each of the sensors is capable of communication to either each other or some headquarters where their information can be jointly analyzed for required calculations.

Algorithm (Multiple-Ship Enemy Detect). Let Bₓᵣᵣᵣᵣᵣᵣᵣ be the vector of bearings from a UUV to a target vessel, where X is set of detecting UUVs, I is set of time units where the target is within sensor range of UUV and RTE equals the set of shipping lanes in the area of operations.
1. Input:

(a) UUV1 Position: $UUV_1 = [Lat_{uuv1}, Long_{uuv1}]$.

(b) UUV2 Position: $UUV_2 = [Lat_{uuv2}, Long_{uuv2}]$.

(c) UUV Detection: $B_{xi} \forall \ i \in I$ and $\forall \ x \ in \ X$.

(d) Shipping Lanes: $RTE_r \forall \ r \in R$

2. Output:

(a) Enemy Estimated Location at time $i$: $[ELAT_i, ELONG_i]$

(b) Enemy Estimated Speed at time $i$: $ESpeed_i$

3. Procedure:

(a) Determine Joint Detection Times: These are the times at which both UUVs are detecting the threat at the same time interval, $i$. OUTPUT: Set of time intervals,
JD.

(b) if $|JD| \leq 1$, end;
else

(c) \begin{enumerate}
\item \begin{enumerate}
\item DO BEARING EXTEND($S_1$ = UUV1 Location, $B = B_{1i}$, $D = 1000m$);
\item OUTPUT := $E_{1i}$
\end{enumerate}
\item DO BEARING EXTEND($S_1$ = UUV2 Location, $B = B_{2i}$, $D = 1000m$);
\item OUTPUT := $E_{2i}$
\item DO POLYXPOLY($S_1 = [UUV_1, E_{1i}], S_2 = [UUV_2, E_{2i}]$); OUTPUT := $INT_i$
\item $[ELAT_i, ELONG_i] = INT_i$
\end{enumerate}
end;

(d) Calculate estimated speed of enemy vessel:
\begin{enumerate}
\item For $i = MIN[JD] + 1 \rightarrow MAX[JD]$ do
\item $DIST_i = DISTANCE((ELAT_i, ELONG_i), (ELAT_{i-1}, ELONG_{i-1}))$
\item $Speed_i = \left(\frac{DIST_i \text{ meters}}{1 \text{ min}}\right) \left(\frac{60 \text{ min}}{hr}\right) \left(\frac{nm}{1852 \text{ meters}}\right)$
\end{enumerate}

(e) Estimate Enemy Information
\begin{enumerate}
\item $[ELAT_i, ELONG_i]$ where $i = MAXI$, Estimated Enemy Location
\item $\frac{\sum_{i=1}^{MAXI} Speed_i}{|i| - 1}$, Estimated Enemy Speed
\end{enumerate}

This algorithm takes advantage of the two UUVs detecting the UUV at the same time, and using the intersection of their bearing calculations to determine the enemy location, and subsequently its estimated velocity.

5.3.5 Comparison of Different Calculations

To compare the two methodologies for determining enemy information, 2500 independent simulation experiments were executed. Each of the two algorithms described in detail above,
output the enemy estimated speed and the enemy’s location at the report time for the same enemy route information.

<table>
<thead>
<tr>
<th>UUV Error Data</th>
<th>Speed</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Ship</td>
<td>3.273kts</td>
<td>193.85 meters</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>2.22</td>
<td>41.22</td>
</tr>
<tr>
<td>Multiple Ship</td>
<td>.344 kts</td>
<td>51.23 meters</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>.22</td>
<td>3.55</td>
</tr>
</tbody>
</table>

Table 5.1: Enemy Estimation Error

As the table shows, the single-ship calculations demonstrate a discernible error in both determining the enemy speed and enemy location. As will be shown later in this thesis, the speed calculation is of critical importance, and the single UUV high-speed error coupled with a large standard deviation, will lend itself to sending the corresponding “killer” UUVs to a sub-optimal location based on erroneous data.

Based on these findings, the simulation was modified to ensure that when possible the multiple-UUV detection algorithm was used, however, when only one UUV detected the threat vessel or there was no joint detection for at least two time intervals, then the single-ship algorithm was used to pass the enemy-estimate information for the remainder of the simulation.

5.3.6 Probability of Route

In addition to determining the threat vessel’s location, speed and bearing, an additional requirement is to estimate information regarding the route that the enemy vessel will utilize through the operational area. As discussed earlier, the friendly vessels cannot remain within range of the faster moving threat, and thus must take advantage of location and geographical information to discern information.

Fundamental Observation: At the time of detection, the enemy ship must be present on at least one route, thus by determining which of the possible routes the enemy vessel is currently located, then it is possible to gain insight into the future travel of the enemy vessel.
**Algorithm (Probability of Route).** Given the estimated enemy position \( \text{Enemy}_\text{estimate} \), shipping lanes \( R_{te_r} \), and shipping lane usage \( P_r \).

1. Input:
   
   (a) Estimated Enemy Position: \( \text{Enemy}_\text{estimate} = [\text{Lat}_\text{enemy}, \text{Long}_\text{enemy}] \).
   
   (b) Shipping Lanes: \( R_{TE_r} \forall \ r \in R \)
   
   (c) Shipping Lane Usage: \( P_r \forall \ r \in R \)

2. Output:

   (a) Probability of Route: \( \text{Enemy}_\text{Prob}, \forall \ r \in R \)

3. Procedure:

   (a) Inter Algorithm Calculations
      
      i. \( W_{ri} \) = Width of route \( r \) at waypoint \( i \).
   
   (b) \( \forall r \in R \) do
      
      i. \( CW_r \) = Calculate Closest Waypoint for each route
      
      ii. \( WE_r = [CW_r - 1, CW_r, CW_r + 1] := \text{Set of Waypoints to examine for each route} \)
      
      iii. \( \forall i \in WE \), Calculate \( W_{ri} \)
      
      iv. \( \text{WIDTH} = \text{MAX}(W_{ri}) \)
      
      v. Draw Circle, \( C \), with diameter \( \text{WIDTH} \) from Enemy Location
      
      vi. If Intersection between route \( r \) and Circle \( C \)
          
          Then \( \text{Int}_r = 1 \)
          
          Else \( \text{Int}_r = 0; \)
      
   (c) \( \forall r \in R \) do

\[
\text{Enemy}_\text{Prob}_r = \frac{\text{Int}_r P_r}{\sum_{i=1}^{R} \text{Int}_r P_r} \quad \text{(5.1)}
\]
It is worthy to note that this process does not account for any knowledge about the enemy ship other than its location and projected speed. Clearly, if it was assumed that the UUV could determine the approximate size or type of ship moving down the corridor, then some routes could be removed from contention based on their inability to travel down specific lanes. This information was not used, however, in this simulation because it is an extensive leap in technology for the UUV to make that determination.

5.3.7 Intercept Location

Even with an accurate portrayal of the enemy position and speed, and a calculated probability of enemy travel down specific routes, a methodology is still needed to intercept the enemy vessel as it travels down the route. Clearly, we are unaware of the exact travel plans or position of the enemy, as both hunters have lost contact during their reporting window.

The terrain characteristics of operating in littoral areas present opportunities to use the shipping route information to intercept the enemy vessel in an area that maximizes the strengths of the UUV and minimizes its weakness. Thus, the intercept algorithm, would like to take into account the specific geography of the shipping lanes and surrounding area to make a "smarter" decision in choosing an intercept location.

The critical observation made is that to maximize the effectiveness of the UUV characteristics, it would benefit the UUV to intercept the enemy vessel in the area of the route that has the smallest navigable area; this minimizes the enemy's ability to maneuver and maximizes the UUV's chances of acquiring the vessel. The danger exists, however, for one to assume that the narrowest point along the route is the optimal intercept location. While a choke point has historically represented an advantageous offensive location, this research suggests that approaching the problem as a smallest area problem lends itself to a more consistent offensive strategy.

Although difficult to describe the area of engagement from a tactical standpoint finitely, it is seemingly obvious that the engagement area would be a function of the enemy's speed; the slower the enemy is traveling, the smaller the area, whereas a fast moving enemy necessitates
a larger area. With that in mind, the engagement area is initially defined as the distance the enemy vessel will travel at current estimated speed over the course of three minutes. Three minutes is chosen to represent the amount of time required to acquire and fire two torpedoes at the vessel.

Additionally, the area of a specific intercept point is defined as the area of the shipping lane that extends forward from the possible intercept point $2/3$ of the engagement distance and backwards from the possible intercept point the remaining $1/3$ of the engagement distance. This is shown pictorially in Figures 5.3 and 5.4 with an enemy traveling at 10 and 25 knots, respectively.

![Intercept Area Diagram](image)

**Figure 5.3: Intercept Area at 10 knots**

With this in mind, the algorithm attempts to find the smallest area of all possible intercept points. It is presented formally as follows.

**Algorithm (Intercept Location).** Given the following inputs that use information from each of the three routes, presented as the set $R$. Each of the routes in the set $R$, are presented through waypoints, using the set $W_R(I)$, where $I$ is the set of waypoints in each route. The solution to this model specifies the intercept location for each of the possible intercepting UUVs, or the “killer” UUVs. These are presented as the set of UUV’s in the set $X$, where $X = [1, 2, .., n]$, and $n$ is equal to the number of killer UUVs.
1. Input:

(a) Estimated Enemy Position: $\text{Enemy}_{\text{estimate}} = [\text{Lat}_{\text{enemy}}, \text{Long}_{\text{enemy}}]$.

(b) Enemy Speed: $\text{ESpeed}$. This is the calculated estimated enemy speed using previous algorithms.

(c) Enemy Probability of Route: $\text{Enemy}_{\text{Prob}}, \forall r \in R$. This is the output of previous algorithms, that is, the probability of the enemy traveling down each of the possible routes in the environment.

(d) Engagement Window: $\text{EW}$. This is the user-set parameter determining the desired engagement window presented in terms of minutes.

(e) Shipping Lane Information: $\text{Waypoint}_r(i), \forall r \in R$. The third waypoint in route $2$ would be denoted $\text{Waypoint}_2(3)$. This data is presented as $\text{Waypoint}_r(i) = [\text{Lat}_{\text{Waypoint}_r(i)}, \text{Long}_{\text{Waypoint}_r(i)}]$.

(f) Friendly UUV Information: This input data includes the friendly UUV locations, and the speed capabilities of the UUVs.

2. Output:
(a) Intercept Grid: \( \text{Int}_{rx} \ \forall r \in R, \ \forall x \in X \)

3. Procedure: For all UUVs \( x \)

(a) For all routes \( R \) where \( \text{EnemyProb}_r > 0 \) do

i. For all \( \text{Waypoint}_r(i), \) where \( i = 1 \) to \( |I| \)

   Calculate the possible Intercept Points:

   A. Calculate Enemy Distance to \( \text{Waypoint}_r(i) \)
   
   B. \( E_{\text{ETA}} = \) Enemy Time to waypoint = \( \frac{\text{EnemyDistance}}{E\text{Speed}} \)
   
   C. Calculate Friendly Distance to \( \text{Waypoint}_r(i) \)
   
   D. \( F_{\text{ETA}} = \) Friendly Time to waypoint = \( \frac{\text{FriendlyDistance}}{F\text{Speed}} \)
   
   E. IF Difference \( E_{\text{ETA}} > F_{\text{ETA}} \) then
      \[ WP_r(i, 1) \text{ (Set of Possible Waypoints on route R)} = i \]
      \[ WP_r(i, 2) = E_{\text{ETA}} - F_{\text{ETA}} \]
   
   end;

ii. \( CW = \) Critical Waypoint = \( \text{MIN}(WP_r(i, 2)) \)

iii. Determine Actual Point of Intercept

   A. Equation for UUV: \( f(x_1) = mx_1 + 0 \), where \( m = \left( \frac{\text{FSPEED}_{nm}}{\text{hr}} \cdot \frac{1\text{hr}}{60\text{min}} \cdot \frac{1852\text{meters}}{1\text{nm}} \right) \)
   
   B. Equation for Enemy: \( f(x_2) = -mx_2 + b \), where \( m = \left( \frac{\text{ESPEED}_{nm}}{\text{hr}} \cdot \frac{1\text{hr}}{60\text{min}} \cdot \frac{1852\text{meters}}{1\text{nm}} \right) \)
      and \( b = (WP_r(CW, 2) \star m) \);
   
   C. \( D_{\text{API}} = \) Solution to system of equations where \( f(x_1) = f(x_2) \)
   
   D. \( \text{API} = \) BEARINGEXTEND\( (S_1 = \text{Waypoint}_r(i), \ B = \) Bearing from \( \text{Waypoint}_r(CI - 1) \) to \( \text{Waypoint}_r(CI), \ D = D_{\text{API}} \)\)

iv. For \( x = \text{API} : 50 \text{ meters} : \) Endpoint\( _r \)

   A. \( IP_r = [IP_r \ x] \)
   
   B. end;

(b) For each of the Intercept Points Calculate the Associated Area using EW.
5.3.8 Shortest Path

The above algorithms discuss in detail the process to determine what the enemy vessel is doing, and predict the most likely avenue of movement, and subsequently determine the best intercept location to attempt to re-acquire and engage the threat vessel. Additionally, a common problem that required an efficient solution was the determination of routing for friendly UUVs. This routing algorithm played a crucial role determining the friendly UUV travel time to each of the waypoints along the route, and is critical for the friendly UUVs to actually move to and ultimately engage the threat vessel.

One difficult aspect of autonomous operations has always been the routing problem, and UUVs operating in a hazardous and/or unknown environment only amplifies the complexity of difficult routing. In terms of this research, however, the underlying complexities of routing have been simplified to a certain extent. It is thus assumed that the friendly UUVs will always travel from Point A to Point B via the shortest path; it is assumed that the risk is uniform throughout the environment, i.e. as long as the water is considered of acceptable depth, there is no preference metric to compare alternate travel routes. With this assumption in place, the next step is to find an efficient algorithm to calculate shortest paths.

The underlying map representation of this simulation lends itself to solving typical network based problems, allowing the shortest route problem to be cast as a network shortest path problem. The shortest path problem has been studied for many years, and there are many applications that have been devised to adapt the shortest path problem to solving the diverse problems that exist throughout the real world.

Based on the digital map designed to describe the area of operations (see Chapter Three), we are presented with a very dense graph; i.e. with many vertices and arcs. Clearly an all-pairs shortest path algorithm would be very computationally expensive to explore. However, for the purposes of this problem, we are attempting to calculate the shortest path distance between a single pair of vertices, the start point and the end point. Additionally, because

(c) $\text{Int}_{rx} = \text{Minimum area in Intercept Points.}$
this network contains only non-negative arc lengths (i.e. they represent the distance between discrete nodes), Dijkstra's algorithm[17] is applicable.

Dijkstra's algorithm maintains a distance label with each node, which is an upper bound on the shortest path length to the node from the beginning source node. At each step of the algorithm, each node is classified as belonging to one of two groups: those that are permanently labeled (i.e. will not be examined again) and those that are temporarily labeled (i.e. those that will be examined again in subsequent steps of the algorithm.) The distance label to any permanent node is the shortest path from the source node to that node. For any temporary node, the distance label is an upper bound on the shortest path distance from the source node to that node. The base algorithm stops when it has moved all nodes from temporarily labeled to permanently labeled. For purposes of this thesis, however, the goal was to determine a shortest path from one single source node to one single sink node. Thus, some modifications were made to speed-up the algorithm's performance; namely, the algorithm is stopped once the sink node is moved into the permanently labeled group, and straight-line checks are made. The straight-line checks simply check to see if it is possible to travel safely along a straight line from the source to sink, and if possible removes the requirement to continue through the entire algorithm. This modified algorithm is formally presented as follows:

**Modified Dijkstra Algorithm [17]**

1. Input:
   
   (a) G(N,A): This is the graph described in Chapter Three with each node, N, numbered based on the grid interval and each arc, A, described as the distance between nodes.
   
   (b) Start Point: This is the start point for the UUV given as \([Start_{LAT}, Start_{LONG}]\)
   
   (c) End Point: This is the end point for the UUV given as \([End_{LAT}, End_{LONG}]\)

2. Output:
   
   (a) Shortest Path
(b) Distance of Shortest Path

3. Procedure: In the evolution of the algorithm, each node can be in one of two sets:

(a) $S =$ Open: The distance label on the node is temporary.
(b) $\bar{S}$Closed: The distance label on the node is permanent.

In subsequent stages of the algorithm, the label entries for any node, $a$, contained in the graph is one of the following:

(a) $d(a) =$ length of shortest path from start node to node $a$.
(b) $p(a) =$ immediate predecessor

(a) Convert Start Point and End Point into a numerical node
   Start Point Node = $s$; End Point Node = $t$;

(b) Check for straight line
   i. Draw hypothetical line between Start Point and End Point
   ii. Move along line between Start Point and End Point
   iii. If no-go terrain is reached by moving along this line, then continue
   else stop. Shortest Path is the straight line between SP and EP.

(c) Step 1: Initialize
   i. $S = N$
   ii. $\bar{S} = 0$
   iii. $d(i) = \infty \forall i \in S$
   iv. $d(s) = 0$ and $p(s) = 0$

(d) While $t \notin \bar{S}$ do
   i. let $i \in S$ be a node for which $d(i) = \min \{d(j) : j \in S\}$;
   ii. $\bar{S} = \bar{S} \cup i$;
   iii. $S = S - i$
iv. for each \((i, j) \in A(i)\) do
   if \(d(j) > d(i) + l(i, j)\), then \(d(j) = d(i) + l(i, j)\) and \(p(j) = i\);
   end;
end;

(e) Determine Route

i. SP = t;

ii. \(k = p(t)\);

iii. While \(s \notin SP\)
   A. SP = SP \cup k;
   B. \(k = p(k)\);
   end;

iv. Shortest Path = [SP]'

v. Shortest Path Distance = \(d(t)\);

The worse case running time of Dijkstra’s algorithm has proved to be \(O(n^2)\). This running time, however, assumes that the algorithm solves the one to all shortest path problem, however, this modified Dijkstra’s shortest path algorithm terminates when the sink node is reached, allowing the algorithm to terminate more quickly, generally. This would not be true, however, if the sink node was in fact the last node to be closed. Additionally, the first step in this algorithm searches for a straight line, which in special cases allow the algorithm to solve almost instantaneously.

Once these shortest path problems are solved, the assignment process takes place. This very simplified process looks first at the route that has the highest probability of having an enemy vessel, and assigns the “hunter” UUV that has the shortest distance to the intercept point for this route. The remaining hunter UUV is then assigned to the next highest probability route. When there is only one possible route for the enemy, then both UUVs are assigned to the same route and possibly the same optimal intercept point. Although not
modeled explicitly in this research, it is assumed that some advanced process of teamwork exists to allow both friendly "hunter" UUVs to operate in close proximity to each other.

5.3.9 Enemy Engagement

At this stage in the simulation flow, the enemy vessel continues to move down the pre-calculated route, and the killer UUVs are en-route to their calculated intercept locations via the shortest path calculated using the modified Dijkstra Algorithm. During this stage of the simulation, the simulation continues to move in 1 minute discrete time intervals. The following steps occur during each of these one minute intervals:

1. Update Enemy Location;
2. Update Friendly Location; and
3. Calculate Distance from enemy position at time interval to both "killer" UUVs

Once the distance has been measured between the actual enemy vessel and both of the killer UUVs, the simulation checks to determine if the distance falls within either the sensor or weapon's range. If the distance falls within the sensor range, then the enemy vessel is considered re-acquired; and if the distance falls within both the sensor range and weapon's range, then an engagement takes place.

The engagements are simplified during this research, however they do include a certain randomness to model failed engagements. Each of the hunter UUVs that engages will shoot a torpedo at the enemy vessel when possible, and in order to receive a kill, the enemy vessel must receive a hit, and this hit must be rated a "kill" shot. Each of the three ships has a different set of probabilities for hits and kills. These probabilities show that the larger ships are harder to kill, but easier to hit, while the smaller vessels are considerably harder to hit, but easier to kill. The probability of hit and probability of kill probabilities are shown in Table 5.2 and Table 5.3, respectively.

The simulation continues until the enemy vessel is either killed or has reached the end point of the route. Now, with the fundamental aspects of the simulation and the decision
Table 5.2: Probability of Hit

<table>
<thead>
<tr>
<th>Distance</th>
<th>Ship 1</th>
<th>Ship 2</th>
<th>Ship 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-300 meters</td>
<td>.99</td>
<td>.85</td>
<td>.99</td>
</tr>
<tr>
<td>301-950 meters</td>
<td>.75</td>
<td>.80</td>
<td>.90</td>
</tr>
<tr>
<td>950-1500 meters</td>
<td>.65</td>
<td>.75</td>
<td>.85</td>
</tr>
</tbody>
</table>

Table 5.3: Probability of Kill given Hit

<table>
<thead>
<tr>
<th>Distance</th>
<th>Ship 1</th>
<th>Ship 2</th>
<th>Ship 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-300 meters</td>
<td>.99</td>
<td>.85</td>
<td>.99</td>
</tr>
<tr>
<td>301-950 meters</td>
<td>.75</td>
<td>.80</td>
<td>.90</td>
</tr>
<tr>
<td>950-1500 meters</td>
<td>.65</td>
<td>.75</td>
<td>.85</td>
</tr>
</tbody>
</table>

algorithms presented, the next chapter presents the experimental design and initial results of this research.
Chapter 6

Experimental Design and Initial Results

The purpose of this chapter is to provide an overview of the experimental design to test the algorithms developed in this research and to present the results for the base-case simulation.

6.1 Experimental Design

With the developmental aspects of the simulation complete, it is imperative to develop an experimental design to measure the impact of UUV enhancements toward the overall effectiveness of the UUV system. As discussed earlier, real-world enhancements to UUVs are currently limited based on a combination of cost, technological realities, and size/weight ratios with relation to endurance, weapons payload and maneuver speed. It is important to begin by choosing reasonable enhancements, develop a viable series of measures by which to evaluate effectiveness, and subsequently utilize a statistical methodology to evaluate the individual experiments against each other.
6.1.1 Examined Parameters

The following parameters were chosen to represent four key areas of UUV research, and to model technological advances that could play a strategic role in the future of UUV operations. Although there are many current engineering challenges surrounding these improvements, as discussed in chapter 2, it is assumed that future improvements will make these parameter changes viable. For example, improving UUV speed is a realistic enhancement, but the true impact that this improvement might have on overall endurance or size of the "improved" UUV is an on-going technological question; however, within the next several years these issues might be solved through improvements in batteries or propulsion. These parameter values are examined with the assumption that all combinations of improvements are possible, either now or in the future.

1. **Sensor Range**: This parameter refers to the capability of the on-board sensor of the UUV to detect and classify a possible ocean-going vessel. The range depicts the distance from the UUV that it is capable of detecting, and for the purposes of this simulation, it is assumed that this is a 360° capability. The high value for this parameter is set at 1500 meters, and represents an assumed best case estimate of future UUV capabilities. The low value for this parameter is 1000 meters.

2. **Weapon Range**: This parameter refers to the range of the torpedoes that are loaded on-board the "killer" UUVs. This range determines the distance away from the enemy where it is possible for the friendly UUV to shoot at the threat vessel. The previously described Probability of Hit and Probability of Kill tables remain unchanged, except that any probability of hit or kill is set to zero when the comparative distance falls outside the range of the sensor and/or weapons range, and thus no shot will be taken. The high value for this parameter is set at 1500 meters, and the low value is set at 1000 meters. For example, if a scenario exists where sensor range is 1500 meters, but weapons range is at the low value of 1000 meters, then the friendly UUV will not engage the target between 1000 and 1500 meters.
3. **UUV Speed**: This parameter refers to the discrete speed at which the friendly UUVs execute all of their movements. This simulation assumes a 5 minute acceleration to maximum speed, and an ability to stop instantaneously once they have reached their intended location. It is assumed that endurance is sufficient to allow the UUV to move at the given speed parameters. The high value for this parameter is 7 knots, and the low value is 4 knots. The rationale behind these parameter levels is based on current UUV technology, and future expectations. LMRS is expected to have a top speed of 7 knots, and is currently under development by Boeing[21], and the Hurin UUV, currently commercially operational, has a proven top speed of 4 knots.[20]

4. **Number of UUV torpedoes**: This parameter is the total number of armed torpedoes on-board each of the “killer” UUVs. Although current unclassified technology does not utilize armed UUVs, it is assumed that the high value for this parameter is 4 torpedoes, and the low value is 2 torpedoes. The rationale behind these parameter levels rests on the concept that UUVs greatest benefit is often its small size. This small size allows it to travel in shallow waters, and retain a certain level of endurance, thus it is not realistic to assume a large number of torpedoes can be placed on a future UUV.

### 6.1.2 Factorial Design

Table 6.1 represents the $2^k$ factorial design for all parameters to be examined, where $k$ equals the number of factors, which in this case is four.[11] The individual design points will consist of specific alternatives and will be statistically analyzed for effects of the changing factors. This factorial design is very beneficial, for it allows the entire scope of alternatives to be examined in only 16 experiments, but provides a high degree of fidelity in examining the interaction of factors onto the prescribed measures of effectiveness.

For illustrative purposes, see Table 6.1, if one looks at experiment number 12, the sensor range is set at 1000 meters, the weapons range is set at 1000 meters, the UUV speed is set at 7 knots and each killer UUV holds 2 torpedoes.
### Table 6.1: Factorial Experimental Design

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Sensor Range</th>
<th>Weapon Range</th>
<th>UUV Speed</th>
<th>UUV Torpedoes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+: 1500m</td>
<td>+: 1500m</td>
<td>+: 7kts</td>
<td>+: 4 Torpedoes</td>
</tr>
<tr>
<td></td>
<td>-: 1000m</td>
<td>-: 1000m</td>
<td>-: 4kts</td>
<td>-: 2 Torpedoes</td>
</tr>
</tbody>
</table>

1. **Percent Kill**

(a) **Definition of the Measure:** This is a proportion of success of a binary measure that is equal to 1 if the individual simulation result is a kill of the enemy vessel, and 0 otherwise. The measure is averaged over the number of simulation runs to determine the proportion of kills over the entire population of experiments.

6.1.3 **Measures of Effectiveness**

With the experimental design established to compare the possible improvements to the UUV, the next step is to determine a set of measures by which to compare the different experiments. These measures of effectiveness (MOE) must represent the end-state goal of the UUV operations, but also demonstrate a reasonable approximation for future capabilities the UUV may have. Thus, it is with this critical eye that the following measures are established, in priority order.

1. **Percent Kill**

(a) **Definition of the Measure:** This is a proportion of success of a binary measure that is equal to 1 if the individual simulation result is a kill of the enemy vessel, and 0 otherwise. The measure is averaged over the number of simulation runs to determine the proportion of kills over the entire population of experiments.
b) **Dimension of the Measure:** This ratio measures the percent of kills of the series of individual simulation runs. A greater ratio, closer to 1, is considered better.

c) **Limits on Range of Measure:** The range of the measure is a number between 0 and 1.

d) **Rationale for the Measure:** The primary interest in the simulation is to determine the feasibility of using UUVs during offensive operations, and thus killing the threat vessel is the paramount measure of success.

2. **Percent Re-Acquire**

(a) **Definition of the Measure:** This is a proportion of success of a binary measure that is equal to 1 if the individual simulation result contains an instance where the enemy vessel is initially detected, and subsequently re-acquired by one or both of the “killer” UUVs in the engagement area. The measure is averaged over the number of simulation runs to determine the proportion of successful re-acquisitions over the entire population of experiments.

(b) **Dimension of the Measure:** This ratio measures the percent of reacquires of the series of individual simulation runs. A greater ratio, closer to 1, is considered better.

c) **Limits on Range of Measure:** The range of the measure is a number between 0 and 1.

d) **Rationale for the Measure:** Additional aspects of using UUVs in offensive operations is the ability for the system of UUVs to re-acquire contact with the enemy vessel, whether or not an engagement occurs or is successful. Future UUV operations could use this aspect of UUV capabilities for the “track and trail” mission described in the UUV master plan.[1]

3. **Accuracy in determining Enemy Information** In addition to the count measures described above, another crucial aspect is calculating accurate information about the enemy vessel(s).
(a) **Enemy Speed**

i. **Definition of the Measure:** This is the absolute difference during a simulation run of the estimated speed when compared to the actual speed of the threat vessel.

ii. **Dimension of the Measure:** The measure is measured in Knots of difference between actual and estimated speed.

iii. **Limits on Range of Measure:** The range on this measure is a real positive number that ranges from 0 to 25 knots. 25 knots is the maximum speed of any threat vessel, and thus the worst case error in speed calculations.

iv. **Rationale for the Measure:** One key aspect of re-intercept of the enemy vessel is determining its future location and possible inference on the type of ship the system is engaging. Calculating an accurate estimate of the enemy speed allows for a more accurate determination of follow-on intercept information.

(b) **Enemy Location**

i. **Definition of the Measure:** This measure is the absolute difference during the simulation run of the estimated enemy location to the actual location of the enemy vessel.

ii. **Dimension of the Measure:** This measure is measured in meters of difference between actual and estimated location.

iii. **Limits on Range of Measure:** This measure can be any distance between 0 and \( \infty \) meters.

iv. **Rationale for the Measure:** Similar to enemy speed, an accurate portrayal of the enemy location is crucial to determination of where the enemy will be located in the future. This measure plays a direct role in determining the intercept location, and thus is crucial to successful engagement.

These measures of effectiveness are not independent of each other, and they each represent the systems performance during the course of the operations. The enemy information
measures of effectiveness are focused on evaluating the “hunter” UUVs ability to both acquire and discern the enemy’s location and speed accurately. The other two measures of effectiveness are more geared toward evaluating the ability of the “killer” UUVs to take the information gathered by the system and actually re-acquire and kill the threat vessel. However, the UUVs cannot kill the vessel without first re-acquiring the threat vessel, and the success of both of these parameters is reliant on accurate information being passed to them.

6.2 Statistical Comparison

In order to compare the factors, the experimental results are segregated based on factors that they have in common, as well as, the one factor that they did not have in common. Tables 6.2 through 6.5 show the comparative experiments for each of the examined parameters:

<table>
<thead>
<tr>
<th>Sensor Range</th>
<th>+: 1500m</th>
<th>-: 1000m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison</td>
<td>ExperimentA</td>
<td>ExperimentB</td>
</tr>
<tr>
<td>a</td>
<td>1(+)</td>
<td>2(-)</td>
</tr>
<tr>
<td>b</td>
<td>3(+)</td>
<td>4(-)</td>
</tr>
<tr>
<td>c</td>
<td>5(+)</td>
<td>6(-)</td>
</tr>
<tr>
<td>d</td>
<td>7(+)</td>
<td>8(-)</td>
</tr>
<tr>
<td>e</td>
<td>9(+)</td>
<td>10(-)</td>
</tr>
<tr>
<td>f</td>
<td>11(+)</td>
<td>12(-)</td>
</tr>
<tr>
<td>g</td>
<td>13(+)</td>
<td>14(-)</td>
</tr>
<tr>
<td>h</td>
<td>15(+)</td>
<td>16(-)</td>
</tr>
</tbody>
</table>

Table 6.2: Sensor Range Experiments

With the basis of comparison established, it is critical to determine the statistical method to compare the measures of effectiveness for each of the changed parameters. In the case of this experiment, there are four measures of effectiveness, which have two distinct characteristics. Percent kill and percent re-acquire both have binomial aspects; each experiment has either success or failure and thus the end result is count data rather than a measurement. In contrast, enemy location and enemy speed are both calculated based on actual data, and have a determinable mean and standard deviation. With this in mind, two different
### Weapons Range

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Experiment A</th>
<th>Experiment B</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1(+)</td>
<td>3(-)</td>
</tr>
<tr>
<td>b</td>
<td>2(+)</td>
<td>4(-)</td>
</tr>
<tr>
<td>c</td>
<td>5(+)</td>
<td>7(-)</td>
</tr>
<tr>
<td>d</td>
<td>6(+)</td>
<td>8(-)</td>
</tr>
<tr>
<td>e</td>
<td>9(+)</td>
<td>11(-)</td>
</tr>
<tr>
<td>f</td>
<td>10(+)</td>
<td>12(-)</td>
</tr>
<tr>
<td>g</td>
<td>13(+)</td>
<td>15(-)</td>
</tr>
<tr>
<td>h</td>
<td>14(+)</td>
<td>16(-)</td>
</tr>
</tbody>
</table>

Table 6.3: Weapons Range Experiments

### UUV Speed

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Experiment A</th>
<th>Experiment B</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1(+)</td>
<td>5(-)</td>
</tr>
<tr>
<td>b</td>
<td>2(+)</td>
<td>6(-)</td>
</tr>
<tr>
<td>c</td>
<td>3(+)</td>
<td>7(-)</td>
</tr>
<tr>
<td>d</td>
<td>4(+)</td>
<td>8(-)</td>
</tr>
<tr>
<td>e</td>
<td>9(+)</td>
<td>13(-)</td>
</tr>
<tr>
<td>f</td>
<td>10(+)</td>
<td>14(-)</td>
</tr>
<tr>
<td>g</td>
<td>11(+)</td>
<td>15(-)</td>
</tr>
<tr>
<td>h</td>
<td>12(+)</td>
<td>16(-)</td>
</tr>
</tbody>
</table>

Table 6.4: UUV Speed Experiments

### UUV Torpedoes

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Experiment A</th>
<th>Experiment B</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1(+)</td>
<td>9(-)</td>
</tr>
<tr>
<td>b</td>
<td>2(+)</td>
<td>10(-)</td>
</tr>
<tr>
<td>c</td>
<td>3(+)</td>
<td>11(-)</td>
</tr>
<tr>
<td>d</td>
<td>4(+)</td>
<td>12(-)</td>
</tr>
<tr>
<td>e</td>
<td>5(+)</td>
<td>13(-)</td>
</tr>
<tr>
<td>f</td>
<td>6(+)</td>
<td>14(-)</td>
</tr>
<tr>
<td>g</td>
<td>7(+)</td>
<td>15(-)</td>
</tr>
<tr>
<td>h</td>
<td>8(+)</td>
<td>16(-)</td>
</tr>
</tbody>
</table>

Table 6.5: UUV Torpedo Experiments
statistical tools are presented to test the significance of parameter changes.

Comparing two proportions

In the case of percent kill and percent re-acquire, we want to compare of the proportions of two groups, namely the experiments shown above, that have the specified measures of effectiveness. Here is the notation we will use in this section[12]:

<table>
<thead>
<tr>
<th>Population</th>
<th>Population Proportion</th>
<th>Sample Size</th>
<th>Count of Successes</th>
<th>Sample proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$p_1$</td>
<td>$n_1$</td>
<td>$X_1$</td>
<td>$\hat{p}_1 = \frac{X_1}{n_1}$</td>
</tr>
<tr>
<td>2</td>
<td>$p_2$</td>
<td>$n_2$</td>
<td>$X_2$</td>
<td>$\hat{p}_2 = \frac{X_2}{n_2}$</td>
</tr>
</tbody>
</table>

Table 6.6: Proportion Definitions

To compare the two populations, define the difference $D = \hat{p}_1 - \hat{p}_2$ between the two sample proportions. For confidence intervals, it is important to estimate the unknown standard deviation $\sigma_D$. First consider a confidence interval for $p_1 - p_2$. Substitute the sample values $\hat{p}_1$ and $\hat{p}_2$ for $p_1$ and $p_2$ in the expression for $\sigma_D$ to obtain

$$S_D = \sqrt{\frac{\hat{p}_1(1 - \hat{p}_1)}{n_1} + \frac{\hat{p}_2(1 - \hat{p}_2)}{n_2}},$$  \hspace{1cm} (6.1)$$

and subsequently the confidence interval is computed with the following

$$(\hat{p}_1 - \hat{p}_2) \pm z^* S_D,$$  \hspace{1cm} (6.2)$$

with $z^*$ the upper $(1-C)/2$ standard normal critical value.
To test the hypothesis

\[ H_0 : p_1 = p_2, \]

compute the z statistic

\[ z = \frac{\hat{p}_1 - \hat{p}_2}{s_p}, \quad (6.3) \]

where

\[ s_p = \sqrt{\hat{p}(1 - \hat{p})(\frac{1}{n_1} + \frac{1}{n_2})} \quad (6.4) \]

and

\[ \hat{p} = \frac{X_1 + X_1}{n_1 + n_2} \quad (6.5) \]

In terms of a standard normal random variable Z, the P-value for a test of \( H_0 \) against

\[ H_a : p_1 \neq p_2 \text{ is } 2P(Z \geq |z|) \quad (6.6) \]

**Comparing Two Means**

Suppose that a random sample of size \( n_1 \) is drawn from a normal population with unknown mean \( \mu_1 \) and that an independent random sample of size \( n_2 \) is drawn from another normal
population with unknown mean $\mu_2$. The notation for this section is presented in Table 6.7.

<table>
<thead>
<tr>
<th>Population</th>
<th>Sample mean</th>
<th>Sample Size</th>
<th>Sample Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\bar{x}_1$</td>
<td>$n_1$</td>
<td>$s_1$</td>
</tr>
<tr>
<td>2</td>
<td>$\bar{x}_2$</td>
<td>$n_2$</td>
<td>$s_2$</td>
</tr>
</tbody>
</table>

Table 6.7: Mean Comparison Definitions

The confidence interval for $\mu_1 - \mu_2$ is given by

$$(\bar{x}_1 - \bar{x}_2) \pm t^* \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}} \quad (6.7)$$

which has confidence level at least C no matter what the population standard deviation may be. Here $t^*$ is the upper $(1 - C)/2$ critical value for the $t(k)$ distribution, with $k$ being the smaller of $n_1 - 1$ and $n_2 - 1$.

### 6.3 Numerical Results

With the experimental design and statistical comparison parameters established, the following results are presented after running 1000 iterations of the 16 established experiments.

#### 6.3.1 Impact on Kill Percentage

In terms of increasing the ability for the system of UUVs to kill the threat vessel, the data shows, with 99% confidence, that increasing sensor range, increasing UUV speed, and increasing the number of torpedoes all have a significant impact on increasing the kill percentage, and weapons range does not. Table 6.8 shows the results for each experimental pairing.
### Table 6.8: Experimental Analysis for Kill Percentage

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Sensor</th>
<th>Weapon</th>
<th>UUV Speed</th>
<th>Torpedoes</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Significant</td>
<td>Significant</td>
</tr>
<tr>
<td>b</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Significant</td>
<td>Significant</td>
</tr>
<tr>
<td>c</td>
<td>Significant</td>
<td>Significant</td>
<td>Significant</td>
<td>Significant</td>
</tr>
<tr>
<td>d</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>e</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Significant</td>
<td>Significant</td>
</tr>
<tr>
<td>f</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>g</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>h</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Significant</td>
<td>Significant</td>
</tr>
</tbody>
</table>

Despite mixed results in some factor changes, when the results are numerically averaged based on the factor level, the results are more apparent, and one can easily recognize from Table 6.9 that UUV speed has the greatest impact on improving the chance of killing the enemy. These statistics appear logical, because as the simulation is designed, the ability for the UUV to move rapidly to the optimal engagement area allows the killer UUVs to intercept in a location that makes engagements from a shorter distance, thus improving the probability of hit and subsequently probability of a kill given a hit. Likewise, the sensor range factor improvement would allow for the target to be acquired initially, and subsequently to be intercepted; a UUV can’t kill an enemy vessel that it can’t detect. Additionally, increasing torpedoes allows engagements to be more successful. The non-significance of weapons range, although somewhat surprising, can most likely be explained by the fact that the engagements are by design taking place in optimal locations, providing a higher opportunity for shots to be taken at a shorter distance, which is within the smaller of the weapons range levels.

### 6.3.2 Impact on Reacquire Percentage

While there is a direct link between killing the enemy and re-acquiring the enemy (i.e. the enemy cannot be killed without being re-acquired), there is a noticeable difference between the factor effects. For each of the experimental pairs, see Table 6.10, UUV sensor range and speed are the only significant factors.
### Table 6.9: Impact on Kill Percentage

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Factor(+)$\mu_1$</th>
<th>Factor(-)$\mu_2$</th>
<th>99% Confidence Interval $(\hat{\mu}_1 - \hat{\mu}_2)$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Range</td>
<td>95.4%</td>
<td>91.91%</td>
<td>0.0355 ± 0.0252</td>
<td>Significant</td>
</tr>
<tr>
<td>Weapons Range</td>
<td>93.68%</td>
<td>93.68%</td>
<td>0.0 ± 0.0268</td>
<td>NOT Significant</td>
</tr>
<tr>
<td>UUV Speed</td>
<td>97.86%</td>
<td>89.51%</td>
<td>0.0835 ± 0.0249</td>
<td>Significant</td>
</tr>
<tr>
<td>UUV Torpedoes</td>
<td>95.2%</td>
<td>92.175%</td>
<td>0.03025 ± 0.0214</td>
<td>Significant</td>
</tr>
</tbody>
</table>

Table 6.10: Experimental Analysis for Reacquire Percentage

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Sensor</th>
<th>Weapon</th>
<th>UUV Speed</th>
<th>Torpedoes</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>b</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>c</td>
<td>Significant</td>
<td>Significant</td>
<td>Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>d</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>e</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>f</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>g</td>
<td>Significant</td>
<td>Significant</td>
<td>Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>h</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Significant</td>
<td>Significant</td>
</tr>
</tbody>
</table>

Table 6.10: Experimental Analysis for Reacquire Percentage
When compared as a whole, it is shown in Table 6.11 that Sensor Range and UUV Speed each show an approximate increase in re-acquire percentage of 3% and 6% respectively. These statistics follow reason, as the ability of the friendly UUVs to re-acquire the threat are directly related to the ability to see the enemy (sensor range) and the ability to move to a more optimal location (UUV Speed). As expected, the weapons factors are not significant in any aspect of the measurement, which lends more credence to the simulation and following examination.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Factor(+)</th>
<th>Factor(-)</th>
<th>99%Confidence Interval</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Range</td>
<td>98.4%</td>
<td>95.263%</td>
<td>0.0313 ± 0.0181</td>
<td>Significant</td>
</tr>
<tr>
<td>Weapons Range</td>
<td>97.375%</td>
<td>96.288%</td>
<td>0.0108 ± 0.0182</td>
<td>NOT Significant</td>
</tr>
<tr>
<td>UUV Speed</td>
<td>99.7%</td>
<td>93.963%</td>
<td>0.0573 ± 0.0136</td>
<td>Significant</td>
</tr>
<tr>
<td>UUV Torpedoes</td>
<td>97.15%</td>
<td>96.51%</td>
<td>0.00637 ± 0.0138</td>
<td>NOT Significant</td>
</tr>
</tbody>
</table>

Table 6.11: Impact on Reacquire Percentage

### 6.3.3 Impact on Enemy Distance Error

For this measures of effectiveness the results are exactly as expected; improved sensor range plays the only significant role in improving enemy distance calculations. As discussed in Chapter 5, the algorithm design ideally uses multiple UUVs to detect the enemy vessel, however when only one UUV detects the ship, the single ship metric is utilized. Thus, it is expected that with improved sensor range, the opportunity for both UUVs to detect the threat vessel is more frequent, and the accuracy of distance estimation is improved.

As Table 6.12 demonstrates, the sensor range is statistically significant in improving the enemy distance calculations in each of the eight independent comparisons. Additionally, as Table 6.13 demonstrates, when examining the total error of enemy location estimation, the improved sensor range provides an approximate improvement of 350 meters.
### Enemy Distance Error

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Sensor</th>
<th>Weapon</th>
<th>UUV Speed</th>
<th>Torpedoes</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>b</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>c</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>d</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>e</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>f</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>g</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>h</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Significant</td>
</tr>
</tbody>
</table>

Table 6.12: Experimental Analysis for Enemy Distance Error

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Factor(+)</th>
<th>Factor(-)</th>
<th>99% Confidence Interval ( (\mu_1 - \mu_2) )</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Range</td>
<td>12.218</td>
<td>359.91</td>
<td>(-347.69 \pm 17.972)</td>
<td>Significant</td>
</tr>
<tr>
<td>Weapons Range</td>
<td>190.43</td>
<td>181.7</td>
<td>(8.7334 \pm 21.52)</td>
<td>NOT Significant</td>
</tr>
<tr>
<td>UUV Speed</td>
<td>190.11</td>
<td>182.02</td>
<td>(8.0969 \pm 22.855)</td>
<td>NOT Significant</td>
</tr>
<tr>
<td>UUV Torpedoes</td>
<td>181.18</td>
<td>190.95</td>
<td>(-9.7772 \pm 34.94)</td>
<td>NOT Significant</td>
</tr>
</tbody>
</table>

Table 6.13: Impact on Enemy Distance Error
6.3.4 Impact on Enemy Speed Error

The improvements to this measure of effectiveness are tied directly to the same rationale on why sensor range plays a significant factor in improvement of enemy speed calculations. Again, because the more accurate the system is in determining the location of the enemy, the subsequent calculation of enemy speed realizes the mutual benefit.

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Sensor</th>
<th>Weapon</th>
<th>UUV Speed</th>
<th>Torpedoes</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>b</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>c</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>d</td>
<td>Significant</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>e</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>f</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>g</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
</tr>
<tr>
<td>h</td>
<td>Significant</td>
<td>Not Significant</td>
<td>Not Significant</td>
<td>Significant</td>
</tr>
</tbody>
</table>

Table 6.14: Experimental Analysis for Enemy Speed Error

As shown in Table 6.14, the sensor range improvement shows a statistical improvement in all eight experiments, with a mean improvement of just over 4 knots when examining enemy speed estimates (Table 6.15).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Factor(+)</th>
<th>Factor(-)</th>
<th>99% Confidence Interval ((\hat{\mu}_1 - \hat{\mu}_2))</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Range</td>
<td>.3439</td>
<td>4.5781</td>
<td>-4.2341 (\pm) .0177</td>
<td>Significant</td>
</tr>
<tr>
<td>Weapons Range</td>
<td>2.4763</td>
<td>2.4457</td>
<td>0.0306 (\pm) .2547</td>
<td>NOT Significant</td>
</tr>
<tr>
<td>UUV Speed</td>
<td>2.4941</td>
<td>2.4279</td>
<td>0.066 (\pm) .23128</td>
<td>NOT Significant</td>
</tr>
<tr>
<td>UUV Torpedoes</td>
<td>2.4255</td>
<td>2.4965</td>
<td>-0.07095 (\pm) .19728</td>
<td>NOT Significant</td>
</tr>
</tbody>
</table>

Table 6.15: Impact on Enemy Speed Error
6.3.5 Observations

These analysis show promising results in potentially improving key measures of effectiveness. As expected, sensor range plays the most significant role in enhancing the system of UUVs. This parameter shows an ability to enhance every single measure of effectiveness, and as a result is presented as the most important factor. Additionally, the speed of the “killer” UUVs is the second most crucial enhancement to the system of UUVs operating in the offensive role. This can best be explained by the ability of the UUVs to quickly move to an improved intercept location, and thus increase the opportunity for the UUVs to re-acquire and shoot at the threat vessel from a shorter, and thus more reliable distance. Any opportunity to enhance sensor range and speed of UUVs represents the most significant enhancement to improve the ability of a system of UUVs operating in an offensive capacity.

However, while these initial results show how enhancements can be made to the individual UUV, there remains a lingering question of how operational guidance can be used to further enhance the system. The next portion of this research will examine a methodology by which the placement of the “killer” UUVs can be optimized to improve the operational measures of system effectiveness.
Chapter 7

Optimization of Killer UUV Location

With the initial findings proving promising and giving significant insight into the interaction of key parameters within the system of UUVs, it is desirable to examine possible improvements in the system. With this in mind, the next stage of this thesis will develop a method to improve system performance by optimizing the initial placement of the killer UUVs.

7.1 Methodology

The intent of the methodology is to design an efficient process that planners would use, prior to military operations, to establish optimal starting locations for the killer UUVs. The core desire in this process is to create an accurate, yet efficient, methodology that analyzes the operational area, accounts for key characteristics of the enemy, adheres to previously established operational restrictions, and improves overall system performance. The following steps are used in developing this optimal location decision aid:

1. Establish baseline assumptions
2. Determine feasible intercept locations
3. Rank order intercept locations
4. Determine feasible killer UUV start locations
5. Assign value to each start location

6. Choose optimal start locations

7.1.1 Establish baseline assumptions

1. Hunter UUVs: The hunter UUVs will remain stationary and their sensor range will be set at the larger value of 1500 meters. This range ensures the worst report location is further down the route, which makes it more difficult to intercept the enemy vessel (less time to respond). This more conservative estimate is the rationale behind using the larger sensor range for all calculations during this algorithm.

2. Enemy Speed: In order to ensure a more conservative solution, the assumption is that the enemy vessel travels down each individual lane at the maximum speed possible for ships that may traverse down that lane. In this case, the maximum speed for all three routes is 25 knots.

3. Engagement distance: Several portions of this optimization use the weapons range parameter. All calculations that use this weapons range are reduced by using 66% of the maximum weapons range. This ensures that planning factors do not always assume the best case scenario, and are consistent with typical military planning factors.

7.1.2 Determine feasible intercept points

In order to avoid exploring every possible intercept point within the operational area, it is imperative to develop a methodology to calculate the feasible intercept points. For the purposes of this process, the intercept point is defined as the geographical point within the operational area that a killer UUV will locate itself in order to acquire and engage the threat vessel. The detailed steps are as follows:

1. **Determine worst case report locations for each route:** Based on the assumption that the hunter UUVs remain stationary throughout the mission and they are capable
Figure 7.1: Sensor Coverage Range of Hunter UUVs

of detecting any threat within its range, then the operational area for the hunter UUV where all acquisitions can occur is known and depicted in Figure 7.1. The squares in the figure represent the UUV locations, and the large circles show the sensor range boundaries for each of these UUVs. It is assumed that the enemy ship travels down the center of the shipping lane and the UUV’s would report the enemy location at the last possible moment. Possible report locations include the set of points along the center-line of the route that falls within the range circles of the sensor boundaries.

Figures 7.2 and 7.3 show the worst case reporting location, represented by a diamond, for each of the UUVs, and the final report location is determined to be the most southern point within each pair of UUVs. As mentioned earlier, the sensor range is set at the maximum value of 1500 meters. At the end of this sub-step, the algorithm has determined the worst case report location for each of the three shipping lanes.

2. **Determine first feasible intercept location:** At this point, the worst case enemy reported location has been determined. It would not be feasible for any killer UUV to engage the enemy vessel earlier than this point as the system of UUVs must first get
permission to engage. Additionally, based on the requirement for engagement permission, this report location can be interpolated further down the route to account for the assumed 5 minute decision time. The triangle, shown in Figures 7.4–7.6, represents the first point at which any killer UUV could potentially engage the threat vessel.
Furthermore, in order to take advantage of the UUV sensor and weapons range, without forcing the UUV to operate at its maximum range, the initial intercept point (point at which UUV positions itself) can be moved further down route from this first engagement point. By assuming the preferred engagement distance is no more than 66%
of maximum weapons range, the initial intercept point is calculated as the geographic point located approximately 950 meters down-route of the earliest point of engagement. These points are shown as the circles in Figures 7.4–7.6.

3. **Determine remaining intercept points:** With the individual route earliest point of intercept established, the remaining intercept points must be cataloged. This is done by starting at the calculated first intercept point and logging the points along the downward direction of the shipping lane center-lines in 200 meter intervals. At the end of this step, every feasible intercept location has been identified and stored as a set for later calculations.

4. **Determine engagement “area” at each Intercept Point:** With each of the feasible intercept points calculated, the next step calculates the engagement area formed at each of the intercept locations. As a reminder, the intercept point area is the area of the shipping lane formed by the boundaries of the shipping lane around the intercept point, and a factor of the distance traveled by the enemy vessel in the three minute engagement time. An example of this calculation is shown in Figure 7.7, and discussed in detail in Chapter 5.
At the conclusion of this stage, the system has calculated the engagement area for each corresponding intercept point. The optimal intercept location for each of the three routes is defined as the intercept point that results in the smallest engagement area.

These optimal locations are shown in the Figure 7.8:
7.1.3 Rank order intercept locations

Within the context of engagement “area” as the measure for determining the value of the intercept locations, it is critical to assign a scoring system to compare the intercept locations against each other. Initially, it seems reasonable to assign the smallest area (best) a score of 100 points and score the remaining intercept locations proportionally. However, this methodology would lead to significantly less than optimal results along Route C. In this case, the smallest area on Route C was significantly small such that the remaining intercept points scored on average, a mere 21 points relative to the score of 100 assigned to point with the smallest area. This case would undervalue many intercept points that would otherwise be considered very good engagement locations for tactical reasons.

With this example in mind, a metric was selected to compare the intercept points while addressing the capabilities of the UUV design. Assuming that the sensor and weapon range of the UUV are assigned the maximum value of 1500 meters, the area of the UUV engagement envelope is $1500^2\pi$ square meters. It would not be prudent nor tactically sound to plan a mission based on the entire envelope; therefore, 66% of the range is used as a metric and points are assigned using the following criteria:

1. For all points whose area is $66% \ (1500^2\pi)$ or less: 100 points.

2. Remaining points: Points $= \frac{66% \ (1500^2\pi)}{Point \ Area} \ (100)$

At this point, each of the feasible intercept locations has been characterized with both an engagement area metric and a subsequent rank determined by the score value between 0 and 100 points. A higher score is considered a more desirable intercept point than one with a lower score.

7.1.4 Determine feasible UUV start locations

With all possible intercept points identified and rank ordered, the next step is to determine the set of possible start points from which the killer UUVs could start their assigned mission.
Although any point in the operational area could serve as a start point for the killer UUVs, it is desirable to reduce these points to limit computational expense. The following reasoning was designed to determine the feasible start points.

Through a detailed analysis of the operational area, it is possible to reduce the number of feasible start points. Each of these key observations applies directly to this operational area but can also be applied to many other operational areas.

1. **Reduce points north of optimal location:** Due to the limited speed capabilities of the killer UUVs, it is not tactically viable for the UUV to start its missions from a point that is north of the optimal location for each individual route; there is no benefit to start further away from an optimal location. All points within a route boundary that fall north of the optimal location can be eliminated as possible start locations.

2. **Reduce points east and west of extreme routes:** Since the decision algorithms in this model assume that the intercept will take place on the centerline of the course, the points that fall east of the eastern most route, and the points that fall west of the western most route can also be removed from the model.

3. **Reduce points on southern portion:** The southern portion of this operational area provides a vast number of possible start points. To reduce these points, the area was split into three main sections with the centerline of the routes forming the lines of separation. Then, moving from west to east, the first obstacle-free line of latitude that connects the centerline of all three routes is selected. This latitudinal line marks the southern boundary of the feasible start points and any points further south of this line can thereby be removed. Points south of this line will be dominated (i.e. have a longer distance) to intercept points along the route center-lines, and thus cannot be part of any optimal solution.

This reduction technique significantly reduced the set of feasible start points to search over in subsequent steps of the algorithm. Figure 7.9 shows the results of this process. Each dot on the diagram represents a feasible start location for the killer UUVs.
7.1.5 **Assign value to each start location**

This process, which is the most computationally expensive portion of the algorithm, examines each start point determined from the previous step and assigns it a value. The goal of this process is to assign each start point a value for each of the three routes. $C_{sp}^r$ represents the value of start point $sp$ along route $r$. $IP_r$ represents the set of feasible intercept points along route $r$, and $Points_{IP_z}(z)$ represents the enumerated point value for each intercept point. The detailed steps are as follows:

1. Initialize: Sort the set of intercept points for each route from highest to lowest value. Thus, each route's optimal intercept point is listed first and the worst intercept point last.

2. For $i = 1 : |SP|$, where SP denotes the set of all start points, do:

   (a) For each route, $r$, included in set of routes, $R$.

   i. For $z = 1 : |IP_r|
A. Calculate Shortest Path distance from $SP_i$ to $IP_r(z)$

B. Calculate UUV time ($t_{UUV}$) and Enemy time ($t_{enemy}$) to $IP_r(z)$

C. IF $t_{UUV}$ is less than $t_{enemy}$, $C_{sp}^r = Points_{IP_r(z)}$

        end;
        ELSE
        continue;
        end;
    end;

At the conclusion of this step, each start point has been assigned a point value for each of the three routes. This point value is equal to the highest valued intercept point along a specific route that the UUV could reach prior to the enemy given the earlier speed assumptions of 7 knots and 25 knots for the friendly and enemy vessels, respectively.

7.1.6 Choose optimal start locations

The final procedure is to solve a linear program that maximizes the total amount of points or value that the two killer UUVs can accumulate through placement in the operational area. A UUV is considered capable of accumulating the points assigned to a start point by being placed at that point. Thus, the start points are presented in a set, $SP$, and $C_{sp}$ is equal to the total value of each point for each of the three routes, where $C_{sp}^r$ is equal to the value of start point, $sp$, along route $r$. For example, the value of some notional start point 1, is equal to the sum of the value that point 1 has on each of the three routes.

\[ C_{sp} = C_{sp}^A + C_{sp}^B + C_{sp}^C \quad \forall sp \in SP \] (7.1)

Equation 7.1 is modeled by the integer program shown as equation 7.2. $x_i$ is equal to 1 if a UUV starts at respective location, and 0 otherwise, and the set $R$ is the set of all three lanes. Two constraints were placed on the system to ensure coverage of the lanes, and to ensure that only two positions were used.
\[
\begin{align*}
\text{maximize} & \quad \sum_{sp \in SP} c_{sp} x_{sp} \\
\text{subject to} & \quad \sum_{sp \in SP} C_{sp}^{r} \geq 1 \quad \forall r \in R \\
& \quad \sum_{sp \in SP} x_{sp} \leq 2 \\
& \quad x_{sp} \in 0, 1 \quad \forall sp \in SP \\
\end{align*}
\]

(7.2)

### 7.2 Initial results of the optimization

Each of the UUV calculated optimal locations was different from the earlier assumed starting locations. Table 7.1 shows the precise difference in location and Figure 7.10 shows the new and old locations pictorially.

<table>
<thead>
<tr>
<th>UUV</th>
<th>Original Location</th>
<th>Optimal Location</th>
<th>Distance Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Killer UUV 1</td>
<td>41.42 -71.401</td>
<td>41.44 -71.406</td>
<td>2279 meters</td>
</tr>
<tr>
<td>Killer UUV 2</td>
<td>41.42 -71.305</td>
<td>41.45 -71.299</td>
<td>3813 meters</td>
</tr>
</tbody>
</table>

Table 7.1: Killer UUV placement comparison

The diamonds on the diagram reflect the original assumed location and the squares show the new "optimal" placement for the two UUVs based on the model solution.

The simulation was executed again with the only change being the two new optimal locations for the killer UUVs. The results are discussed in the next section.
7.3 Revised experimental results

As shown in Table 7.2 - 7.5, the revised experiments initially show that sensor range, UUV speed, and UUV torpedo enhancements have a statistical relevance to the UUV system kill percentage. Sensor range plays a significant role in enhancing re-acquire percentage, as well as, threat vessel location and speed estimates. However, the original 8% enhancement for kill percentage gained from increased UUV speed (see Table 6.9), is reduced in the revised experiment to only 2.2% using the new optimal UUV locations.

Therefore, where as UUV speed and sensor range enhancements were both determined significant factors of UUV capabilities, this is no longer the case when start positions are optimized using the methodology described in this chapter.
### Table 7.2: Impact on Kill Percentage

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\hat{\mu}_1$</th>
<th>$\hat{\mu}_2$</th>
<th>99% Confidence Interval $(\hat{\mu}_1 - \hat{\mu}_2)$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Range</td>
<td>97.18%</td>
<td>92.85%</td>
<td>4.0% ± 2.1%</td>
<td>Significant</td>
</tr>
<tr>
<td>Weapons Range</td>
<td>98.9%</td>
<td>96%</td>
<td>−2.35% ± 2.44%</td>
<td>NOT Significant</td>
</tr>
<tr>
<td>UUV Speed</td>
<td>98.60%</td>
<td>96.40%</td>
<td>2.2% ± 1.25%</td>
<td>Significant</td>
</tr>
<tr>
<td>UUV Torpedoes</td>
<td>96.76%</td>
<td>93.25%</td>
<td>3.51% ± 2.11%</td>
<td>Significant</td>
</tr>
</tbody>
</table>

### Table 7.3: Impact on Reacquire Percentage

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\hat{\mu}_1$</th>
<th>$\hat{\mu}_2$</th>
<th>99% Confidence Interval $(\hat{\mu}_1 - \hat{\mu}_2)$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Range</td>
<td>99.9%</td>
<td>97.125%</td>
<td>2.75% ± 1.25%</td>
<td>Significant</td>
</tr>
<tr>
<td>Weapons Range</td>
<td>98.35%</td>
<td>98.67%</td>
<td>0.325% ± 0.525%</td>
<td>NOT Significant</td>
</tr>
<tr>
<td>UUV Speed</td>
<td>98.32%</td>
<td>98.7%</td>
<td>−0.38% ± 1.11%</td>
<td>NOT Significant</td>
</tr>
<tr>
<td>UUV Torpedoes</td>
<td>99.42%</td>
<td>97.56%</td>
<td>1.90% ± 1.96%</td>
<td>NOT Significant</td>
</tr>
</tbody>
</table>

### Table 7.4: Impact on Enemy Distance Error

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\hat{\mu}_1$</th>
<th>$\hat{\mu}_2$</th>
<th>99% Confidence Interval $(\hat{\mu}_1 - \hat{\mu}_2)$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Range</td>
<td>48.25</td>
<td>313.72</td>
<td>−265.65 ± 10.95</td>
<td>Significant</td>
</tr>
<tr>
<td>Weapons Range</td>
<td>197.21</td>
<td>188.20</td>
<td>−9.01 ± 12.52</td>
<td>NOT Significant</td>
</tr>
<tr>
<td>UUV Speed</td>
<td>172.97</td>
<td>188.83</td>
<td>−15.85 ± 19.54</td>
<td>NOT Significant</td>
</tr>
<tr>
<td>UUV Torpedoes</td>
<td>195.47</td>
<td>199.22</td>
<td>4.75 ± 8.478</td>
<td>NOT Significant</td>
</tr>
</tbody>
</table>

Table 7.2: Impact on Kill Percentage

Table 7.3: Impact on Reacquire Percentage

Table 7.4: Impact on Enemy Distance Error
Table 7.5: Impact on Enemy Speed Error

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Factor(+)</th>
<th>Factor(-)</th>
<th>99% Confidence Interval ((\hat{\mu}_1 - \hat{\mu}_2))</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Range</td>
<td>.7184</td>
<td>4.36</td>
<td>-3.65 \pm 2.135</td>
<td>Significant</td>
</tr>
<tr>
<td>Weapons Range</td>
<td>2.02</td>
<td>2.56</td>
<td>-0.54 \pm 0.69</td>
<td>NOT Significant</td>
</tr>
<tr>
<td>UUV Speed</td>
<td>2.42</td>
<td>2.66</td>
<td>0.24 \pm 1.25</td>
<td>NOT Significant</td>
</tr>
<tr>
<td>UUV Torpedoes</td>
<td>2.58</td>
<td>2.33</td>
<td>0.25 \pm 0.87</td>
<td>NOT Significant</td>
</tr>
</tbody>
</table>

Table 7.5: Impact on Enemy Speed Error

7.4 Conclusion

These new results show some significant differences when compared to the initial placement results, but they must be compared as a whole to truly discover the actual benefit gained through the use of the optimal placement methodology. The following table shows the comparison:

<table>
<thead>
<tr>
<th>Measure of Effectiveness</th>
<th>Original</th>
<th>Optimal</th>
<th>99% Confidence Interval ((\hat{\mu}_1 - \hat{\mu}_2))</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kill proportion</td>
<td>93.68%</td>
<td>95.11%</td>
<td>1.43% \pm 1.87%</td>
<td>Significant</td>
</tr>
<tr>
<td>Reacquire proportion</td>
<td>96.80%</td>
<td>98.50%</td>
<td>1.70% \pm 2.14%</td>
<td>Significant</td>
</tr>
<tr>
<td>Distance Error</td>
<td>186.12</td>
<td>180.90</td>
<td>5.22 \pm 8.54</td>
<td>NOT Significant</td>
</tr>
<tr>
<td>Speed Error</td>
<td>2.46</td>
<td>2.54</td>
<td>-0.09 \pm 0.27</td>
<td>NOT Significant</td>
</tr>
</tbody>
</table>

Table 7.6: Measure of Effectiveness Comparison

As Table 7.6 demonstrates, the use of the optimal placement methodology plays a significant role in enhancing the system of UUVs capability to both re-acquire and kill the threat vessel, and as presented in the previous section, the ability to enhance the sensor range plays the most significant role in improving the systems ability to improve in all measures of effectiveness.
Chapter 8

Conclusion

The purpose of this chapter is to provide a summary of the research in this thesis and to offer suggestions for future research that could enhance the performance of future UUVs in the offensive role.

8.1 Research Summary

The objective of this research was to both develop usable decision algorithms and test UUV enhancements for UUV offensive operations, as tactically established in the UUV Master Plan. This problem was approached as a series of complementary algorithms. A simulation was created that both validated the decision algorithms, and provided a testbed to analyze changes to key UUV parameters and statistically analyze their benefit to four distinct measures of effectiveness.

The initial results demonstrated the ability to successfully employ teams of UUVs in an offensive capacity using the developed decision algorithms. Additionally, through simulation, results showed that technological improvements in sensor range, and UUV speed both provide statistical enhancements in kill percentage and re-acquire percentage. Additionally, improving sensor range greatly improves the accuracy of the enemy information algorithms.

Subsequently a successful methodology was developed to enhance the placement of killer
UUVs. This methodology specified these optimal placements, and results demonstrated that while sensor range remains critical to maximizing the UUVs success, the level of effectiveness earlier presented by UUV speed was quickly abated through this optimal placement.

When conducting offensive operations in similar littoral terrain, as demonstrated through simulation and statistical analysis, the single most critical enhancement to UUV operations is improved sensor range. Additionally, it has been shown that teams of UUVs could operate semi-autonomously in these littoral areas and be decisive against hostile targets.

8.2 Areas for Future Research

There are several areas for future research within the context of this thesis, and they would enhance the future improvement of the decision algorithms and further validate their benefit to offensive UUV operations.

8.2.1 Expand initial research to different terrain

One weakness of the analysis conducted in this thesis is the limited test terrain. More precisely, the Narragansett Bay harbor region was the only tested area. The algorithms were designed as generally as possible, but specifically designed toward success in the selected terrain. For example, the many choke points along each of the routes, and the fact that the hunter UUVs were able to cover the majority of the width of the shipping lane, both facilitated successful engagements. Thus, a more thorough analysis using an area with different terrain aspects would provide valuable information about the overall success of these algorithms.

8.2.2 Expand aspects of simulation

1. Smart Enemy Reactions: In the case of this research, the enemy selected its route in the beginning of the simulation, and failed to react to any friendly activity. It would be insightful to examine the simulation environment if enemy reactions were added to the
simulation. These reactions could include reaction to being shot at, or a probabilistic reaction when within a close range to operating UUVs.

2. Hunter UUV movement: In this research, the hunter UUVs did not move to gather information about the enemy, and in fact acted more like stationary sensor arrays. There could be multiple enhancements tested through the simulation if one considered the possible movements of the hunter UUVs.

3. Engagements: In this research, the engagement was a simple random number probability of hit based on distance from the target, and an additional random number probability of kill based on distance and probability of hit. The simulation did not account for the complexities of getting a specific target analysis of the threat vessel, and the subsequent complexities with getting into the proper position to aim and fire torpedoes.

4. Simulation area noise: In this research, the only vessels operating in the operational area were the six friendly UUVs and the single threat vessel. Reality, however, dictates that a harbor region would be flooded with commercial, personal and other threat vessels. A true engagement would necessitate that the system of friendly UUVs be able to operate in this noisy environment, and be able to re-acquire the "correct" vehicle and engage it, but also make smart decisions as to when certain engagements pose too high a risk for collateral damage, i.e., if a cruise ship is in close proximity to a threat vessel, the UUV should wait until the cruise ship is at minimal risk, even if this action makes the subsequent engagement more difficult.
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Bibliography


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