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SEABED INFRASTRUCTURE DEFENSE ANALYSIS

by

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Traditional fleet operations and technologies are not adequately suited to counter the growing threat to undersea infrastructure from autonomous undersea systems. A cost-effective unmanned and manned system of systems is required to provide defense of this seabed infrastructure. This paper proposes possible system architectures to defend against this emerging threat to include passive barriers and active defense systems. The effectiveness of those candidate systems is evaluated through multiple agent-based modeling simulations of UUV versus UUV engagements. Analysis resulted in two major findings. First, point defense of critical assets is more effective than barrier defense. Second, system design must focus on minimizing the time required to effectively engage and neutralize threats, either through improvement to defensive UUV speed or investment in more UUV docking stations and sensor arrays. Cost analysis suggests that acquisition and operations cost of the recommended defensive system is less than the projected financial impact of a successful attack.

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ABSTRACT

Traditional fleet operations and technologies are not adequately suited to counter the growing threat to undersea infrastructure from autonomous undersea systems. A cost-effective unmanned and manned system of systems is required to provide defense of this seabed infrastructure. This paper proposes possible system architectures to defend against this emerging threat to include passive barriers and active defense systems. The effectiveness of those candidate systems is evaluated through multiple agent-based modeling simulations of UUV versus UUV engagements. Analysis resulted in two major findings. First, point defense of critical assets is more effective than barrier defense. Second, system design must focus on minimizing the time required to effectively engage and neutralize threats, either through improvement to defensive UUV speed or investment in more UUV docking stations and sensor arrays. Cost analysis suggests that acquisition and operations cost of the recommended defensive system is less than the projected financial impact of a successful attack.

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LIST OF ACRONYMS AND ABBREVIATIONS

ASME	American Society of Mechanical Engineers
ASW	Anti-Submarine Warfare
AUV	Autonomous Underwater Vehicle
C2	Command and Control
CIA	Central Intelligence Agency
COA	Course of Action
CONUS	Continental United States
DDG	Guided Missile Destroyer
DOE	Design of Experiment
EEZ	Economic Exclusion Zone
FARPS	Forward Arming and Refueling Point
GDP	Gross Domestic Product
LCS	Littoral Combat Ship
LDUUV	Large Diameter Unmanned Underwater Vehicle
MANA	Map Aware Non-Uniform Automata
MARPAT	Maritime Patrol Aircraft
MDUUV	Medium Diameter Unmanned Underwater Vehicle
MOE	Measure of Effectiveness
NOLH	Nearly Orthogonal Latin Hypercube
NPS	Naval Postgraduate School
NSA	National Security Agency
NSC	National Security Cutter
OODA	Observe, Orient, Decide and Act
RAMCAPSM	Risk Analysis and Management for Critical Asset Protection
ROI	Return on Investment
ROV	Remote Operated underwater Vehicle
SDUUV	Small Diameter Unmanned Underwater Vehicle
SEA	Systems Engineering Analysis

SEED	Simulation Experiment and Efficient Designs
SONAR	Sound Navigation and Ranging
SOSUS	sound surveillance system
SPAWAR	Space and Naval Warfare Systems Command
USID	Undersea Infrastructure Defense
USIDS	Undersea Infrastructure Defense System
USNORTHCOM	U.S. Northern Command
UUV	Unmanned Underwater Vehicle
XLDUUV	Extra Large Diameter Unmanned Underwater Vehicle

EXECUTIVE SUMMARY

This study investigates effective ways to defend against attacks on undersea infrastructure using primarily active defense measures. The analysis takes place through two case studies; the defense of underwater infrastructure in the Natuna Besar natural gas fields in the South China Sea, and the defense of oil infrastructure in the Gulf of Mexico. The research team built a series of models that were used to analyze the impact of alternative undersea infrastructure defense systems. A cost analysis team researched existing systems to determine a reasonable and credible cost estimation for the proposed systems and used current industry estimates to determine the complete cost impact should a successful attack occur on the undersea infrastructure.

Undersea infrastructure defense comprises two primary functions: sensing the threat, and responding to it—with assets assigned to perform one or both functions. In the most basic concept, this consists of an array of acoustic buoys as sensors, and a flotilla of response unmanned underwater vehicles (UUVs). Some of our larger models utilize supporting air assets and surface vessels to augment the sense and response functions at different levels of threat; in smaller models, only UUVs (with comparable sensor capabilities) are involved.

Effective positioning and layering of assets enable undersea infrastructure defense. These techniques employ distinct schemes: area defense, point defense, or barrier defense (or some combination of the three). Each defensive scheme has a particular objective. Point defense attempts to protect a singular asset or position from an expected threat. Barrier defense is an attempt to maintain some sort of security perimeter to ensure that any asset or position within the barrier is better protected to a significant degree than assets or positions beyond the protect region. Area defense shares with barrier defense the same goal of improving the security of a designated region; however defending assets are not physically confined to specific barriers paths, and instead patrol the entire region. Figure 1 provides an aid for conceptualization.

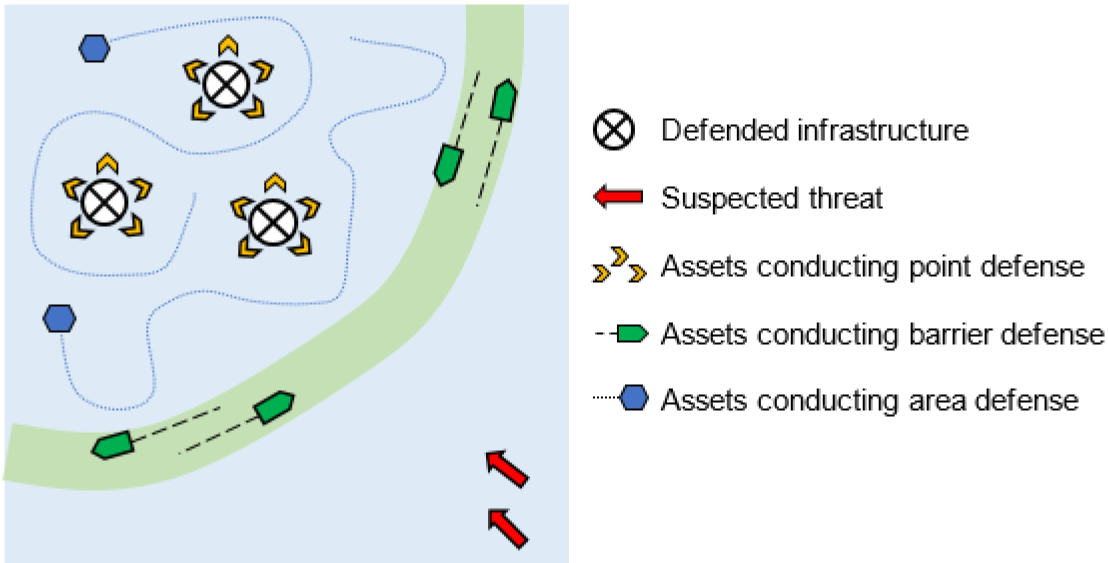

Figure 1. Visualization of defensive schemes

B. ANALYSIS APPROACH

The project team developed four models to identify the alterations to operational concepts and system employment that impact the effectiveness of undersea infrastructure defense systems. These range from small scale models examining the tactical defense of underwater infrastructure in the Natuna Besar region against UUVs to a large-scale model examining theater-wide defense of the Gulf of Mexico against a wide range of threats.

1. Natuna Besar Models

The Natuna Besar models investigate the effectiveness of defending key infrastructure nodes (for example, single oil platforms) and the pipelines that connect them.

Natuna Besar Model 1 focused on the point defense of critical infrastructure nodes from enemy UUV attacks. This model employs defensive UUVs that perform both the sensing and responding functions; there are no additional sensors in this model. The defensive UUVs are either static or patrolling and are assumed to have the same sensor capabilities and limitations as a stand-alone sensor buoy, thereby negating the need for a pre-existing or temporary array of sensors. The intent is to investigate the idea of whether an architecture of inexpensive, easily deployable UUVs with a long shelf-life can effectively provide point defense of key infrastructure nodes against UUV threats. By reducing the types of assets, this model explored the idea of a minimally-manned, cost-effective defense that can be applied in almost any scenario or region, and can be implemented by any entity.

Natuna Besar Model 2 investigates the defense of the long stretches of pipeline that connect the critical extraction nodes to the shore. It does so by looking at how combinations of static and patrolling UUVs and static underwater sensors can be employed in a barrier parallel to the defended asset to defend against threat UUVs. The lessons learned about defending the 4 km stretch can then be scaled up and applied relative to the overall length of the pipeline. While the anticipated threat is the same as Natuna Besar Model 1, the incorporation of sensor arrays increases the available engagement window.

2. Gulf of Mexico Models

The Gulf of Mexico groups explored the defense of a large region. The two primary threats considered in this region were the destruction of a large number of infrastructure nodes disrupting industry in the region, or an attack on one of the critically vulnerable nodes causing catastrophic damage, similar to the Deepwater Horizon spill in 2010. Either would have economic effects that could reach into the hundreds of billions of dollars. The models address these concerns by trying to determine what types of defensive arrangements could successfully defeat such attacks.

Gulf of Mexico Model 1 sought to answer the question of how well a barrier of UUV and sensors provide a perimeter defense to keep underwater enemy UUVs from transiting submerged into the target rich environment of the Gulf of Mexico. The design is based on equally spaced sensor buoys, with Defender UUVs in docking stations poised to attack upon detection of enemy UUVs.

Gulf of Mexico Model 2 examined the effectiveness of such a barrier when scaled up to a theater-wide defensive scheme against a wider range of threats, not just the long range LDUUV threat posited by Gulf of Mexico Model 1. The new threats are neutral flagged enemy cargo ships that are capable of sailing over the barrier undetected and either dropping off small diameter UUVs (SDUUV) in close proximity to their targets or acting as "Bomber Ships" themselves, dropping depth charges or even dragging their anchors to deal damage. In order to combat these additional threats, this model utilizes a defense in depth approach combining point, barrier, and area defense assets including ships, aircraft, UUV from underwater docking stations, and underwater sensor networks.

C. MODELING AND ANALYSIS APPROACH

The team utilized an agent based simulation, Map Aware Non-Uniform Automata (MANA), to conduct analysis. MANA uses configurable agents that simulate attackers, defenders, and pipeline or platform targets. Figure 2 presents an example graphic from a MANA program.

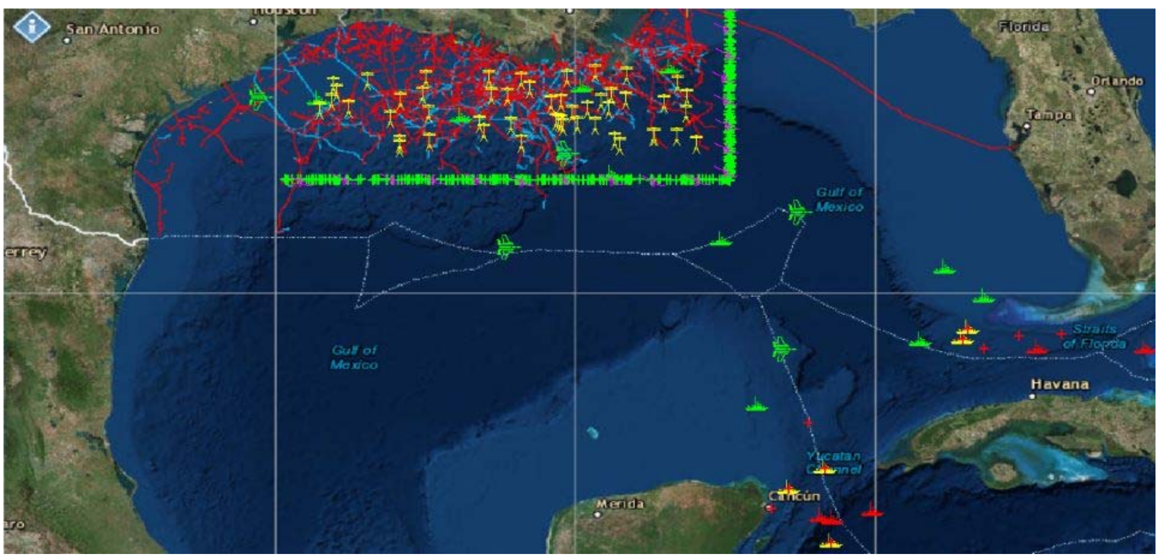

Figure 2. Gulf of Mexico MANA Simulation

The team utilized space filling Nearly Orthogonal Latin Hypercube (NOLH) designs to define simulation runs to explore the full design space. Regression analysis of data output provided insight into the performance of different defense systems across multiple concepts of operation.

D. CONCLUSIONS

Implementing an active defensive system responsible for protecting underwater infrastructure defense of the Natuna Besar or Gulf of Mexico regions is a proposition of breathtaking proportions. It will require significant amounts of capital for both the initial design of and deployment of the defensive systems in the short term and for the administration, maintenance, and eventual replacement of those systems over the ensuing decades. Before pushing ahead with any such projects in a piecemeal fashion, high-level decision makers should take several factors into consideration

A simple point defense of critical assets must be included in a defensive scheme whenever possible. Barrier Defenses composed of roving or stationary patrols are insufficient, even in conjunction with area defense assets that can supplement them. So far as the design factors surrounding defensive weaponry itself are concerned, the number of weapons and their accuracy has been found to be more important than any other factor, including sensor range, weapon range, and weapon lethality to name a few.

For a barrier defense of a pipeline it also holds true that a large number of UUVs in fixed docking stations is better than roving patrols. This system performs best when continuous targeting updates are provided to the UUVs from a fixed sensor array. The wider the sensor array, the better because this provides the defending UUVs with more time to engage the threat. One option to increase the width of the array would be make the array two or preferably three rows deep.

The proposed system of sensor arrays and UUVs is not intended to replace all traditional maritime and coastal defenses. The defense of undersea infrastructure has the highest success rate when existing surface and air assets are able to receive information from the sensor array and provide additional firepower to the defending UUVs.

To place a minimal barrier of just UUVs in the Gulf of Mexico will cost $1.5 billion. Adding an integrated sensor array network and point defense for 100 critical infrastructure nodes brings the total cost to $6.2 billion, excluding the operational and maintenance cost for the surface ships and patrol aircrafts. This system is cost effective compared to the estimated $62 billion that was lost in revenue and damages during the Deepwater Horizon oil spill.

For Natuna Besar, acquisition of a barrier that covers the entire pipeline is estimated to cost $1.9 billion and an additional $66 million for point defense of each platform. With 152 platforms, defense of the entire undersea infrastructure in Natuna Besar, we estimate an initial cost of $10 billion.

While there is substantial appeal in investing in active defenses such as those investigated in this paper due to the optimism generally associated with new technologies and the potential applications they may have towards unforeseen uses, equal attention should be paid towards passive defensive measures, resilient and redundant systems, and repair and recovery capabilities. Additionally, if active defenses are developed and deployed, it is critical that a thorough systems engineering process guides that effort. Such process is necessary to avoid cost overruns, incompatible systems, and substandard performance due to the enormous number of shareholders, technical challenges, evolving nature of the threat, and the significant capital required to tackle every major aspect of the problem.

ACKNOWLEDGEMENTS

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I. INTRODUCTION

A. MOTIVATION

Of all the challenges facing 21st century defense and security planners, the defense of underwater infrastructure is one of the most difficult to solve (Barker, 2018). The opportunities, capabilities and hostile intentions that might lead to the exploitation of undersea infrastructure around the world have existed for as long as that infrastructure has been in place. With few exceptions however, for most of modern history they have either not resided together in one adversary or, when they have, whatever benefits were to be had by such actions were far outweighed by the associated costs and risks. With so few recorded instances of attacks against underwater infrastructure there has been a correspondingly low amount of preparation for its defense (Kashubsky, 2011; Glenney, 2019). Indeed, in the past it has generally been assumed that strong conventional surface and subsurface forces from national Coast Guards and Navies were sufficient for the defense of national interests, particularly the underwater infrastructure in littoral waters and economic exclusion zones.

As the global environment has evolved economically, technologically, and politically over the past decades, the defense and security communities have become increasingly aware that the cost/risk/reward factor associated with exploiting underwater infrastructure has been continually shifting in favor of the would-be attacker (Glenney, 2019). In particular, the changing environment has drastically increased the number of opportunities for exploitation around the world, lowered the cost of acquiring necessary capabilities for various types of exploitation, and increased the number of possible motivations for hostile intent.

This study investigates effective ways to defend against attacks on undersea infrastructure. The analysis takes place through two case studies; the defense of underwater infrastructure in the Natuna Besar natural gas fields in the South China Sea, and the defense of oil infrastructure in the Gulf of Mexico.

B. BACKGROUND

Opportunity, capability, and intent are useful standards for examining the danger posed by a possible threat. This section will provide a background understanding of opportunity, capability, and intent in the context of the exploitation of undersea infrastructure defense.

1. Opportunity

Opportunity is represented by the wide variety of vulnerabilities that could be exploited by potential adversaries. For defense and commercial purposes, these vulnerabilities fall into three main categories; fossil fuel extraction and transfer, electrical power transfer, and communications information transfer (Wrathall, 2010). The increases in opportunity for exploiting underwater infrastructure can be attributed to two main causes; increased numbers of targets and increasingly critical vulnerabilities. For example, between 1988 and 2013 an average of over 31,000 miles of submarine cable was laid per year, totaling over 750,000 miles. These cables form the backbone of the digital age infrastructure, collectively carrying over 99% of all internationally transmitted data (Main, 2015). Offshore oil and gas production is also on the rise. In the Gulf of Mexico alone, offshore oil production has risen from under 300 billion barrels per year in 1990 to over 600 billion barrels per year in 2017 (Zeringue, 2017). These increases have been the result of increasing investment in offshore and especially deep-water extraction technology, the proliferation of which has helped expand oil and gas production globally (Manning, 2016). Cumulatively, communications and energy infrastructure projects around the world have had the effect of ensuring that underwater infrastructure targets are available and plentiful in virtually every region of the world.

Beyond the mere proliferation in number of targets, the nature of the targets themselves has led to the formation of increasingly critical vulnerabilities. Whereas several decades past a major attack on underwater infrastructure would have had a fairly small impact on the global community, today the stakes are far higher. Increased reliance on the undersea infrastructure used for communication has created an opportunity for attackers to disrupt banking and impact national economies. Concentrated routing of communication cables creates chokepoints that if severed would result in wide area outages. Targeting data for these cables and oil/natural gas pipelines are readily available in the public domain making both systems easy to target. Additionally, security responsibility gaps complicate agencies' ability to coordinate defense (Wrathall, 2010). Given the complexity of the issue, the opportunity for an adversary to strike is real and would cause severe damage to our underwater infrastructure with compounding economic and environmental consequences.

2. Capability

Capability is represented by the various assortment of tools that could be used to conduct an exploit. They range from the simple kinetic weapons such as commercial ships intentionally dragging their anchors across seabed infrastructure to high tech weaponry that has been purpose built for any number of undersea missions (Dean, 2017).

New capabilities have come about in the form of Unmanned Underwater Vehicles (UUVs). These systems are smaller, cheaper and quieter than manned submersibles and in many cases entirely expendable. The decreasing costs of acquiring and operating them means that more adversaries will have them, and will likely be able to employ them in large numbers. Increased levels of global commerce and shipping both in size and quantity creates higher levels of ambient noise. This makes an already quiet UUV increasingly harder to detect.

The increased number of ships also means an increased danger from the ships themselves. More shipping means more ships to keep track of, an increased likelihood that one may have hostile intentions, and an increased lethality from larger ships. This makes threat detection, identification, evaluation, and response a substantially more difficult problem for any surface vessel defense force.

In the realm of underwater threats, the capability to conduct stealthy and effective seabed warfare operations has existed for decades. For example, declassified Cold War operations like Operation Ivy Bells when the NSA and CIA tapped Soviet undersea cables, demonstrate the utility and effectiveness of underwater assets in exploiting underwater infrastructure (Gaskill, 2018). While the cost of special mission submarines such as the one used in operation Ivy Bells is still immense, the revolution in autonomous vehicles has begun to make available some similar capabilities at a much lower price and to a much broader audience (Dean, 2017). This broader audience includes potential adversaries, but it also includes commercial and scientific endeavors, thereby complicating the already challenging targeting problems of undersea warfare even further.

3. Intent

Hostile intent, in both the surface and subsurface threat categories, is made especially difficult to identify as a result of the aforementioned proliferation of threat capability to new audiences. These motivated adversaries could come from a wide range of sources, including both nation states and non-state actors which range from private companies to international terrorist organizations. Given that they could be motivated by wildly different objectives, the ways in which adversaries would attempt to exploit underwater infrastructure investments is worth particular exploration. The following examples illustrate the broad nature of these motivations. Understanding the motives leads to defensive schemes that can be developed and analyzed.

One motive for attack is to drive up costs for the owners of the industry in question. This type of exploitation has the capacity to cause far greater harm than merely the amount of damage done to the infrastructure itself. For example, in the Deepwater Horizon oil spill in 2010 the British Petroleum company lost operation of its oil well which was valued at approximately $560 million (Staff, 2010). The loss of this asset alone would be a significant but ultimately minor setback for a company with over $280 billion in assets and a net operating income of $9.5 billion annually. Taking into consideration the environmental costs, however, and the damage balloons to over $65 billion (Bousso, 2018). While there is no suggestion that the Deepwater Horizon oil spill was a malicious act, the costs associated with stopping and cleaning it indicate that a future attack designed to inflict similar financial damages to a company is certainly within the realm of possibility.

Another motive could be to deny access to those resources so as to stop their utilization. For example, if a community relies on offshore natural gas to power its industrial manufacturing, denying access to that gas will decrease or eliminate the manufacturing capability until it can be restored. Amplified to its natural extreme, this approach could be used to deny critical energy resources to an entire nation in times of war.

A third possible motive is to raise the cost of resources on the global market by decreasing the amount of global supply. This can be achieved by physically impeding their delivery, or by raising the cost of doing business (building, operating, maintaining, etc.) to prohibitive and uncompetitive levels. For example, when the Deepwater Horizon spill occurred, there was substantial speculation that increasing taxes, regulations, and insurance costs would be implemented that would drive up the cost of doing business in U.S. waters. Such measures could have drastic effects of increasing the costs of energy in the short and the long term, and there would be big winners and big losers as a result. In particular, the big winners would be the individuals, companies, and nations able to profit from the ability to produce oil at lower costs and cash in on the higher rate of return.

A fourth motive might be the theft of some of those resources. This is really only feasible on the information communication side, wherein an actor could potentially tap into underwater communications cables to intercept data transmissions. This approach has been utilized in the past, but the nature of digital communications and the widespread utilization of encrypted message traffic suggests that it would be of substantially reduced value today.

A fifth possible motive is the use of an attack to send a message, possibly as a way to coerce some other actor into some decision they would otherwise have avoided. This could include anything ranging from an environmental terrorist organization aiming to pin the blame of an environmental disaster on an industry so as to push for stronger long-term regulation all the way to a nation state signaling that certain actions on the international stage would not be tolerated.

Without precise foreknowledge of which potential adversaries will become real hostile actors, and without the ability to thoroughly investigate means, motives, and opportunities for every particular threat in advance, it is nearly impossible for any universal defensive scheme to be developed and optimized to employ a perfect defense with existing or even future technologies that can be anticipated within the short term. Rather, undersea infrastructure defense is best approached with the goal of meeting the most significant threats with as high a degree of defense possible given cost related constraints. This suggests that the problem is well suited to a systems engineering approach, which would help ensure that stakeholder requirements are well understood and the system architecture employed takes into consideration a thorough assessment of critical measures of analysis and measures of performance required to provide the requisite multi-faceted defense.

C. TASKING STATEMENT AND PROJECT SCOPING

Recognizing the complexity associated with developing a multi-faceted defense for global undersea infrastructure, the Naval Postgraduate School (NPS) Chair of Systems Engineering Analysis developed the following tasking statement as a way of scoping and bounding the undersea infrastructure defense problem:

> Design a cost effective, deployable and resilient unmanned and manned system of systems employed to provide seabed infrastructure defense in the 2030–2035 timeframe. Consider employment requirements, power requirements, operating areas, bandwidth and connectivity, interoperability, sensor data processing, transfer and accessibility, logistics, forward arming and refueling (FARPS) basing support in forward areas or from CONUS bases. Where possible, include joint contributions in the systems of systems. Develop alternative architectures that include defensive systems, sensors, manning, communication and network connectivity, and their operational employment concepts. Investigate current commercially off the shelf technologies for rapid acquisition. Use two regional undersea infrastructure systems to analyze the cost- effectiveness of the alternatives: the Gulf of Mexico oil and communication system and the Natuna Gas Field (Greater Sarawak Basin) feeding into Singapore.

Based on the discussion of opportunities, capabilities, and intent presented previously, the team identified key areas of emphasis within the tasking statement in order to determine what to address given the allotted time and resources. The first part of the tasking statement, the design of a system of systems that considers a large number of factors, was particularly challenging given that the project timeline precluded the development and testing of any physical instantiations of undersea infrastructure defense systems.

In order to overcome this hurdle, the team decided to build a series of models which could be used to analyze the impact of alternative undersea infrastructure defense systems.

The selection of the models built was made through consideration of the second key point of the tasking statement, the creation of alternative architectures that could guide the development and employment of the defensive schemes utilized. Both the computer models and their guiding architectures were developed with consideration towards the third major aspect of the tasking statement, undersea infrastructure defense of both Natuna Besar and the Gulf of Mexico. A cost analysis team researched existing systems to determine a reasonable and credible cost estimation for the proposed systems and used current industry estimates to determine the complete cost impact should a successful attack occur on the undersea infrastructure.

D. PROJECT TEAM

The team assigned to perform this task was Systems Engineering Analysis Cohort 28 (SEA 28), comprised of Naval Postgraduate School (NPS) students with a diverse range of specialties, programs, and nationalities. Team members have backgrounds in aviation, surface warfare, subsurface warfare, armor infantry, engineering, logistics, human resources and air defense. The team includes military officers from the United States Navy, Marine Corps, Israeli Defense Force and Singaporean Army and Air Force. To emphasize the interdisciplinary expertise of the project team, a list of the members and their backgrounds is presented in Table 1.

Table 1 Project Team Roster

Name	Country	Service	Job Specialty	Undergraduate Education	Graduate Education Track
Antonio, F. Aaron	USA	USN	Surface Warfare	Criminal Justice	Systems Engineering Analysis
Asmus, Jared	USA	USN	Surface Warfare	Environmental Systems	Systems Engineering Analysis
Belcher, Kyle	USA	USN	HR	Math	SE and OR
Berger, Asaf	ISRAEL	IDF	EW Engineer	EE & Physics	Electrical - EW
Bey, Ben Muwei	SINGAPORE	RSAF	Engineer	Electrical Engineering	Electrical - EW
Chen, Zhaolin	SINGAPORE	RSAF	Engineer	Electrical Engineering	Electrical - Cyber
Chew, Jian Ming	SINGAPORE	SAF (Army)	Armor Infantry	Info Tech & Multimedia	System Engineering
Constantine, Scott	USA	USN	ASW Aviation	Finance	Systems Engineering and Analysis
Eich, Dolph	USA	USN	Surface Warfare	Chemistry	Systems Engineering and Analysis
Hanacek, Joseph	USA	USN	Surface Warfare	History	Systems Engineering and Analysis
Kui, Jie Ren	SINGAPORE	RSAF	Ground Based Air Defense	Chemical Engineering	Physics - Combat Systems
Lee, Cheng Qian	SINGAPORE	SAF (Army)	Combat Engineer	Materials Engineering	Systems Engineering and Analysis
Lian, Weiwen Mervyn	SINGAPORE	Civilian	Engineer	Electrical Engineering	MOVES
Newgren, Brian	USA	USN	ASW Aviation	Aerospace Engineering	Systems Engineering and Analysis
Morgan, John	USA	USN	Surface Warfare	Chemistry	Systems Engineering and Analysis
Rydalch, Wilson	USA	USN	Submarine select	Mechanical Engineering	Mechanical Engineering
Se, Xi Yang Ronald	SINGAPORE	Civilian	Software Engineer	Computer Engineering	Cyber Security
Shi, Ronghua	SINGAPORE	Civilian	Mechanical Engineer	Mechanical Engineering	Cyber Security
Tan, Kang Hao	SINGAPORE	RSAF	Ground Based Air Defense	Electrical Engineering	Systems Engineering
Wheeler, Kevin	USA	USMC	Logistics	Mechanical Engineering	Operations Research
Yee, Jun Xian Jeremy	SINGAPORE	SAF (Army)	Engineer	Mechanical Engineering	System Engineering

II. INITIAL RESEARCH

In order to develop systems to operate in and defend the regions of the Gulf of Mexico and Natuna Besar the team needed to understand what those areas looked like. What followed was research into the physical layout such as climate, water depth, bottom composition and what made up the underwater infrastructure. The geopolitical layout of the two regions are very different and play a crucial role in understanding how to defend the undersea infrastructure.

The following sections will outline key information that was used to build the models starting with a review of previous work on infrastructure defense. The next section is on the Gulf of Mexico's environment and infrastructure followed by the same for Natuna Besar as well as a discussion of the complex geopolitical issues specific to that region. The final section of this chapter covers the potential threats and new technology that could become readily available to an adversary or used for defense of undersea infrastructure.

A. SE PROCESS: RESEARCH APPROACH

Due to the need to examine alternative systems for undersea infrastructure defense in multiple operational environments SEA28 developed a tailored research approach. The team executed an analysis methodology as presented by (MacCalman, 2016) focused on identification of desirable systems and operational tactics to support undersea infrastructure defense. Given that the approach suggested development of multiple simulation models, the team split up into groups in order to research the infrastructure in the two different regions. This included information about the existing pipelines, communication cables, applicable regulations regarding both and the systems in place if any that are used to defend them. From there we began to explore probable technology and methods that a State or Non-State actor could use to subvert those systems and attack the pipeline or cable infrastructure. We used that information to generate threat scenarios and functional and physical system architectures to counter those threats.

The architectures that our teams developed included active and passive defensive systems, sensors, networked communication and command and control. In accordance with our tasking statement, we investigated current commercially off-the-shelf technologies for rapid acquisition taking into consideration employment requirements, power requirements, operating areas, bandwidth and connectivity, interoperability, sensor data processing, transfer and accessibility, logistics, forward arming and refueling (FARPS) basing support in forward areas or from CONUS bases.

The following chapter will cover the pertinent information about the two distinct undersea regions that we focused on as well as a description of the potential threats and the current range of capabilities. From there the rest of this report will cover the methods used to model threats and defensive systems, the design of experiments to use on those models and an analysis of the results. Our solution is not a detailed design of a specific workable defense system. Instead the objective of this research is to arrive at an analysis of what factors in system development provide the greatest return on investment, and which concepts of operation will increase the probability of success against an agile foe.

B. INFRASTRUCTURE DEFENSE

National and global events like the terrorist attacks on 9/11, hurricane Katrina, and the Fukushima nuclear disaster highlight the importance of protecting the infrastructure that societies have come to rely on. Accordingly, there is an extensive body of work on various aspects of infrastructure defense ranging from prediction tools to protection methods.

Organizations like the American Society of Mechanical Engineers (ASME) have created processes like Risk Analysis and Management for Critical Asset Protection (RAMCAP^{SM}) to identify and prioritize infrastructure in order to better protect against damage from these events and improve the ability to return to full function (ASME Innovative Technologies Institute, LLC, 2009). Predicting the attacks from a motivated, intelligent network of terrorists seems nearly impossible, but several papers from the Operations Research department of the Naval Postgraduate School outline reasonable ways to make such predictions and some of the potential risks from using probabilistic methods (Brown, 2011). Additional work from the same department shows how to optimize defense

(Brown, 2008) and analyze how vulnerable infrastructure systems are to attack (Brown, 2005).

Whether the system in question is an electric grid, bridge or nuclear power plant, infrastructure that has been designed for public use and serves a critical need is not only an attractive target to attack but also highly vulnerable. While improvements have been made with these threats in mind incorporating defensive principles like redundancy, security and shielding there is always the potential for an adversary to find a way to attack. An active pursuit of ways to defend against new threats is critical to the continued operation of the systems we have come to rely on. As we continue to expand infrastructure on the seabed it is just as important to develop new technology needed to defend this growing frontier. The complex environment of the undersea world can look very different depending where you are in the world and the Gulf of Mexico accordingly is quite different from the waters of Natuna Besar.

C. NATUNA BESAR

1. Environment

a. Natural Environment

The physical location for the Natuna Gas Fields is an area of the South China Sea called the "Greater Sarawak Basin," which is approximately one thousand miles north of Jakarta, Indonesia and 140 miles northeast of the Riau Islands. There are multiple gas fields in the region (Figure 1) that are welled and currently supplying natural gas in the area surrounding the waters North of the Riau Island Chain are Anoa, Naga, Gajah Baru, Natuna Sea Block A, Natuna Sea Block B, Kakap South, and Kakap North (Natuna Gas Field - Greater Sarawak Basin, 2018). These various gas fields can be seen in Figure 2. To maintain consistency of terminology, our team primarily used this reference in researching and applying characteristics of the region to our analysis.

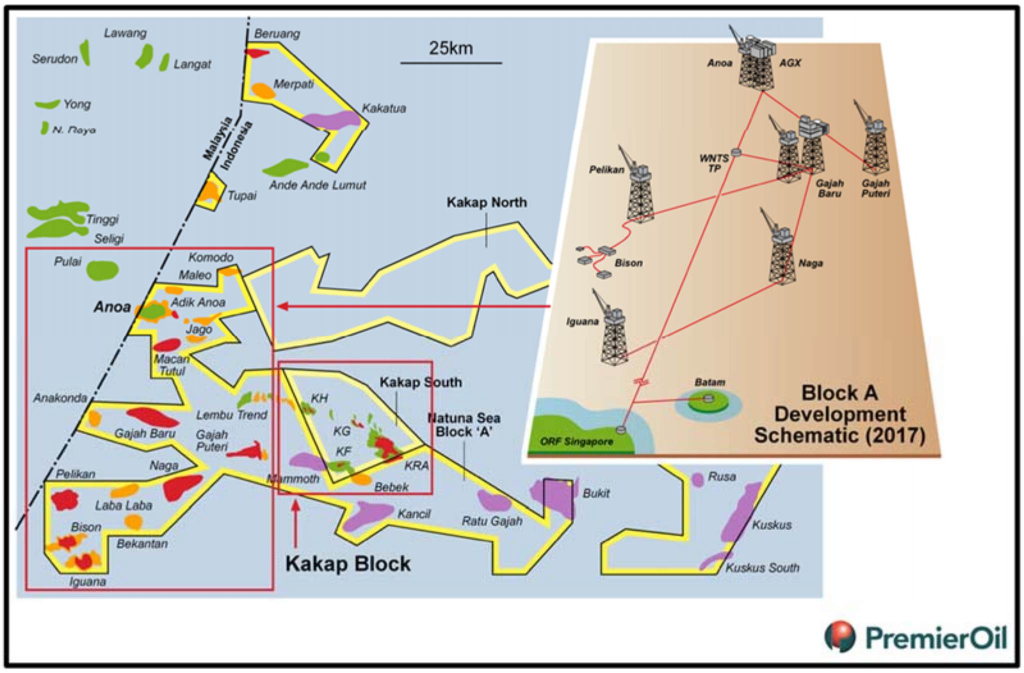


Figure 1 Pipeline Connections. Source: Gas Exports (2010).

Figure 2 Natuna Besar Region and Pipeline. Source: Natuna Gas Field – Greater Sarawak Basin and Google.

The water depth around the pipeline is between 70 and 100 meters with a few deeper exceptions, as illustrated in Figure 3. The depth of the water played some part in determining the level of threat to the undersea infrastructure and then in selecting the possible locations of attack along the pipeline. Different methods of attack were determined depending on the depth of the sea above the pipes. This helped the team determine the most dangerous and most probable courses of action for a possible enemy in the region and produced some interesting discussions on emerging technology capabilities. Distance between the countries in the region helped shape the team's build of a likely scenario and also spurred discussion of the geopolitics in the region. After reviewing this information, an area surrounding the grid box MGRS 48N WH 2695 8658 was selected as a likely location of attack (Figure 4).

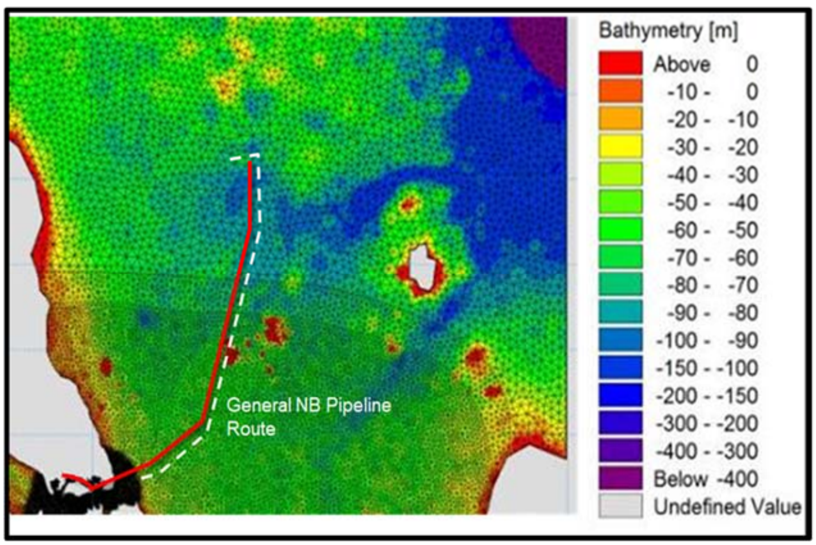


Figure 3 Sea Depth.

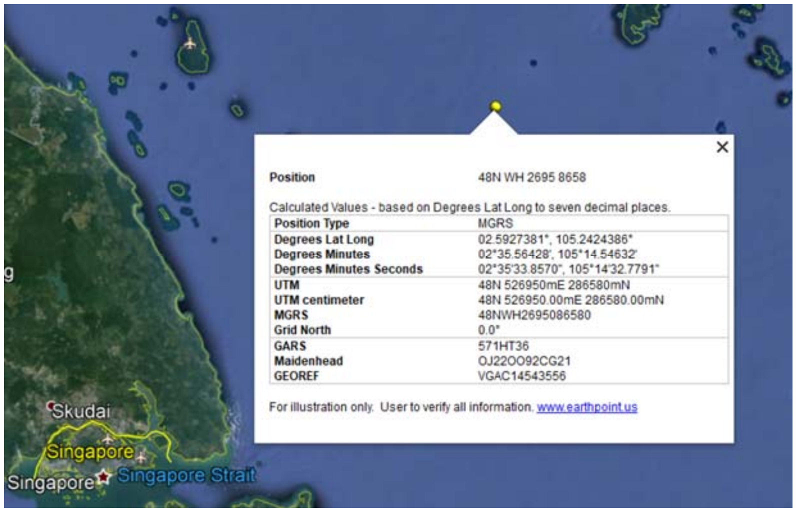


Figure 4 Likely location of attack. Source: Earthpoint.

b. Political Environment: Competing Powers in the Natuna Besar Region

Natuna Besar is centrally located between several countries with interest in the region. As seen in Figure 5, Indonesia and Malaysia play a major role in territorial control and defense of the areas around the gas fields. Both Malaysia and Indonesia possess large militaries with modern Army, Navy, and Air Force components. Indonesia has the most significant military presence in the area, with ground forces occupying military bases and anti-aircraft artillery positions on Natuna Besar Island itself.

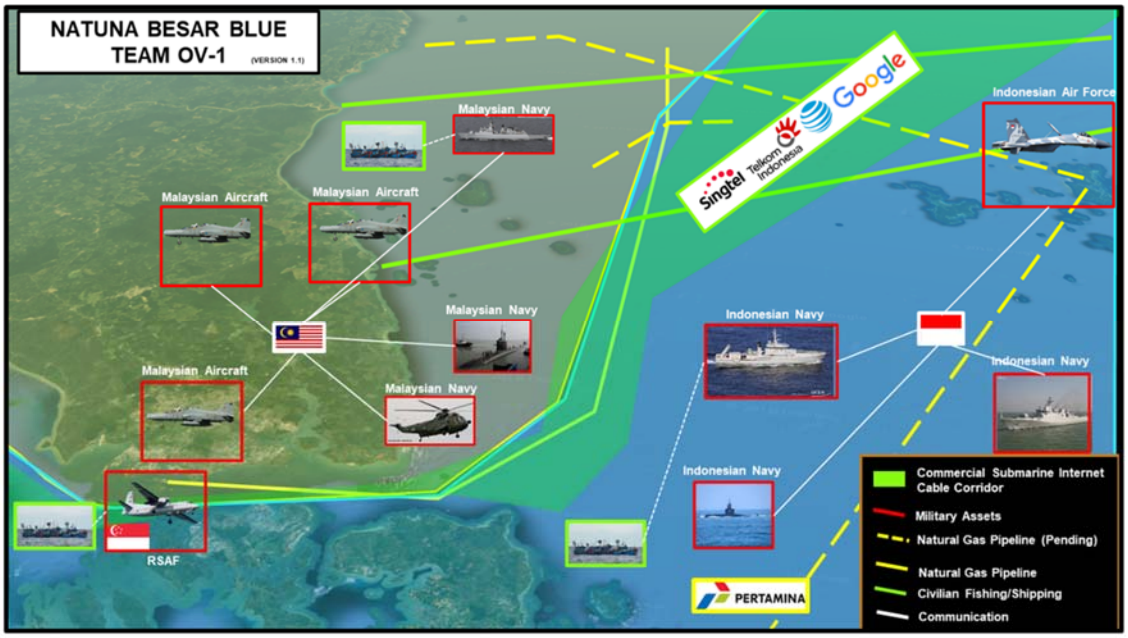


Figure 5 Regional Countries and Technology Companies

Singapore shares interest in the area, as it is an international cargo and petroleum shipping hub. According to the Maritime Port Authority of Singapore, over 130,000 ships pass through the port in Singapore per year (MPA, 2019). Although Singapore does not produce any of its own oil, it is the top bunkering (ship refueling) site in the world (MPA, 2019). The infrastructure and business processes to manage and efficiently move ships has made Singapore one of the busiest ports in the world, with a ship arriving or departing every 2–3 minutes (MPA, 2019).

Singapore has had a long fight from its initial declaration of independence in 1965 and it continues to fight for relevancy and self-sustainment. Surrounded by countries dwarfed by the small city-state's Gross Domestic Product (GDP) earnings, tensions are high between nations in the region. Deteriorating relations and disputes over borders have created a natural progression of saber-rattling and enhancement of defenses in the region.

2. Infrastructure

a. Natuna Besar Natural Gas Access History

There are several articles that discuss how the region has passed back and forth from national to commercial entity over the past 40 years (MSTAR, 2013; ABC Aus, 2017). A large pool of investors over decades created potential stakeholders in the region who have influence over decisions made on infrastructure, defense, and future investment. Understanding the fractured history is important for understanding the greater context of why this region is in danger of conflict. As the process of fracking natural gas becomes more cost-effective, many nations have started to stake claims to their own plots of sea and well-heads. In turn, Indonesia has been required to answer with military force in the region and continues to bolster is defenses on the Riau Island chain at large.

Around the year 1980, a split venture between Pertamina (Indonesia's state-owned petroleum company) and Exxon Mobil Corporation of the United States of America, was initiated in Natuna Sea Block A and the East Natuna region. Although there was significant capital invested, the research did not result in production. Environmental conditions made extraction of the natural gas difficult, especially during this timeframe when off-shore drilling technology was still under development (Gas Exports, 2010). For the next 15 years, little was done in the area due to political disruption, and its remote location. Nonetheless, Exxon continued exploration and invested almost $400 million (combined with Pertamina's $60 million investments), before the Indonesian Government terminated its contract with Exxon in 2007 leaving Pertamina in charge (Natuna Gas Field - Greater Sarawak Basin, 2018).

Starting in 2001, the various companies working in the region began developing the Belanak field in West Natuna, intending to export natural gas to Malaysia through a 22 inch submarine pipeline from producing fields to the Belida/Belanch tie-in, with a subsequent 28 inch line to Singapore. (Natuna Gas Field - Greater Sarawak Basin, 2018). This is significant for current (2019) and future development of this region and provides more context for expansion of the gas production capability of the Natuna Besar region. This system of pipelines will be the focus of our analysis in the Natuna Besar region.

b. Other Infrastructure in the Region

The Natuna Besar teams were tasked with creating a scenario which determined what undersea infrastructure was to be protected in the region. Working together, a streamlined "road to war" was created, setting the stage for two competing powers to enter into aggression against each other. Part of creating the scenario was choosing a target for attack. While researching local possible undersea infrastructure targets, the team found a large amount of undersea internet cabling (Figure 6) connecting the world's data network infrastructure. These networks of cabling had major hubs located in Singapore and Malaysia and directly connected these economies to other Asian Countries and the United States of America (Kuzian, 2015). Upon further research, it was found that multiple redundancies and back-ups made targeting the cables unlikely. Various scenarios were "war-gamed" and in the end it was decided that the most likely and most dangerous attack would likely come against the undersea pipeline networks connecting the gas fields to locations such as Singapore. However, it is important to note that these cable networks exist and are potentially vulnerable to a similar style attack as discussed in this report.

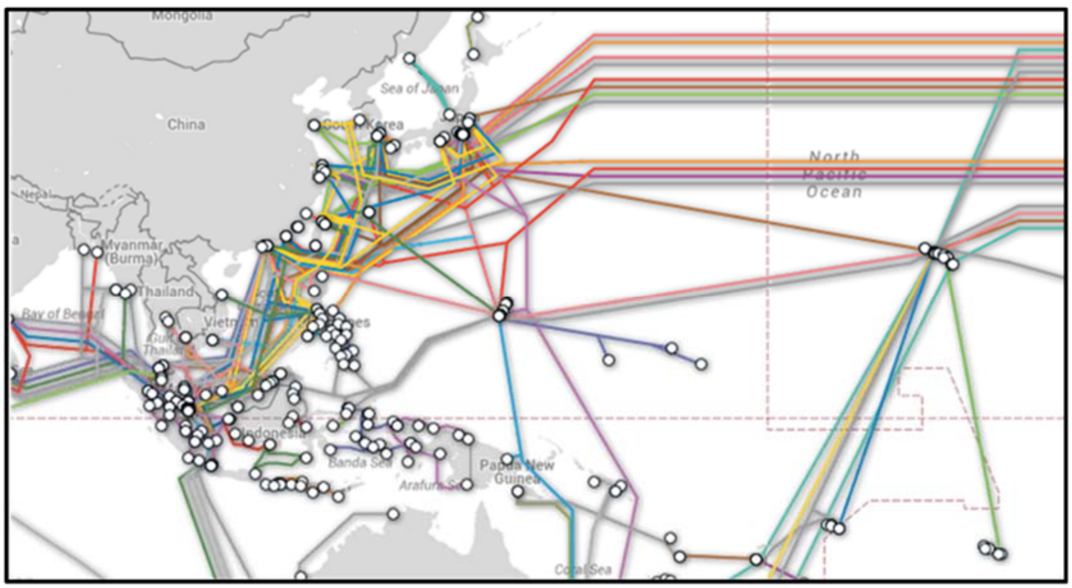


Figure 6 Communication Cables.

3. Current Defenses

Indonesia, Singapore, and Malaysia all currently have some limited air, surface, and subsurface defensive capability in vicinity of the Natuna Besar Gas and Oil fields. For example, Indonesia has land and sea-based anti-aircraft defenses in place on Natuna Besar Island, its air force operates Maritime Patrol Aircraft (MARPAT), and it has a sizeable naval force that includes surface ships, submarines, and minesweepers. Figure 7 depicts land-based anti-aircraft defenses installed aboard Natuna Besar Island (MAREX, 2019) and their ship-board anti-submarine defenses on the KRI Imam Bonjol (Soeriaatmadja, 2019). These capabilities are shared to varying degrees by the Singaporean and Malaysian militaries, with the exception that Singapore currently lacks long range MARPAT. There is currently no agreed upon regional strategy or cooperation agreement for mutual defense of undersea infrastructure. As China builds its influence in the region, it will also financially and militarily support partner nations in the region. This will likely tip balances of power and further strain tensions between nations in the region.

Figure 7 Indonesian Military Weapons. Source: MAREX (2019) and Soeriaatmadja (2019).

D. GULF OF MEXICO

The Gulf of Mexico is a semi-closed basin located in North America measuring 1600 km in length and up to 1300 km in width. It is bounded by the following nations: (1) United States from North East to North West consisting of Florida, Mississippi, Louisiana and Texas spanning 2700 km, (2) Mexico from the South West to South spanning 2805 km, and (3) Cuba at the South East (See Figure 8). The size of the Gulf basin is around 1.6 million km^2 with a depth of up to 3600 m (María Adela Monreal-Gomez, 2004).

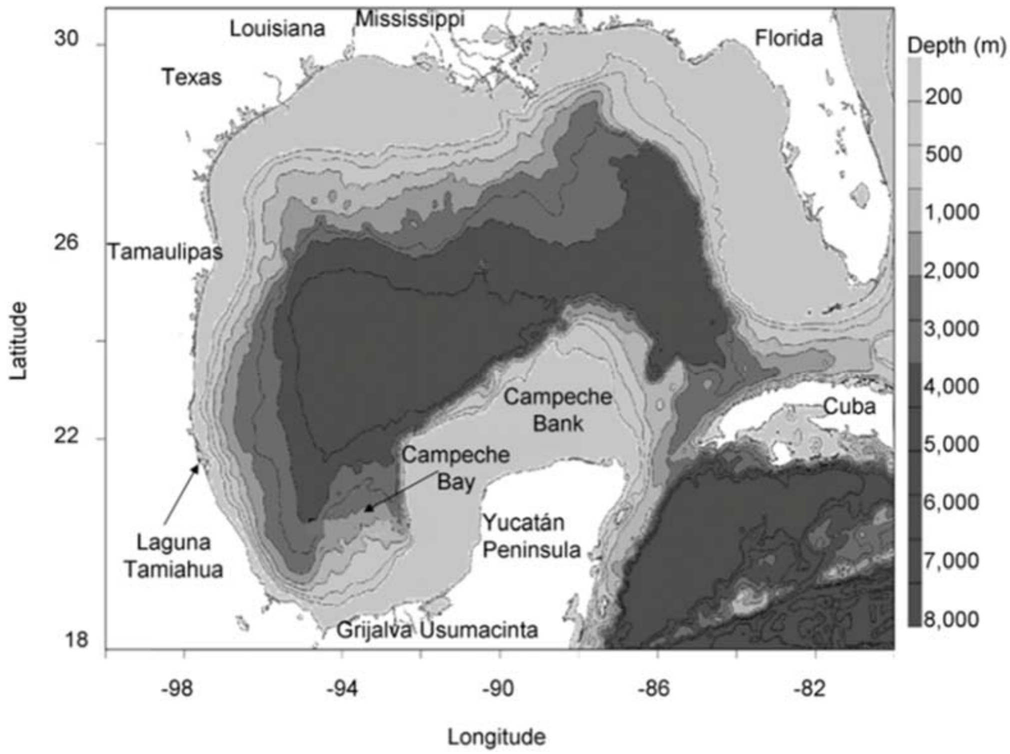


Figure 8 Gulf of Mexico. Source: Gomez (2004).

1. Environment

a. Natural Environment

The Gulf of Mexico is characterized by warm and humid climates with rain year-round. Temperatures ranges from 28–29°C during summer and 19–20°C during winter as the cold winds from the North resists the warm waters from the South East (Gomez, 2004).

A warm ocean current called the Loop Current dominates the surface currents in the Gulf of Mexico. It follows a clockwise loop with an average speed of 0.7 m/s (Figure 9) flowing northwards between the Yucatan Peninsula and Cuba into the Gulf before looping east and south, exiting through the Florida Straits (Love, 2013).

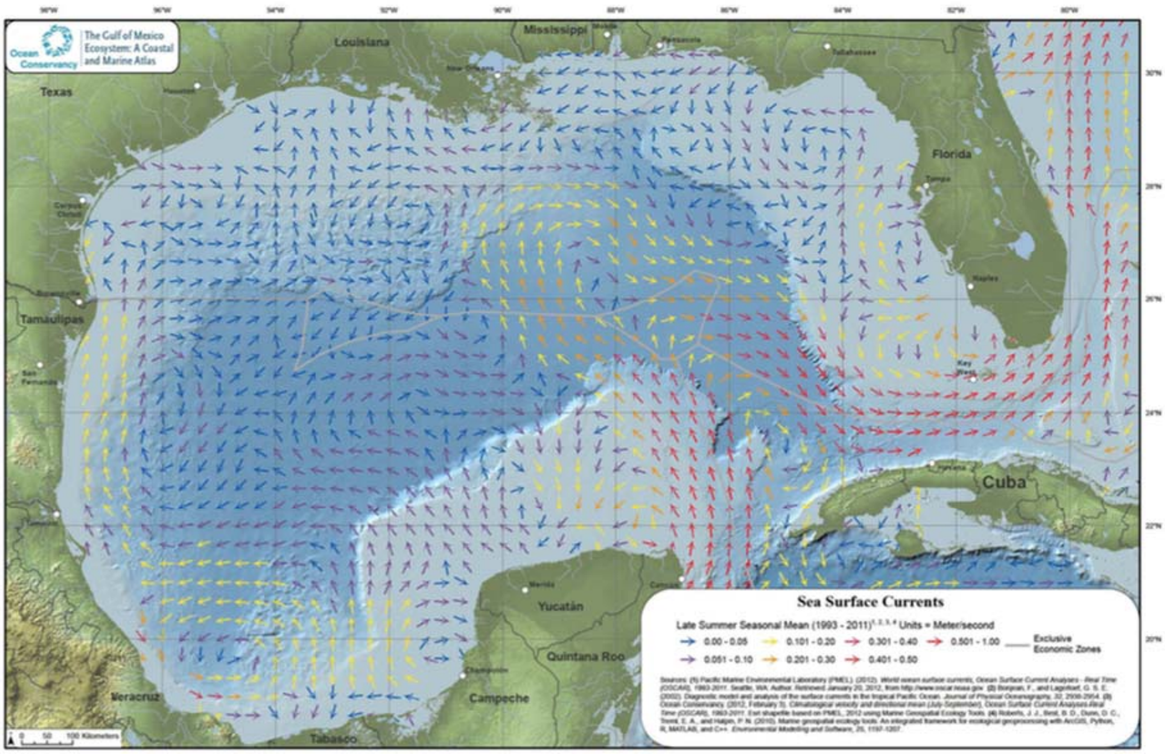


Figure 9 Sea Surface Currents at Gulf of Mexico. Source: Love (2013).

The seabed at the center of Gulf of Mexico and along the southern U.S. coastline consists of mainly mud (see Figure 10). Other forms of sediments at the bottom ranges from fine particles to gravel and rocks (Love, 2013). These bottom sediments form the habitats for a range of organisms which are responsible for performing key eco-functions such as nutrient cycling and stabilization of sediments.

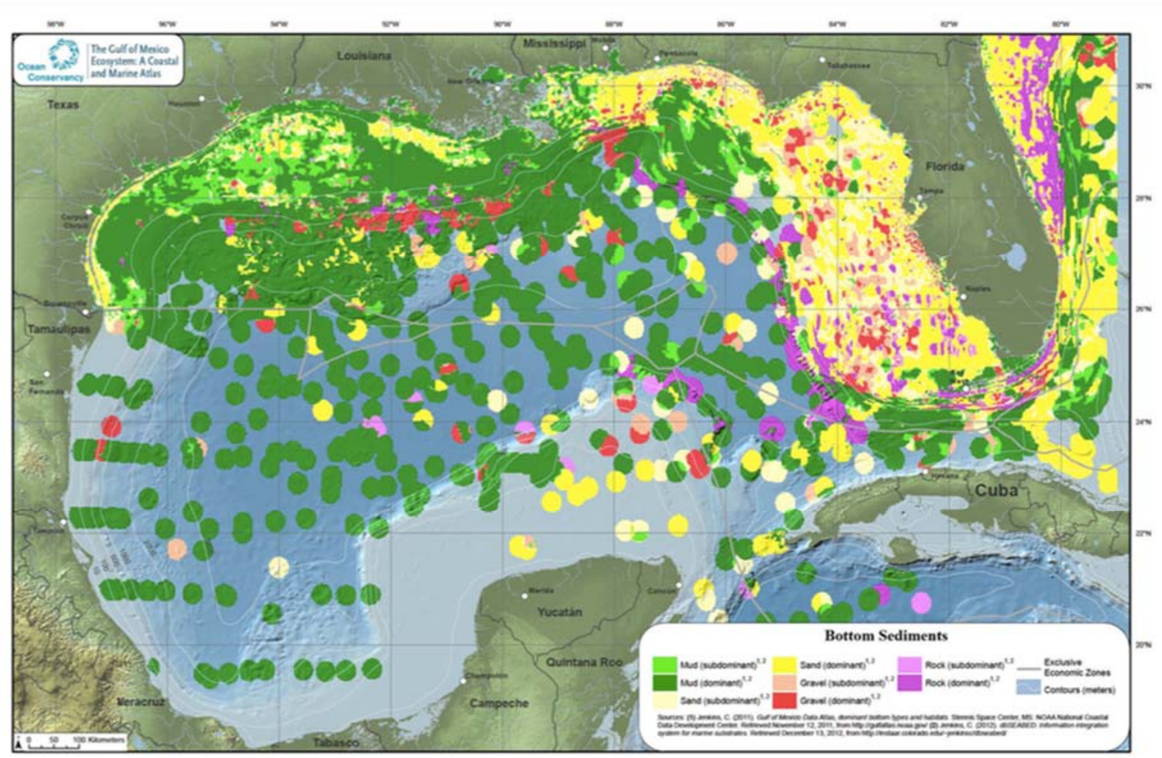


Figure 10 Sediment Composition at Bottom Gulf of Mexico. Source: Love (2013).

The Gulf of Mexico is home to a diverse range of habitats, ranging from oyster reefs, salt marshes, corals and mangrove forests (Love, 2013). Invertebrates (like shrimps and crabs), fishes (like bull shark, red snapper and bluefin tuna), birds, turtles and marine mammals (like dolphins and manatees) all can be found in this region (Love, 2013).

a. Political Environment

The Gulf of Mexico is a major economic resource for the countries surrounding it, particularly with regards to offshore energy production, commercial shipping, commercial and sport fishing, and various types of tourism.

2. Infrastructure

Amidst this diverse environment, the Gulf of Mexico is one of the most important regions for energy resources for the United States via the production of oil and gas (Gulf of Mexico Fact Sheet, n.d.). Figure 11 highlights the distribution of oil and gas in the U.S.

portion of the Gulf, where we can find about ~3,200 active structures (NOAA Gulf of Mexico Data Atlas, n.d.) and 17,507 miles of active pipelines (Enforcement, n.d.) (see Figure 12). As of 2017, a total of 53,000 wells had been drilled in the Gulf, with 87% of them in water depth of less than 400 feet (Kaiser, 2018). Regulations require pipelines with diameters of greater than 8 5/8 inches that are installed in water depths less than 200 feet are to be buried to a depth of at least 3 feet below the mudline (Cranswick, 2001). In addition, if the authorities deem that the pipeline (regardless of size) constitutes a hazard to others, these pipelines must be buried as well. Within Federal waters, the pipeline must be buried to a depth of 10 feet below a fairway and 16 feet below an anchorage (Cranswick, 2001).

The Gulf of Mexico accounts for greater than 25% of the total U.S. domestic oil production and 7% of the total U.S. natural gas production. Furthermore, more than 30% of all the U.S. petroleum refining capacity and natural gas processing capacity (comprising of major players such as Shell, BP and Total) are located in the Gulf of Mexico (Love, 2013) as shown in Figure 13, highlighting the importance of the region to the energy requirements of the U.S. The development of oil and gas resources in the Gulf of Mexico is split into three main planning areas (Eastern, Central and Western), of which a total of 2,505 leases covering 160 million acres are in use (BOEM, 2019).

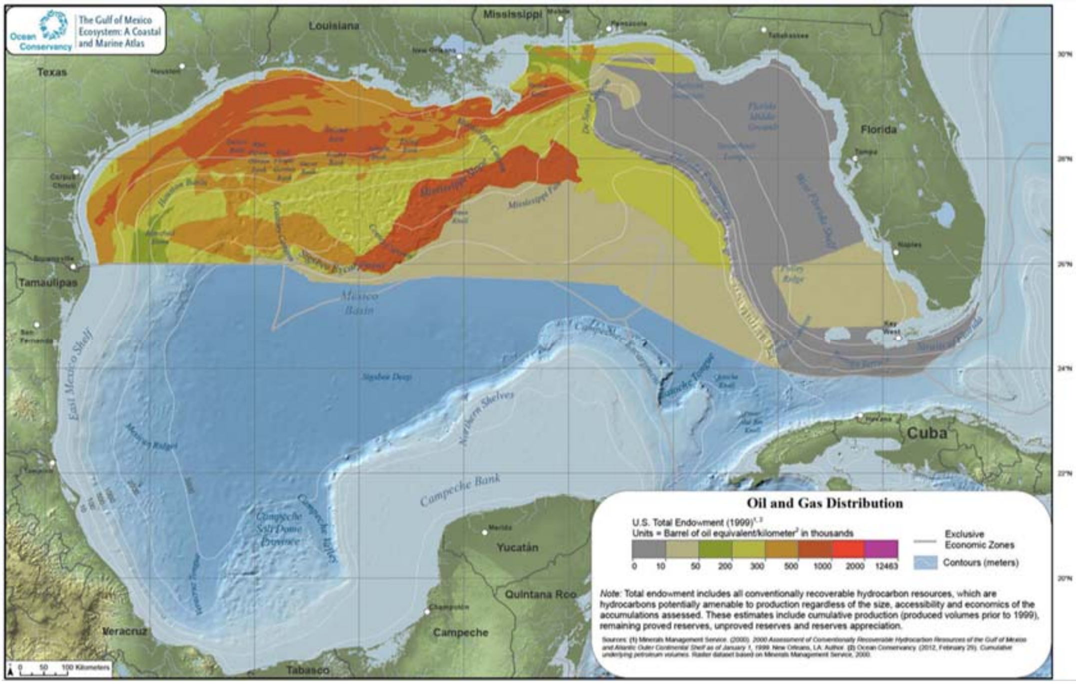


Figure 11 Oil and Gas Distribution at Gulf of Mexico. Source: Love (2013).

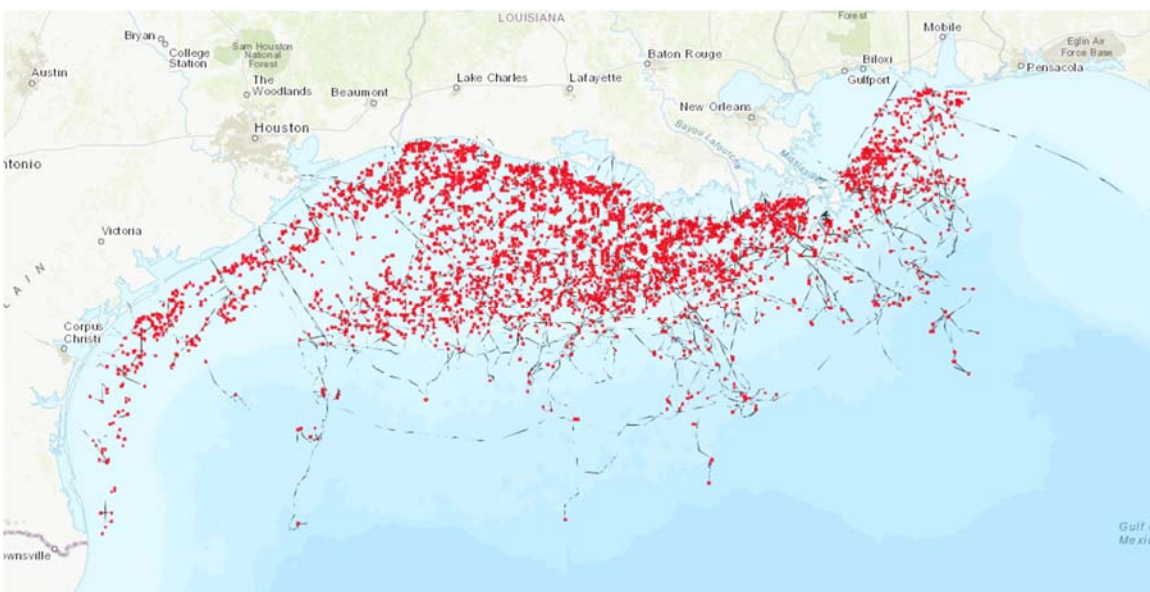


Figure 12 Oil and Gas Pipeline/Platform Locations. Source: Edelstein (2017).

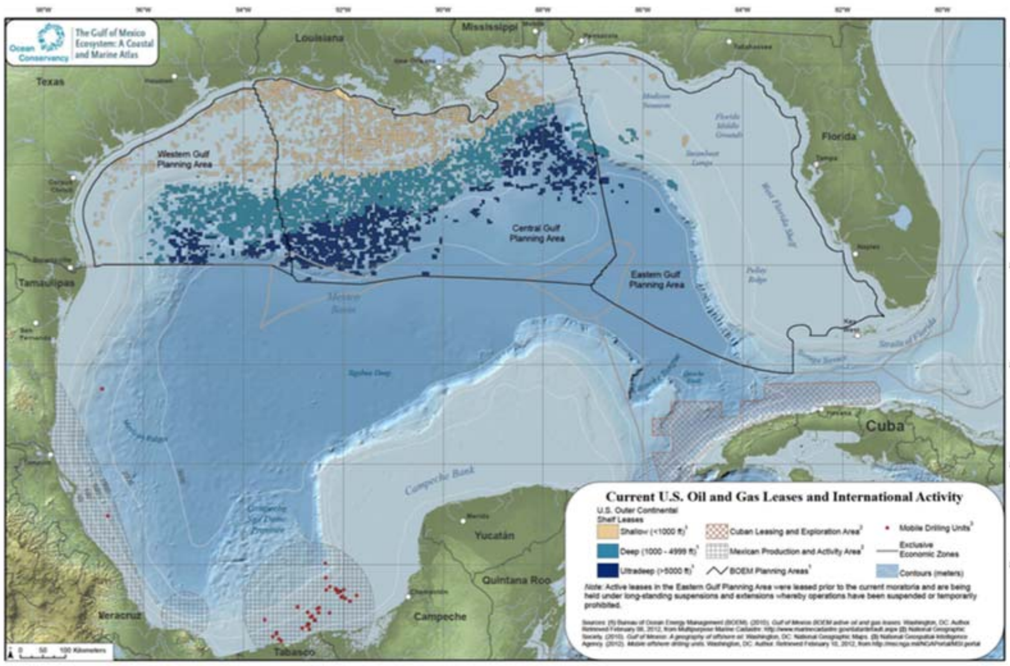


Figure 13 Oil and Gas Activities at Gulf of Mexico. Source: Love (2013).

3. Current Defense

The current defense of the Gulf of Mexico is centered upon the traditional air, land and sea domains with little emphasis on dedicated protection of the oil platforms and pipelines in the Gulf of Mexico. The homeland defense of the Gulf of Mexico currently falls under the ambit of the U.S. Northern Command (USNORTHCOM) (U.S. Northern Command, n.d.). Forces under the USNORTHCOM includes the Air Forces Northern (headquartered in Tyndall Air Force Base in Panama City) (U.S. Northern Command, n.d.). The 8th District Coast Guard is responsible for operations such as law enforcement and search and rescue in the Gulf of Mexico (United States Coast Guard Atlantic Area, n.d.). Furthermore, private security firms are only employed in areas whereby there is a higher threat due to militants, piracy or criminals like in the Gulf of Aden. Hence, protection of the oil platforms and pipelines are currently minimal in the Gulf of Mexico (Husband, 2013). Recent emphasis has been placed by the Navy on under-sea surveillance through the sources-sought notice by the Office of the Space and Naval Warfare Systems Command (SPAWAR) for maritime surveillance (Keller, 2014).

E. CONVENTIONAL THREATS TO UNDERWATER INFRASTRUCTURE

As previously discussed, an adversary has the capability to harm underwater infrastructure using conventional technology such as bombs, dragging anchor on the seabed or using manned submarines. The following technologies and scenarios are not new threats but have existed for decades and are presented as examples of how vulnerable undersea infrastructure is to a highly motivated adversary.

1. Bomb Dropping from Ship Scenario

An enemy vessel (can be disguised as a commercial vessel) can sail along a pipeline and drop munitions ("carpet bombing"). It is relatively easy to get intelligence on the precise location of the pipelines and release bombs when directly above it, the bombs will start sinking due to gravity but they will also drift with the currents so the bombs will not move directly downwards and will hit the seabed with some miss distance from the pipeline. A sophisticated enemy can measure or estimate the currents speed and direction and adjust the releasing point accordingly to get the bomb seabed impact point as close as possible to the pipeline. The desired outcome is for the miss distance to be smaller than the bomb kill radius (the radius that the bomb will damage the pipeline). Although as simple calculations show (Appendix C) dropping even a single large diameter bomb (considering the average Gulf currents) over an oil pipe has a high probability of successfully damaging the pipe.

2. Anchoring Scenario

A large vessel can drop an anchor in a proximity to a pipeline and drag it over the pipe. Terrorist groups can hijack a larger container ship or tanker and use the anchor as a weapon to damage seabed infrastructure. The impact of the anchor hitting the pipe can damage the pipeline, even for a buried pipe if it is less than the depths shown in Table 2

Table 2 Required Pipeline Burial Depth

Mass of anchor (kg)	Impact energy (J)	Effective burial depth (m)
3060	36435	0.66
4890	103557	1.18
6900	208032	1.71
1050	443709	2.54
14100	717386	3.25
20000	1211871	4.25

Depth provides protection from deep water anchoring. Source: Yuan Zhuang (2016)

3. Manned Submarine Attack

An enemy submarine can launch a torpedo or come within close proximity of a pipeline and attach an explosive.

In our work we decided not to focus on the conventional threats as existing systems (Keller, 2019) and previous works have already explored the scenarios such as Antisubmarine warfare (Broadmeadow, 2008; Anti-Submarine Warfare, 2004) and detection of abnormal behavior of vessels (Liraz, 2018; Morel, 2008).

Also, these types of attacks require the enemy to send manned vessels or submarines to the pipeline area. These operations come with higher risk and higher acoustic signature compared to the emerging threats to be discussed in the next section.

F. UNMANNED UNDERWATER VEHICLES

UUVs have been around for many years but in recent years they have started to get a more important role in the undersea world, both for civilian use such as monitoring, repairing and laying undersea infrastructure and military use such as patrol and reconnaissance.

1. Background

A UUV is a device that operates in the underwater environment that is either remotely controlled via cables or preprogramed to perform specified tasks. The remote-controlled version is commonly called an ROV (Remote Operated underwater Vehicle), and the preprogramed version is referred to as an AUV (Autonomous Underwater Vehicle).

Due to the nature of underwater communication limitations there are big advantages for an AUV versus an ROV configuration (Office of CNO, 2004).

UUVs are generally comprised of a sensor in the front, a payload (such as explosives), an energy unit, usually in a form of a battery and an electrical engine and fins for steering (Chu, 2010). A basic configuration is show in Table 3.

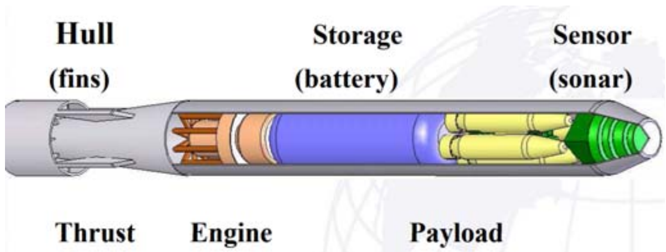


Figure 14 Generic UUV Architecture. Source: Chu (2010)

A different type of UUV known as gliders use wave energy for propulsion. As the waves move a tethered float up and down the glider uses wings to convert the vertical movement to horizontal movement. Gliders are very energy efficient and can travel great distances with long endurance.

2. UUV Classes and Specifications

The Navy's 2004 UUV master plan (Office of CNO, 2004) divides UUVs into four categories (Button, 2009) as shown in Table 3, the UUV classes are divided by size and endurance.

Table 3 UUVs Classes. Source: Button (2009)

Class	Typical Size [Kg]	Endurance [Hours]
Man-Portable	50	20
Light-Weight Vehicle (LWV)	250	40
Heavy-Weight Vehicle (HWV)	1500	80
Large Vehicle	10000	>400

As the classes were assigned in 2004, recent developments in commercial UUVs (that can be used for military purposes) do not necessarily fits those classes. Examples include large Gliders and Biomimetic AUV and ROVs (Gassier 2007; Wood 2019; Davis, 2002; Ahmad, 2015).

For illustration purposes this paper will use the following size classifications in Table 4 that correspond approximately to the UUV classes previously mentioned.

Table 4 UUV Sizes

Name	Acronym	Diameter
Small Diameter UUV	SDUUV	< 0.5 m
Medium Diameter UUV	MDUUV	0.5 - 1 m
Large Diameter UUV	LDUUV	1 - 2 m
Extra Large Diameter UUV	XLDUUV	> 2 m

Different classes of UUVs were examined (see Appendix A) and minimum and maximum values for speed, endurance and payload weight were identified in Table 5. In the cases when payload weight was not available it was estimated at 20% of the total weight.

Table 5 UUV Specifications

Characteristic	Min value	Max Value	Units
Speed	1	10	kph
Endurance	8	8000	Hour
Payload weight	3	2000	Kg

3. Torpedo Types and Specifications

Torpedoes were in use a long time before the development of UUVs (Barber, 1874) but they can be treated as a special case of UUV with no return capability ("suicide mission"). Torpedoes vary in size, range, speed and propulsion systems. Propulsion can come from a piston engine using compressed air or steam such as the "Whitehead" torpedo

(Barber, 1874), an electric engine such as the French “F21” (DCNS, 2019), gas turbine such as the British “Spearhead” (Tovey, 2014) or a solid fuel rocket engine such as the Russian “Shkval” (Russia, 1995; Tyler, 2000).

Different types of torpedoes were examined (see Appendix A) and the minimum and maximum values of the different characteristics are shown in Table 6. Not all torpedoes specifications had warhead weight data. From the data we had the warhead is about 15% of the total weight of the torpedo. “Shkval” and “Spearfish” torpedo were omitted due to their high cost and big size making them less likely to be relevant to our scenario.

Table 6 Torpedo Specifications

Characteristic	Min value	Max Value	Units
Speed	50	92	kph
Range	10	50	Km
Warhead weight	3	2000	Kg

4. Underwater and UUV Detection

Underwater detection of objects usually rely on acoustics as sound propagates in water with much less attenuation than electro-magnetic fields and can achieve much greater detection range (Sun, 2018).

Acoustic underwater target detection systems are usually called “Sonar” (SOund NAvigation and Ranging). The sonar systems can be divided to active sonars that transmit sound wave and locate the target by receiving the echo wave reflected from the target, and passive sonars that have only a receiver that is used to pick up sound emitted by the target.

Active sonars frequency ranges from 50Hz to above 600KHz. Higher frequencies will tend to have more attenuation but give a better range resolution. For better angle resolution some sonars use an array of sensors and can achieve angular resolution less than 1° while other sonars use omnidirectional sensors that only alert to the presence of a target without any angular data (Bjorno, 2013).

Passive sonars usually consist of a hydrophone, basically an underwater microphone designed to receive sound waves. Most hydrophones are built using special ceramic materials that produce electric current when the water pressure around them changes (piezoelectric) (U.S. Dept. of Commerce, 2018).

Other underwater detection technologies are magnetometers, sensors which sense disturbance in a magnetic field caused by a metallic object. For short ranges laser-based detection systems can also perform underwater (Zha, 2019).

UUVs are challenging targets for a sonar as most UUVs have low acoustic signatures for both passive and active sonars and tracking the UUV for a long period of time can be even more challenging as their signature is very dependent on the aspect angle (Acker 2016).

To determine likely detection range, we utilized information from multiple sources. In (Button 2009) it was estimated that a UUV can carry a detection system with a UUV detection range of 0.25 NM (463 m) and from (Sun 2018) the detection range of current UUV systems is 100–500 m. Putting those together we used a reasonable UUV detection of about 500 m.

III. CONCEPT OF OPERATIONS FOR UNDERSEA INFRASTRUCTURE DEFENSE

To organize the complex undersea infrastructure environment across the regions of interest, both functional and physical analyses were conducted to aid in identification of commonalities and differences between the areas. Generally, the Gulf and Natuna regions share a common structure and defense situation. Both regions contain undersea communication cables and oil or gas pipelines with corresponding drilling/pumping platforms and switching nodes. Existing defenses are minimal and rely almost entirely on the difficulty in access due to depth. Redundant pipelines and systems provide limited failsafe operation. The only active defensive measures are from local coast guard or naval military forces. The two regions do have some differences both in size, scope and layout of the undersea infrastructure.

A. FUNCTIONAL ANALYSIS

There are two primary functions that must be conducted as a part of undersea infrastructure defense: sensing the threat, and responding to it—with assets assigned to perform one or both functions. In the most basic concept, this consists of an array of acoustic buoys as sensors, and a flotilla of response UUVs. Some of our larger models utilize supporting air assets and surface vessels to augment the sense and response functions at different levels of threat; in smaller models, only UUVs (with comparable sensor capabilities) are involved.

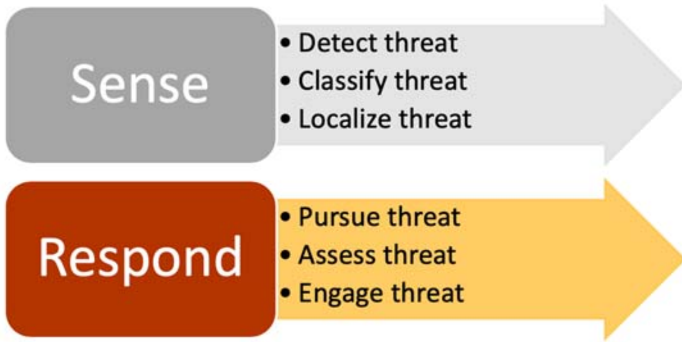


Figure 15 Undersea Infrastructure Defense System Functions

1. Sub-Functions

Each of the primary functions has three sub-functions, as arranged in Figure 15: *detection*, *classification*, and *localization* fall under the sensing function, while *pursuit*, *assessment*, and *engagement* fall under the response function. Figure 16 shows the generic sequencing of these sub-functions; depending on the asset, these may be performed near-simultaneously.

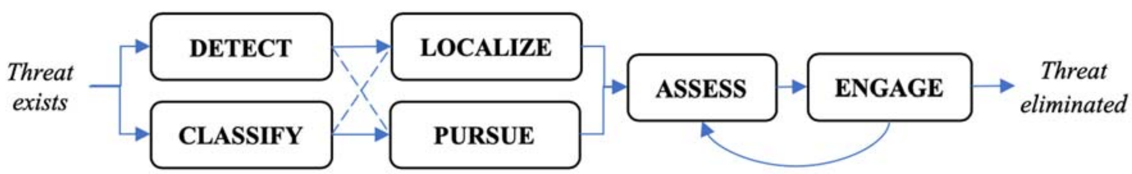


Figure 16 Functional Flow Block Diagram (FFBD)

a. Detection

The initial detection of a threat is the critical starting point of the kill chain. Threat detection utilizes an array of sensor nodes and relay nodes, either around infrastructure or at key choke points, to find suspected threats. The geo-political climate can determine our defensive posture, and early warnings and indicators from reliable intelligence reports may help specify detection parameters and thresholds.

b. Classification

The type of threat will determine which assets are used to prosecute it. A coast guard vessel might be used to intercept/inspect a commercial ship with suspected weapons; a swarm of UUVs would be deployed to defend against similar threat. Proper identification and classification of the threat is necessary to employ the appropriate assets and defensive measures. Depending on the asset, this sub-function can be performed near-simultaneously as detection.

c. Localization

As multiple sensors detect the threat, its specific location can be triangulated and transmitted to the response assets for pursuit. If the threat location is intermittent or lost, then a likely attack path can be extrapolated based on last known positions, vector, and other threat characteristics ascertained by the classification sub-function. A continuous update of the threat position and status among sensors, response assets, and command & control (C2) stations is crucial to the effectiveness of the defense system.

d. Pursuit

Response assets move towards the threat location. A destroyer would swiftly seek out the last position of an enemy submarine; point-defense UUVs would deploy from their charging docks to intercept an incoming UUVs or torpedo. Depending on the threat capabilities, additional assets may be employed or re-tasked to pursue the most dangerous or most probable threat.

e. Assessment

As response assets arrive at the threat position, they can determine method of prosecution. The current threat level or stage of attack certainly contributes to the assessment: if an attack is imminent or in progress, point-defense measures would be employed; if a threat is reported but not found (its position lost), search/patrol measures would be taken. Assessment also includes the determination of an appropriate engagement method, as well if the method was successful.

f. Engagement

Response assets execute appropriate measures against a target to neutralize the threat. This can range from a simple inspection of a suspect vessel, to full deployment of UUV swarms, to anti-submarine warfare tactics by allied warships. Assets that can perform both sensor and response functions may already be in the location and can immediately assess/engage the threat (as with a coast guard ship intercepting and inspecting a commercial vessel suspected of carrying hostile UUVs or other weapons). Engagement continues until the threat is assessed to be incapacitated (mission kill) or eliminated (total kill).

2. Defensive Schemes

The performance of all functions of a defense system can be accomplished through effective positioning and layering of complementing assets. This can be employed through distinct schemes: area defense, point defense, barrier defense, or some combination of the three. Each defensive scheme is designed with a particular objective in mind. Point defense is defined as an attempt to protect a singular asset or position from an expected threat. Barrier defense is an attempt to maintain some sort of security perimeter to ensure that any asset or position within the barrier is better protected to a significant degree than assets or positions beyond the protect region. Area defense shares with barrier defense the same goal of improving the security of a designated region, but is differentiated in that defending assets are not confined physically to specific barriers paths, and instead patrol the entire region. Figure 17 provides an aid for conceptualization.

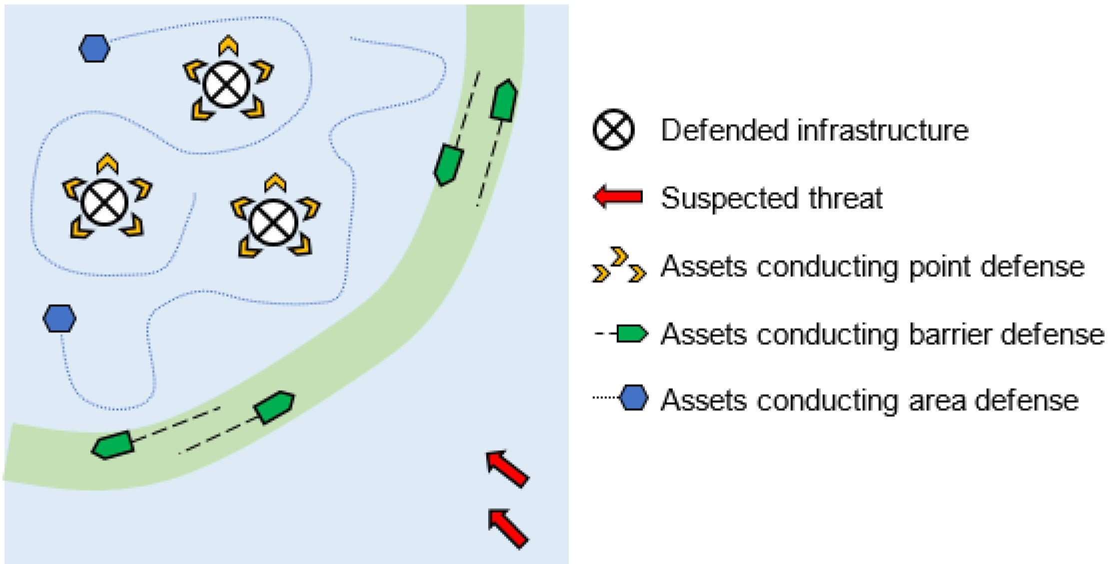


Figure 17 Visualization of Defensive Schemes

B. ANALYSIS APPROACH

The project team developed four models to help answer key questions that were brought to light during the initial research phase. These range from small scale models examining the tactical defense of underwater infrastructure in the Natuna Besar region against UUV to a large-scale model examining a theater-wide defense of the Gulf of Mexico against a wide range of threats.

1. Natuna Besar Models

The Natuna Besar models investigate the effectiveness of defending key infrastructure nodes (for example, single oil platforms) and the pipelines which connect them. Since Natuna Besar offshore oil and gas infrastructure is privately owned by various corporate consortiums from a large number of countries and is located in international waters with pipelines traveling through multiple nations EEZ, there is no single country that is solely responsible for their defense. Instead, a collaboration of private and multi-national naval and coast guard activities are tasked with that duty. In the event that any country or group is particularly concerned with the safety of their infrastructure, the defensive schemes they employ will most likely be developed to protect their individual ownership of various segments of infrastructure rather than to protect the region as a whole.

As such, the Natuna Besar models developed with the perspective of defending the underwater gas infrastructure that supplies Singapore from the Natuna Besar region.

Natuna Besar Model 1 focused on the point defense of critical infrastructure nodes that are in the gas fields from enemy UUV attacks. These include expensive oil platforms and accompanying systems which extract fossil fuels for transport via pipeline to the shore. This UUV-only model employs defensive UUVs which are either static or patrolling, and are assumed to have the same sensor capabilities and limitations as a stand-alone sensor buoy, thereby negating the need for a pre-existing or temporary array of sensors. The intent is to investigate the idea of whether an architecture of cheap, easily deployable UUVs with a long shelf-life could effectively provide point defense of key infrastructure nodes against UUV threats. Ideally, this type of defense would negate the need to develop, deploy, and maintain a static sensor array in the area. By reducing the types of assets, this model explored the idea of a minimally-manned, cost-effective defense that can be applied in almost any scenario—that is, a point-defense model that is indifferent of region, and can be implemented by any entity (corporate, military, or private). The anticipated threat for this model are UUVs of similar capability, which the point-defending UUVs quickly respond upon detection. As such, this model assumes a small timeframe to respond to the threat, and therefore emphasizes certain sub-functions, as shown in Figure 18.

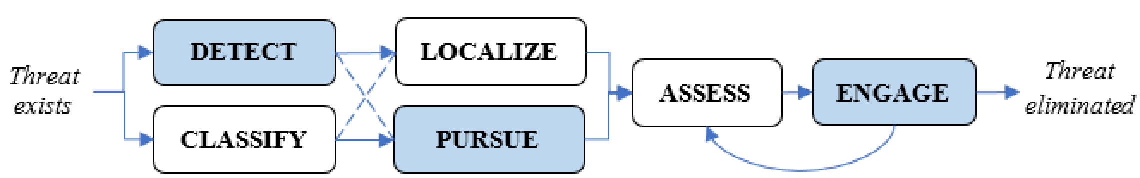


Figure 18 FFBD of Natuna Besar Model 1

Natuna Besar Model 2 investigated the defense of the long stretches of pipeline which connect the critical extraction nodes to the shore. It does so by looking at how combinations of static and patrolling UUVs and static underwater sensors can be employed in a barrier parallel to the defended asset to defend against threat UUVs. The lessons learned about defending the 4 km stretch can then be scaled up and applied relative to the overall length of the pipeline. While the anticipated threat is the same as Natuna Besar

Model 1, the incorporation of sensor arrays puts an emphasis on the localize sub-function, as shown in Figure 19.

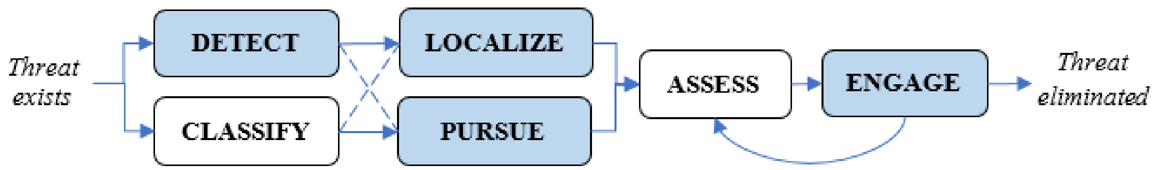


Figure 19 FFBD of Natuna Besar Model 2

2. Gulf of Mexico Models

The Gulf of Mexico groups explored the defense of a large region. A conclusion from the initial research phase was that there are two primary goals that an attacker might have that could cause the most amount of damage to the United States. The first is the destruction of the large number of critical infrastructure nodes that would be required to disrupt a large portion of the offshore energy industry in the region. The second is to attack one of the critically vulnerable nodes in such a way as to cause catastrophic damage, similar to the Deepwater Horizon spill in 2010. Either would have economic effects that could reach into the hundreds of billions of dollars. The models address these concerns by trying to determine what types of defensive arrangements could successfully defeat such attacks.

Gulf of Mexico Model 1 sought to answer the question of how well a barrier of UUV and sensors could be utilized as a perimeter defense to keep underwater enemy UUVs from transiting submerged into the target rich environment of the Gulf of Mexico. The design is based on two staggered, 20 km rows of equally spaced sensor buoys, with UUV docking stations positioned every six kilometers. When an enemy UUV is detected by the sensors, they send targeting data to the UUV docking stations which launch Defender UUVs to destroy it. The anticipated threat for this model are UUVs of similar capabilities, but this model does explore the aspect of *overspeed* (the ability for defending UUVs to achieve higher maximum velocities than threat UUVs) to find and engage the threat. Additionally, the positioning of the sensor array is assumed to be far enough from the infrastructure to allow a substantial window of time to classify threats (Figure 20).

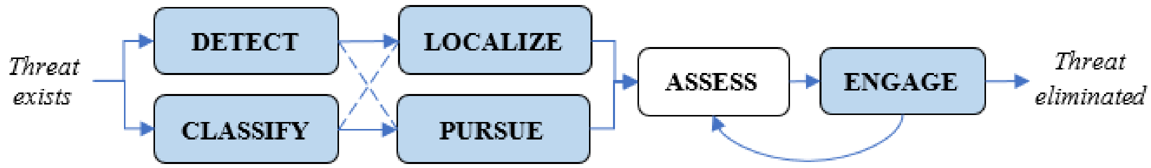


Figure 20 FFBD of Gulf of Mexico Model 1

Gulf of Mexico Model 2 examined the effectiveness of such a barrier when scaled up to a theater-wide defensive scheme against a wider range of threats, not just the long range LDUUV threat posited by Gulf of Mexico Model 1. The new threats are neutral flagged enemy cargo ships that are capable of sailing over the barrier undetected and either dropping off SDUUV in close proximity to their targets or acting as "Bomber Ships" themselves, dropping depth charges or even dragging their anchors to deal damage. In order to combat these additional threats, this model utilizes a defense in depth approach combining point, barrier, and area defense assets including ships, aircraft, UUV from underwater docking stations, and underwater sensor networks. The complexity of this model emphasizes all six sub-functions (Figure 21), particularly since classification and assessment allows for and necessitates the use of the appropriate assets to respond to the myriad of threats.

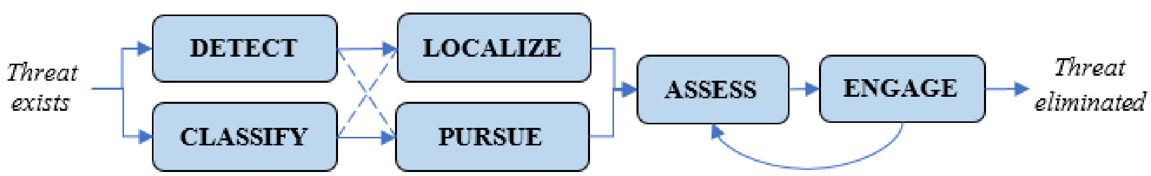


Figure 21 FFBD of Gulf of Mexico Model 2

IV. UNDERSEA INFRASTRUCTURE DEFENSE: NATUNA BESAR

The analysis of the underwater infrastructure defense in Natuna Besar is divided into two categories—pipelines transporting oil and underwater infrastructure of the oil mining platforms. The analysis is conducted separately because the latter is assessed to be a point defense around the platforms whereas the former was assessed to be the defense over a long corridor along the pipeline.

Map Aware Non-Uniform Automata (MANA) simulation is conducted on both categories to examine the CONOPS, performance and tradeoffs under different settings. Different scenarios for each category are assessed before focusing on the most threatening scenario for deeper analysis. Different parameters are experimented using a design of experiments framework, and the ensuing statistical analysis provided insights into how the different parameters affect cost and performance effectiveness.

A. DEFENSE OF SINGLE OIL PLATFORM

This section covers the analysis of the defense of the oil mining platform.

1. CONOPS Implementation

a. Red CONOPS

Figure 22 shows the Concept of Operations (CONOPS) for the Red Force. Their attack scenario comprises 5 phases: Preparation of mission, acquisition of intelligence of blue assets, movement to target, communication, and conduct of attack.

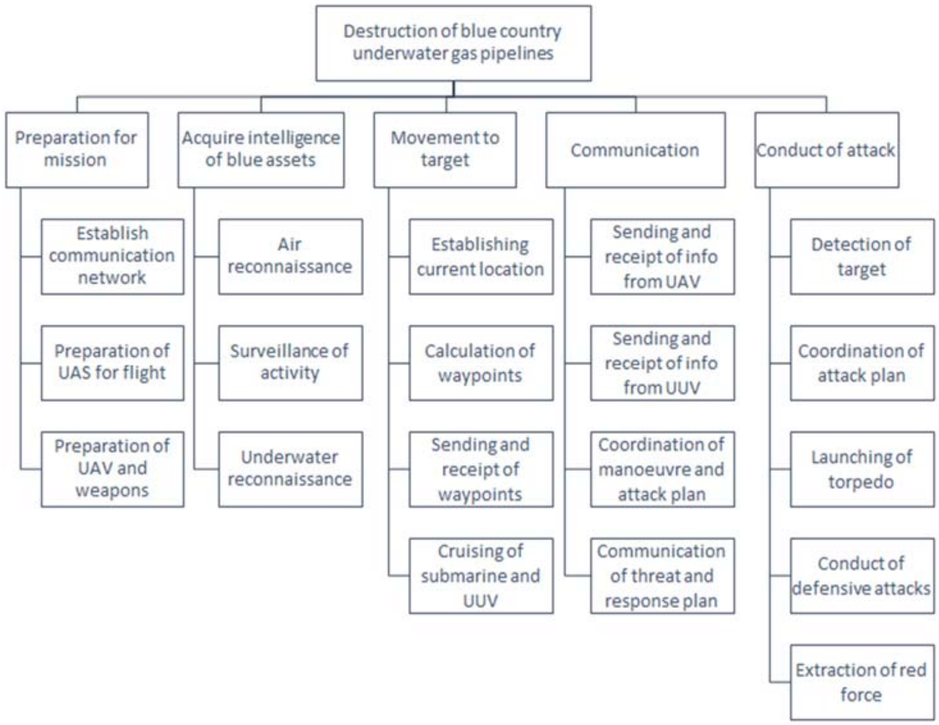


Figure 22 CONOPS Description—Pipeline Destruction

It can be difficult to establish hostile intent during the first three phases, so the response solution focuses on the fifth phase, assuming that the hostile intent is determined in the fourth phase or the fifth phase. The enemy course of action involves the transport of the attacking assets on a ship that masquerades as a commercial vessel. The commercial vessel releases the attacking assets, which comprises of Unmanned Underwater Vessels (UUVs), before sailing away. After deployment, the UUVs travel to the oil platform infrastructure and any UUV that successfully arrives to the platform will execute an attack.

The team focused on a scenario with a solo-diversion UUV combined with a swarm attack of other UUVs. This tactic allows the Red Force to achieve a high probability of success with the least number of UUVs.

The Red plan is comprised of two phases. The first phase diverts Blue Force's patrol defenses, opening a channel with less resistance. This is achieved by employing a single Red UUV to lure the Blue Force away from its defense position. The second phase involves the infiltration of the attacking Red UUV swarm via the open channel. Two different modes of Red swarm attacks are considered:

1. The Red Force UUVs converge on the oil platform from all directions as shown in Figure 23. We refer to this as the *distributed* approach. Note the large Red UUV represents the solo diversion UUV.

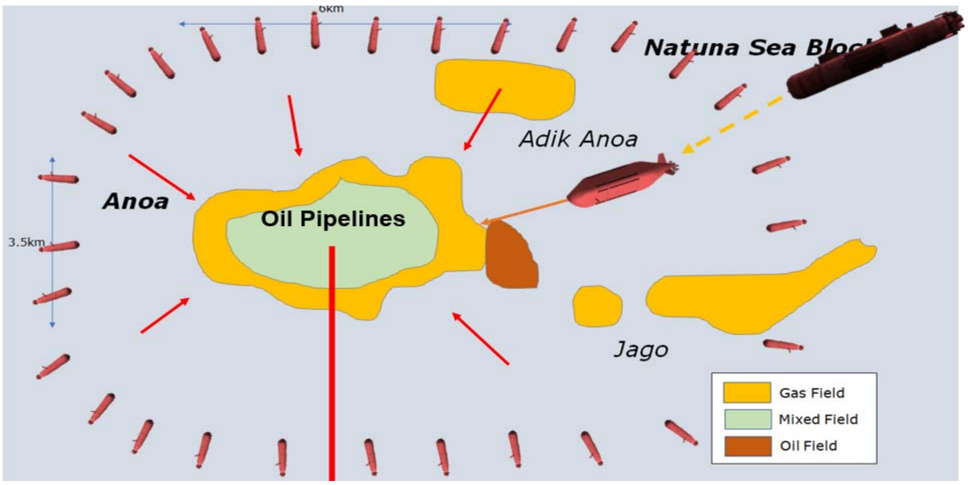


Figure 23 Red CONOPS Using Distributed Approach

2. The Red Force UUVs approach the oil platform from a single direction as shown in Figure 24. We refer to this as the *concentrated* approach. The diversion UUV approaches separately from a different direction and heading.

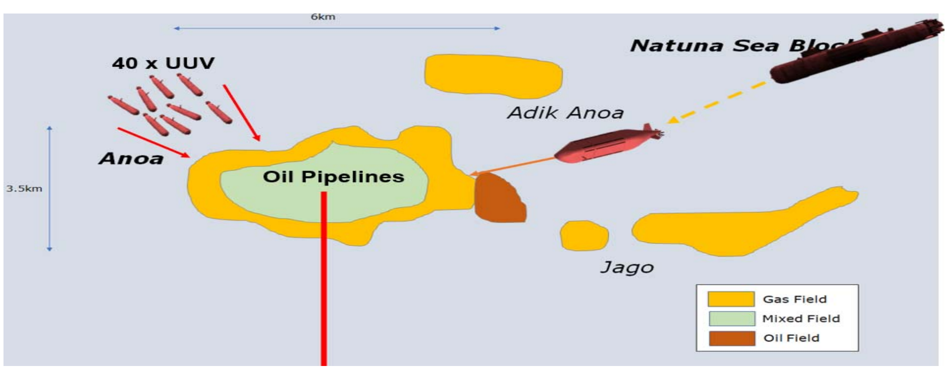


Figure 24 Red CONOPS Using Concentrated Approach

b. Blue CONOPS

Two defensive configurations are examined for the Blue Forces to defend the oil platform. They are:

1. Blue Forces utilize a *point defense* strategy where defenders are stationed close to the oil platform and wait for Red Forces to approach before engaging the Red Forces. Figure 25 shows this Blue CONOPS.

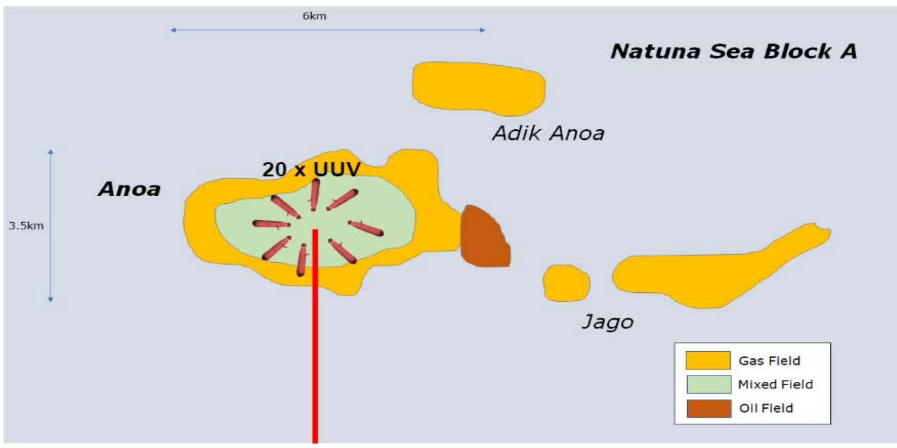


Figure 25 Blue CONOPS Using Point Defense Strategy

2. Blue Forces conduct *patrols* along the edges of a 6 km by 3.5 km rectangle that bounds the Anoa gas field and patrol in a clockwise direction. Figure 26 shows this Blue CONOPS.

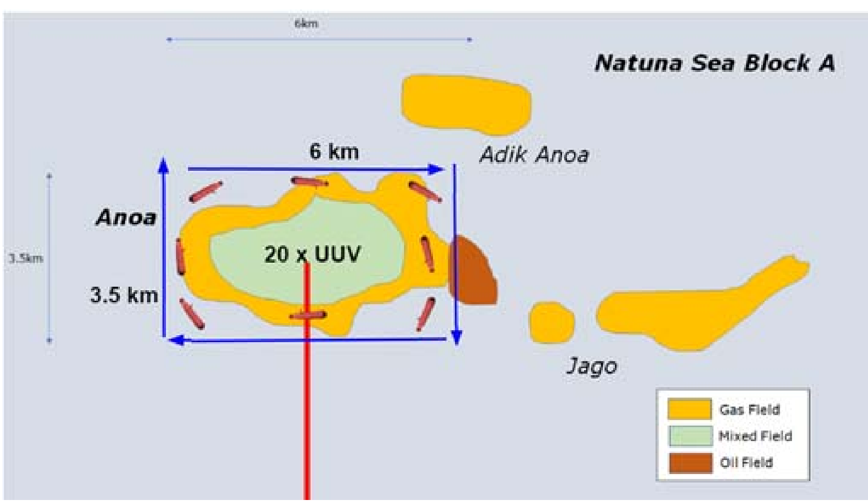


Figure 26 Blue Force Using Perimeter Defense CONOPS

The Blue UUVs are deployed with both defensive sensing and incident response. The following describes the assumptions about the defense setup:

- No other detection assets are allocated to the defense area.
- A blue UUV chases after any Red UUV that is detected by the blue UUV's sensor
- A blue UUV does not disengage from pursuing a detected Red UUV and will continue to chase the Red UUV until the Red UUV is killed.
- When a blue UUV destroys a Red UUV or loses track of a Red UUV, it will return to its patrol (for patrolling configuration) or position (for point defense configuration).
- If the blue UUV encounters a Red UUV on its way back to its patrol or position, the Blue UUV will engage it.
- Blue UUVs are unable to communicate with one another, so each blue UUV is limited to its own sensor range.

The assumptions and rules of engagement listed above reveal that Red's diversion tactic can potentially be effective at distracting blue UUVs; specifically without the ability to communicate and coordinate, many Blue UUVs may pursue the diversion UUV for a long period of time. A sensor field is not considered since this is a defense of just one platform over a small area. A sensor field is more important when defending a corridor, where the blue UUVs benefit from acting earlier to intercept the Red UUV effectively in the area it is defending. While it is not considered in this implementation, having a sensor field as a secondary defense system could be useful as a failsafe mechanism if any hostile UUV manages to sneak through the defense barrier.

2. Systems Implementation

The team developed an agent-based simulation in MANA to represent the scenario described in the previous section. Red has two attack modes (distributed or concentrated) and Blue has two defense modes (point or patrols); which yields four combinations that will be conducted in our simulation. The following systems are modelled in MANA for utilization in all four of the CONOPS:

- A single oil platform that is to be defended
- A squad of blue UUV assets, each carrying explosive payloads that can be fired at Red Force UUVs.
- A single large diameter UUV that is used by the Red Force to divert the defenders.
- A swarm of Red UUV assets. Each UUV carries a single explosive payload that is transported to the oil platform to be detonated to impair or destroy the oil platform.

Table 7 shows the parameters that are used by the Red Forces and the Blue Forces in all four scenarios. The focus of the MANA simulation at this point is to determine the most effective CONOPS for each side. Hence, some parameters, such as number of munitions and weapon ranges, are set to artificially high limits.

Table 7 MANA System Configuration

System	System Parameters	Value / Description
Blue defending UUV	Number of blue defending UUVs	22
	Movement speed	0 km/h during point defense 13 km/h during patrol 25 km/h during engagement of Red UUV
	Type of UUV	Large diameter UUV
	Sensor detection and classification range for Red attacking UUV	500 meters
	Sensor detection and classification range for Red diversion UUV	2000 meters
	Sensor classification probability	0.5
	Blue probability of hit	0.5
	Number of hits to destroy Red	1
	Amount of ammo carried	15
	Weapon range	1000 m
Red diversion UUV	Number of Red diversion UUVs	1
	Movement speed	25 km/h
	Type of UUV	Large diameter UUV
Red attacking UUV	Number of Red attacking UUVs	40
	Movement speed of Red attacking UUV	10 km/h
	Type of UUV	Small diameter UUV

A quantity of 22 Blue UUVs is chosen because that is the minimum number of UUVs needed to cover the detection edges of the 6 km by 3.5 km rectangle that bounds the Anoa gas field. 7 blue UUVs are required to cover the 6 km length and 4 Blue UUVs are required to cover the 3.5 km width of the rectangle. Thus, total number of Blue UUVs required = $2 \times (7 + 4) = 22$. Each Blue UUV will patrol in a clockwise direction with a detection capability of 500 m radius.

In the MANA model, each Blue UUV has to detect a Red UUV with its sensor before a Blue UUV can attempt to intercept the Red UUV. During each model time step, a Blue UUV has a probability (based on the parameter "Sensor classification probability") to successfully classify a Red UUV within its classification range (based on the parameters "Sensor detection and classification range for Red attacking UUV" and "Sensor detection and classification range for Red diversion UUV").

A blue UUV is only able to engage a Red UUV after successful classification. Subsequently, a weapon is launched to destroy the Red UUV. If the Blue UUV scores a one successful hit (based on the parameter "Blue probability of hit") against a Red UUV (due to the parameter "Number of hits to destroy Red" being set to 1), the Red UUV is considered destroyed.

3. Model

In all four CONOPS, the Blue Forces will achieve their victory condition when they destroy all the attacking Red UUVs. The diversionary UUV does not count towards the requirement for the Blue Forces' victory condition. The Red Forces achieve victory if at least one attacking UUV reaches the oil platform.

The following assumptions are made for the models:

- A single detonation of the explosive charge is carried by a Red UUV and is sufficient to compromise the functionality of the oil platform
- The Red Forces are released sufficiently close to the target, so they will not run out of fuel. Hence, fuel utilization of the Red Forces is not modelled.

- It is not possible to establish hostile intent of a hostile vessel masquerading as a commercial vessel until they have unloaded the offensive UUVs. Thus, the simulation begins with the Red diversion and attacking assets in position to commence the attack, outside the sensor ranges of the Blue defenders.

- The Red Force uses a diversion tactic to create a distraction for the defending Blue assets, while the attacking systems utilize stealth to close the distance to the oil platform it is targeting. The stealth factor is the main factor why the speed of the attacking assets is much slower than the defending assets.

- Battery/fuel is not a limitation for the defending UUV assets because the point defenders are docked to a charging station until they need to be deployed, while the patrolling configuration can implement a shift rotation system where another set of UUVs can be charged/refueled while others are patrolling.

Figure 27 shows the scenario where the blue UUVs perform a point defense of the oil platform. The blue UUVs are organized in a ring of radius 500 m around the oil platform. The Red Forces will execute a concentrated attack with all 40 Red UUVs approach the platform together. The black lines indicate the movement directions of the Red UUVs. The blue UUVs in the Red rectangle are susceptible to the Red diversion UUV. Note these figures are not drawn to scale.

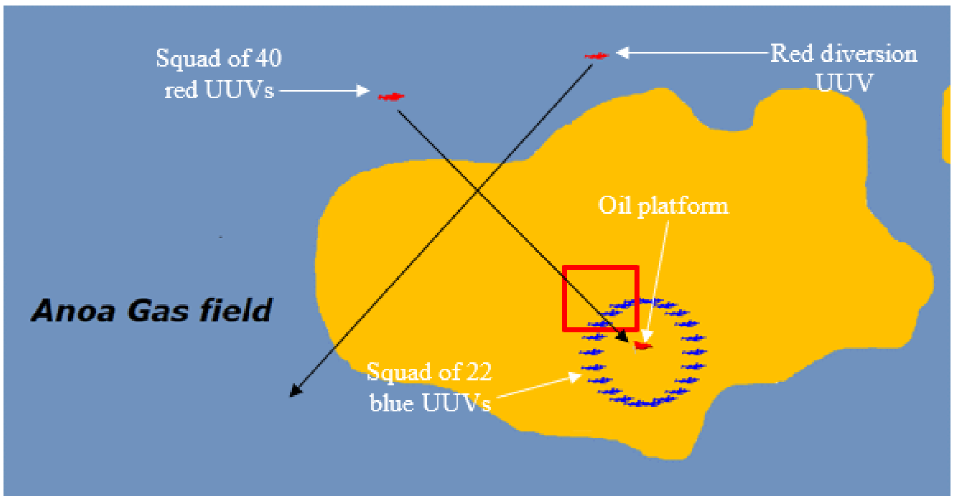


Figure 27 Blue Force Defense against Concentrated Red Force

Figure 28 shows the scenario where the Blue UUVs perform a point defense in a ring of radius 500 m around the oil platform against the squad of 40 Red UUVs executing a distributed attack on the oil platform. The Red UUVs are distributed around a circle of radius 3.46 km around the oil platform. The Red attacking UUVs close in on the oil platform simultaneously from all directions. The Blue UUVs in the Red rectangle are susceptible to the Red diversion UUV.

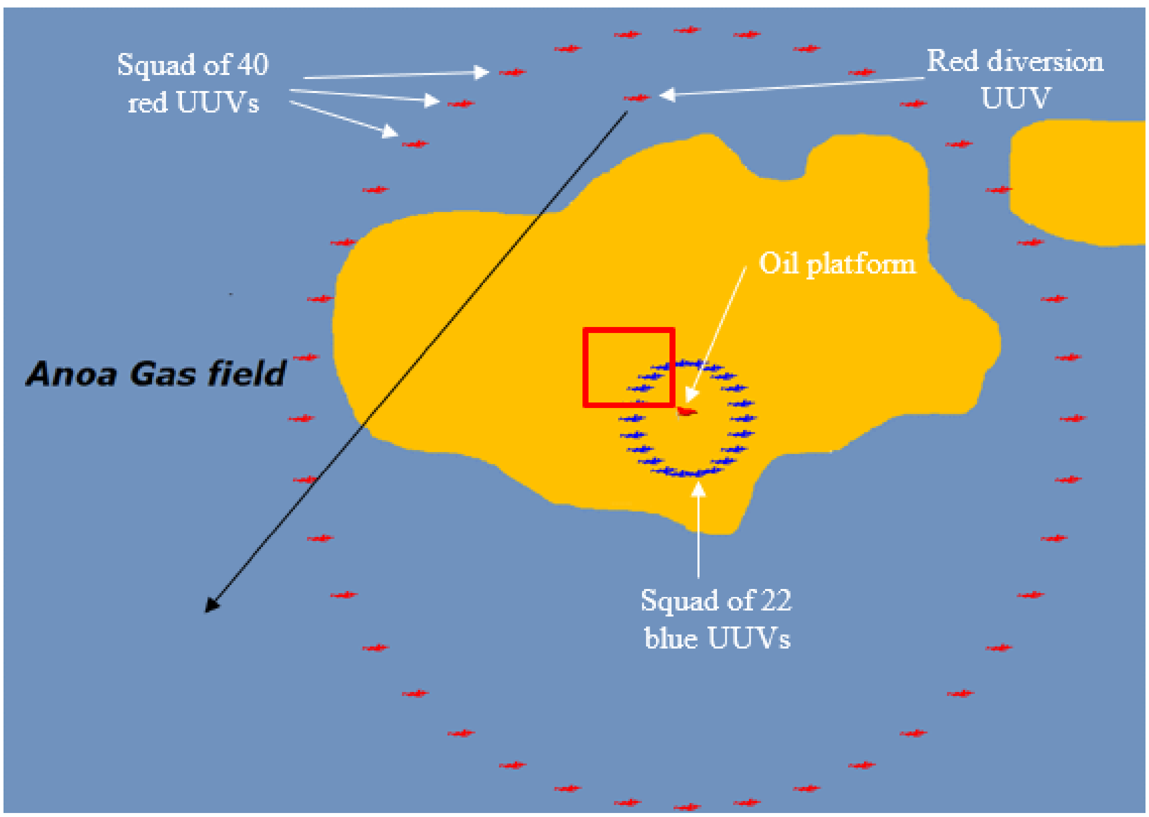


Figure 28 Blue Force Defense against Distributed Red Force

Figure 29 shows a Red concentrated attack against a Blue patrol defense. The Blue UUVs will perform a patrol in a rectangular formation in a clockwise direction. The rectangle has a length of 6 km and a width of 3.5 km and is centered on the oil platform. The black lines indicate the direction of movement of the Red Force UUVs. The Blue UUVs in the Red rectangle are susceptible to the Red diversion UUV.

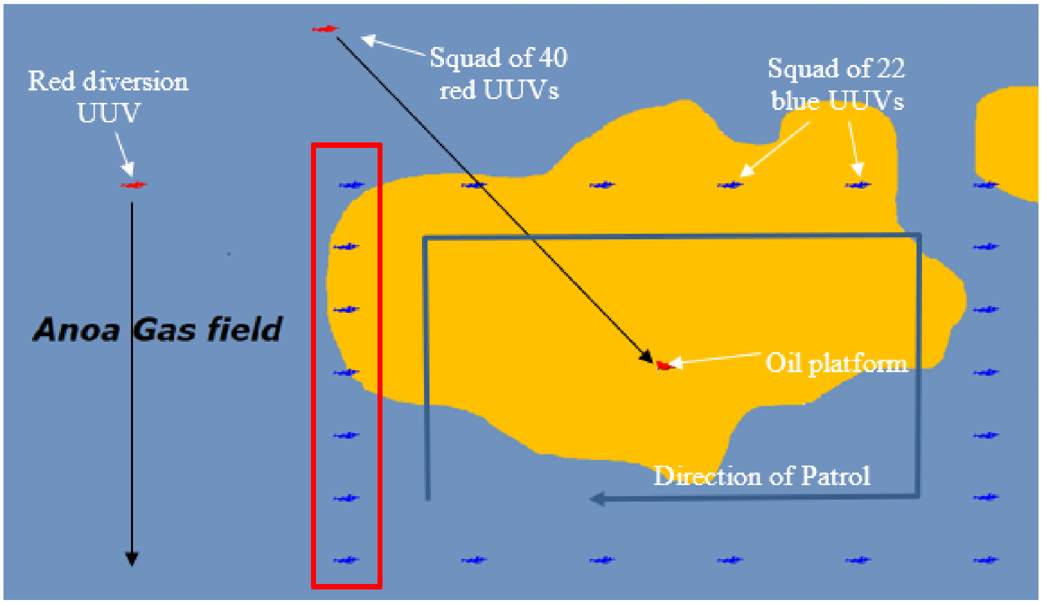


Figure 29 Patrolling Blue Force against Concentrated Red Force

Figure 30 shows the scenario where the Blue UUVs perform a patrol around the oil platform in a rectangle against a Red distributed attack. The Red attacking UUVs will close in on the oil platform from all directions.

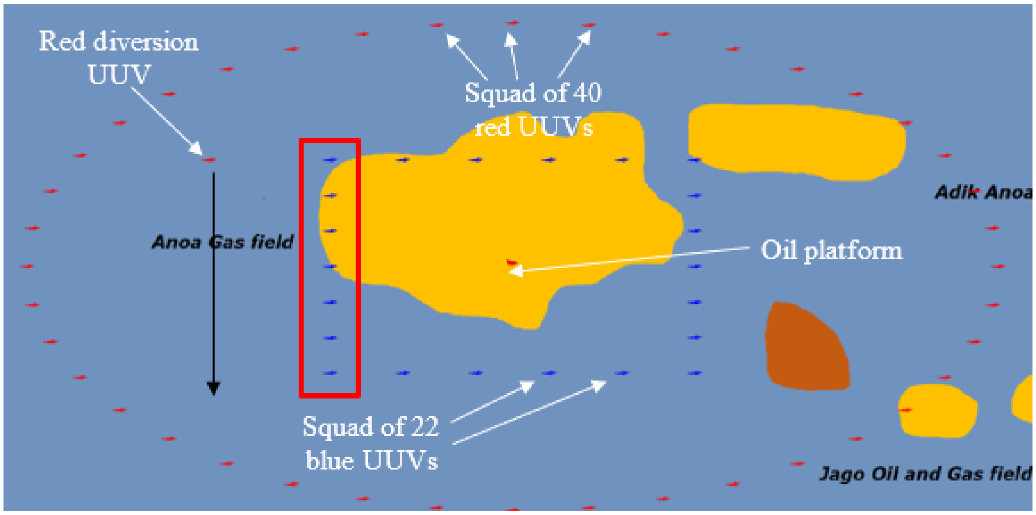


Figure 30 Patrolling Blue Force against Distributed Red Force

B. ANALYSIS

This section covers the results of the MANA simulation for the Natuna scenarios. The measure of effectiveness in the simulation is the probability of success of the Blue Forces in defending the oil platform.

1. Scenarios Analysis

Table 8 shows the results of the four combinations of attack and defense plans. Each scenario was simulated with 100 runs each on the MANA farmer software.

Table 8 CONOPS Results

Scenario number	Scenario description	Number of Blue successes in 100 runs	Average number of Red attackers destroyed
1	Concentrated Red Force against point defense Blue Force	60	38.02
2	Distributed Red Force against point defense Blue Force	100	40
3	Concentrated Red Force against patrolling Blue Force	0	7.66
4	Distributed Red Force against patrolling Blue Force	0	29.78

The most threatening scenario for Blue is the case where the Red Forces make a concentrated attack from a single direction. Note the numbers in Table 8 are optimistic from Blue's perspective because Blue UUVs hold unrealistically high ammunition. In reality, each Blue UUV will have a small amount of ammunition and so Blue will be at a greater disadvantage. In this preliminary analysis we merely wanted to evaluate fixed vs. patrol. In the next section we reduce ammunition levels to realistic levels.

The defensive ring with radius of 500 m is too large because defenders at the opposite side of the circle could not detect the incoming Red Forces, so they did not move to engage them. Consequently, Blue would not deploy all defensive UUVs against a concentrated attack. The defensive ring is subsequently reduced, which will be discussed in the detailed analysis.

From a defensive perspective, a point defense strategy is more effective than to conduct a perimeter patrol. The patrolling model would need to defend a larger area, so the defense forces were spread thin. As a result, a concentrated attack by the Red attacking force easily overwhelmed the few defenders in the patrolling configuration. Furthermore, the Red diversion UUV also drew away the defenders which further reduced the reaction time against the Red attacking force, allowing them to bypass the defense line without resistance. This led to a catastrophic failure of the Blue Force's defense configuration in patrolling scenarios.

Another lesson learnt relates to the pursuit of the Red diversion UUVs. There is no maximum chase distance implemented for the Blue UUV, so it is possible for the diversion to draw a significant number of defenders away. If the Blue UUVs are able to communicate with each other and coordinate a response action, fewer UUVs would leave their position to investigate a contact. Consequently, there would not be large openings, which create an undefended sector, and Blue would be less susceptible to a diversion.

In the next section, we focus on Scenario 1 to investigate how different parameters might affect the defense solution. This CONOPS is chosen because it provides the best results for each side where Red executes a concentrated attack and Blue uses point defense.

2. Detailed Analysis

a. Parameters

Table 9 shows the parameters modeled in the simulation with design points varying the defense capability and the force size for Red.

Table 9 Parameters of Model

Parameter	Abbreviation	Minimum value	Maximum value
Blue Probability of Hit	P_{hit}	0.5	1
Number of Hits to Destroy Red	D_{red}	1	2
Number of Blue Ammo Carried	Q_{ammo}	1	4
Number of Blue UUVs	N_{blue}	3	6
Number of Red UUVs	N_{red}	1	6
Blue UUVs Speed	v	10 km/ h	25 km/h
Blue UUV Detection Range	R_D	100 m	1000 m
Probability of Classification by Blue UUV	P_c	0.5	1
Blue Weapon Range	R_w	2 m	5 m

The Blue probability of hit is selected for further investigation to allow the team to investigate the effect of a highly sophisticated and maneuverable Red attacking UUV, which may be feasible in the near future.

The number of hits to destroy Red is selected to simulate an adversary that is capable of employing countermeasures (analogous to chaff in air combat) or producing decoys (analogous to flares in air combat).

The amount of Blue ammunition carried is chosen to investigate cost-benefit tradeoffs between having more Blue defending UUVs versus being able to carry more ammunition.

The number of Red UUVs is varied to investigate the breaking point of the defense solution.

The numbers for Red UUVs and Blue UUVs in the scenarios are reduced from 40 and 22 respectively to a maximum of 6. 22 Blue UUVs is the minimum required to surround the Anoa gas field perimeter without gaps and is kept constant across the previous four scenarios for fairness. Since the focus is on the oil platform, the area to be defended is much smaller, so 22 Blue UUVs were considered excessive. Hence, a maximum of six Blue UUVs was utilized for this simulation.

To ensure that the scenario is still defendable, the number of Red UUVs must be reduced. It is obvious that if Red attacks have an overwhelming numeric advantage, it will succeed with certainty as it will use all of Blue's defense capacity. The rule of thumb for a scenario to be considered reasonable is one where the following inequality holds:

$$N_{Blue} \times P_{hit} \times Q_{ammo} \geq D_{red} \times N_{Red}$$

N_{Blue}: *number of blue UUVs*

P_{hit}: *blue probability of hit*

Q_{ammo}: *quantity of blue ammo carried*

D_{red}: *number of hits to destroy red*

N_{Red}: *number of Red UUVs*

Blue UUV speed is an important parameter because the amount of ammunition and the number of Blue UUVs have been greatly decreased, so all UUVs must be mobilized to repel the Red attacking force, including those on the opposite side of the circle defending the oil platform. A higher speed allows a Blue UUV on the opposite side of the circle surrounding the oil platform to move to engage the incoming Red attacking UUV successfully.

Blue UUV detection range is important because a longer detection range gives the Blue UUVs more time to react to the incoming Red attacking UUVs. A hypothesis proposed is that the UUV detection range and the maximum speed of the UUV are closely related.

The final MANA scenario is shown in Figure 31. It incorporates the lessons learnt from the first 4 CONOPS, which are:

- Reducing the radius from 500 m to 250 m. The radius is not reduced to zero because of concerns that the shockwave from the destruction of a Red attacking UUV that is too close to the oil platform might damage the oil platform. An average oil platform has a size of 122 m by 76 m.
- The maximum distance that a Blue defending UUV will stray from its docking station is reduced to 250 m. This limits the effectiveness of the Red diversion tactic.

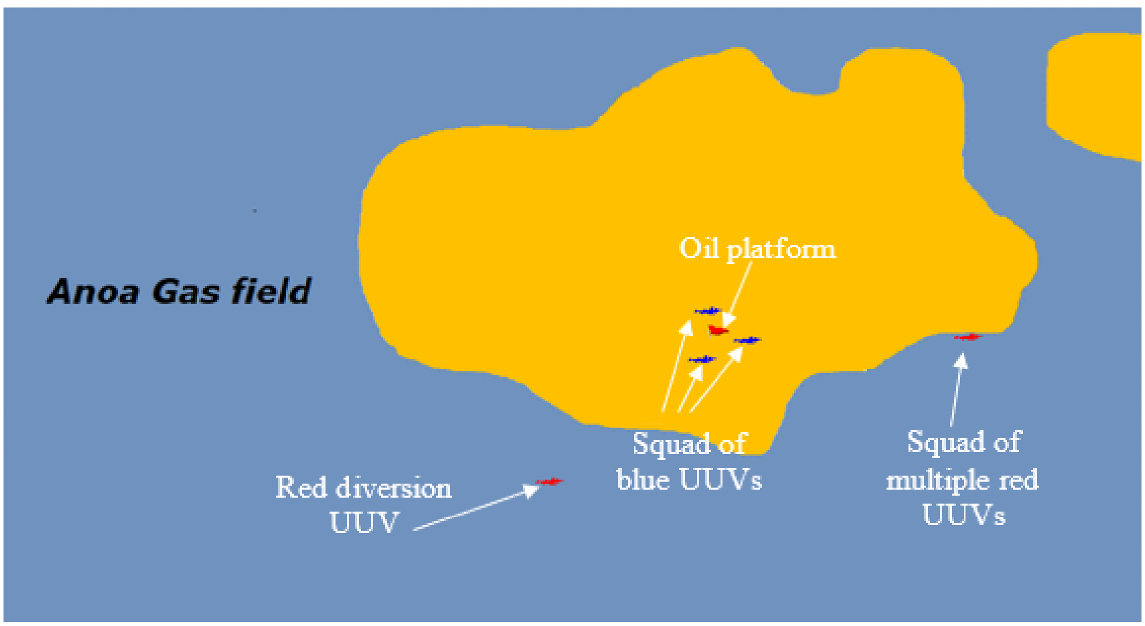


Figure 31 Varied Parameters of a Concentrated Blue Force Defense

b. Results

To perform an in depth analysis of the impact of each system parameter a 33 design point NOLH design was utilized. To account for model variability each design point was replicated 30 times, the average results for each design point are shown in Table 10.

Table 10 Results of NOLH DOE

DP No.	Blue Probability Of Hit (P_{hit})	Number Hit To Destroy Red (D_{red})	Number Blue Ammo Carried (Q_{ammo})	Number Blue UUVs (N_{blue})	Number Red UUVs (N_{red})	Blue UUVs Speed (v)	Blue UUV Detection Range (R_D)	Blue UUV Probability Classify (P_c)	Blue UUV Weapon Range (R_w)	P(Blue success)
1	1	1	2	4	5	19	719	0.73	5	96.7%
2	0.95	2	1	4	3	13	775	0.66	5	0.0%
3	0.94	1	4	3	1	19	747	0.52	3	100.0%
4	0.78	2	4	4	6	12	831	0.53	3	16.7%
5	0.97	1	2	4	4	21	466	0.78	2	96.7%
6	0.98	2	2	4	3	13	241	0.94	2	0.0%
7	0.84	1	4	4	1	20	438	0.95	5	100.0%
8	0.77	2	4	4	6	14	297	1	4	3.3%
9	0.83	1	2	5	5	15	100	0.59	4	0.0%
10	0.88	2	2	5	2	18	184	0.69	5	60.0%
11	0.86	1	3	6	3	11	213	0.58	3	36.7%
12	0.89	2	3	6	5	25	522	0.7	3	100.0%
13	0.8	1	2	5	4	12	972	0.89	3	100.0%
14	0.92	2	2	6	2	18	944	0.86	3	100.0%
15	0.81	1	4	6	3	10	691	0.88	4	100.0%
16	0.91	2	3	6	5	24	606	0.83	4	96.7%
17	0.75	2	3	5	4	18	550	0.75	4	90.0%
18	0.5	2	3	5	2	16	381	0.77	2	96.7%
19	0.55	1	4	5	4	22	325	0.84	2	96.7%
20	0.56	2	1	6	6	16	353	0.98	4	0.0%
21	0.72	1	1	5	1	23	269	0.97	4	100.0%
22	0.53	2	3	5	3	14	634	0.72	5	93.3%
23	0.52	1	3	5	4	22	859	0.56	5	100.0%
24	0.66	2	1	5	6	15	663	0.55	2	0.0%
25	0.73	1	1	5	1	21	803	0.5	3	100.0%
26	0.67	2	3	4	2	20	1000	0.91	3	100.0%
27	0.63	1	3	4	5	17	916	0.81	2	96.7%

(continued on next page)

DP No.	Blue Probability Of Hit (P_{hit})	Number Hit To Destroy Red (D_{red})	Number Blue Ammo Carried (Q_{ammo})	Number Blue UUVs (N_{blue})	Number Red UUVs (N_{red})	Blue UUVs Speed (v)	Blue UUV Detection Range (R_D)	Blue UUV Probability Classify (P_c)	Blue UUV Weapon Range (R_w)	P(Blue success)
28	0.64	2	2	3	4	24	888	0.92	4	0.0%
29	0.61	1	2	3	2	10	578	0.8	4	60.0%
30	0.7	2	3	4	3	23	128	0.61	4	3.3%
31	0.58	1	3	3	5	17	156	0.64	4	0.0%
32	0.69	2	1	3	4	25	409	0.63	3	0.0%
33	0.59	1	2	3	2	11	494	0.67	3	70.0%

Recall, the rule of thumb for Blue Force to have a chance at success:

$$N_{Blue} \times P_{hit} \times Q_{ammo} \geq D_{red} \times N_{Red}$$

The value on the left hand side can be viewed as the total effective firepower of Blue and the value on the right-hand can be viewed as Red's effective force size. If Blue's effective firepower is not greater than Red's effective force size, then Blue cannot win. In order evaluate this hypothesis, we introduce a new parameter F representing Blue's firepower advantage.

$$F = (N_{Blue} \times P_{hit} \times Q_{ammo}) \text{—} (D_{red} \times N_{Red}).$$

A negative firepower advantage is regarded as an essentially impossible mission because there is insufficient ammunition to take out the Red Forces.

Figure 32 shows the relationship between fire power advantage and the probability of success. There are five design points in Figure 32 (two of them are very close together) that have negative values for fire power advantage and all of them correspond to Blue failure. Those are design points 2, 20, 24, 28 and 32. Figure 32 confirms our hypothesis about the importance of firepower advantage.

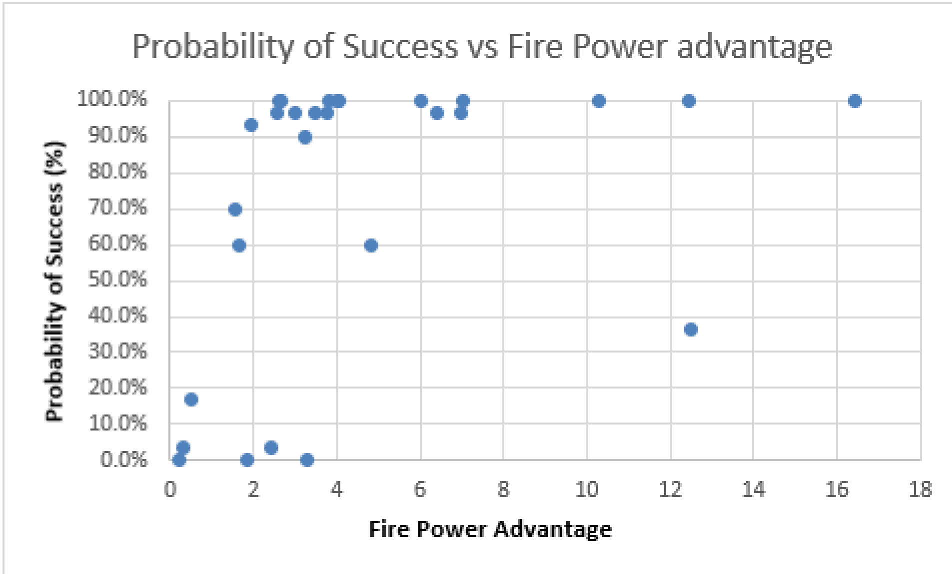


Figure 32 Probability of Success vs Fire Power Advantage

While not surprising that scenarios with negative firepower produced no successes, there are several scenarios that have very low success probabilities even with a firepower advantage. In particular, design point 11 has a significant firepower advantage (12.48) but less than a 40% success probability. Investigation of design point 11 reveals a slow UUV speed of (11 km/h) and a short detection range of 213 m. This shows that firepower is not the only factor for success and motivates us to account for other factors.

Another hypothesis about what drives Blue's success is the higher values of Blue UUV speed (v) and higher Blue UUV detection range (R_D). If the Blue Force cannot effectively find, classify, localize, track, and engage the adversary, then firepower has limited value. This hypothesis ties in strongly to the Observe, Orient, Decide and Act (OODA) loop, where the increased Blue UUV detection range improves the observe portion, while the faster Blue UUV speed and higher firepower advantage contribute to the Blue Forces' capability to act.

To test this hypothesis, we modified our firepower advantage F to incorporate the importance of the OODA variables. We multiply F, v and R_D, and call this parameter OA advantage: $OA = F(v)R_D$.We choose OA advantage for Observe and Act. We define OA in this manner for a few reasons. First it is simple and increases in F, v, and R_D. Second increasing any of the inputs F, v, R_D by a certain percentage has the same impact on the output OA. We primarily wanted to create one parameter that incorporates the OODA variables and examine how well this parameter predicts the outcome. Later we will examine additive relationships (rather than multiplicative) when we perform linear regression. Figure 33 shows the relationship between this new parameter OA advantage and mission success.

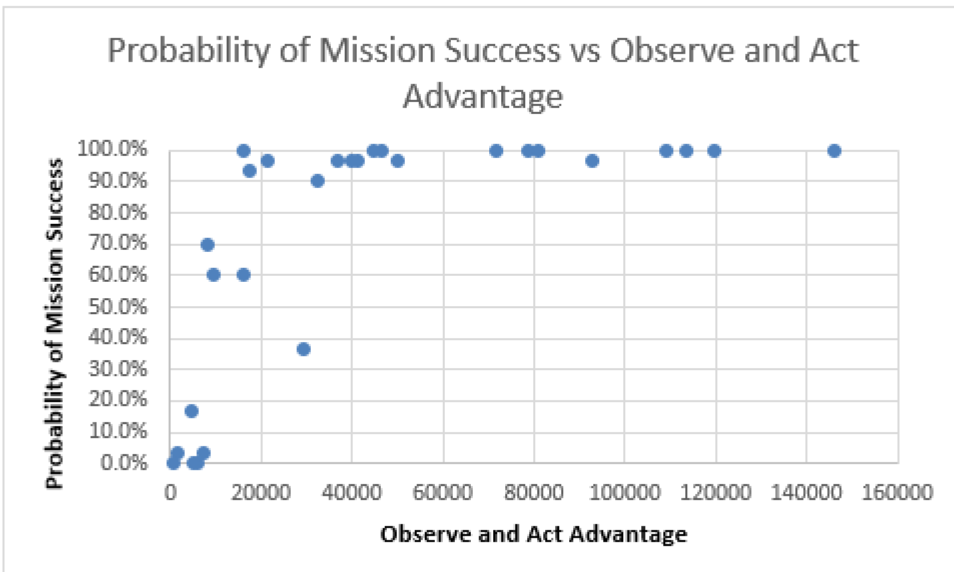


Figure 33 Probability of Mission Success vs Observe and Act Advantage

From Figure 33, there appears to be strong support for this new hypothesis. An *OA* advantage greater than 30,000 greatly improves the probability of mission success with P(success) having values of 90% and above.

Given the importance of Blue firepower, speed, and detection range, we form a partition tree to examine the impact of the variables in more detail. Figure 34 shows these results.

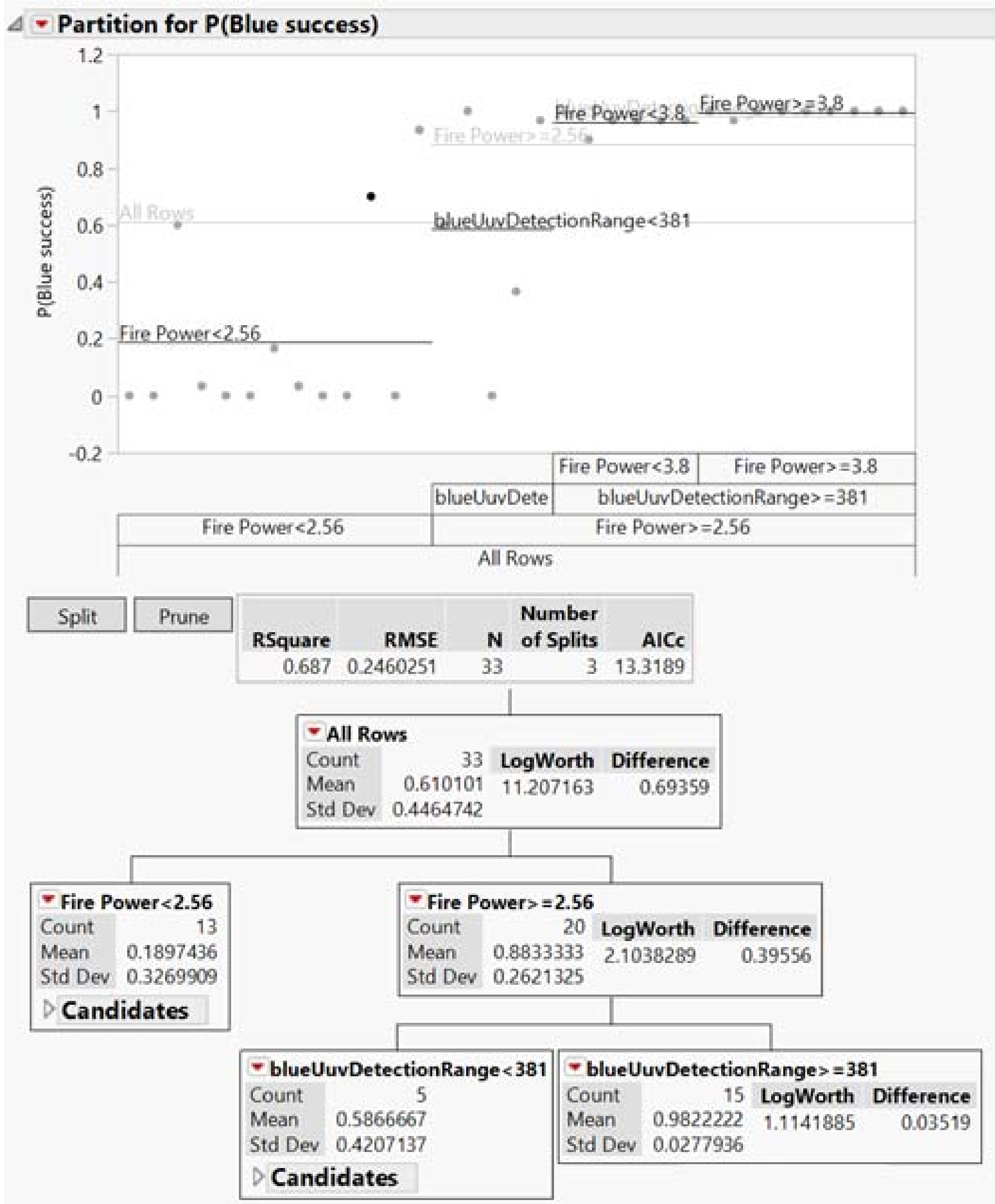


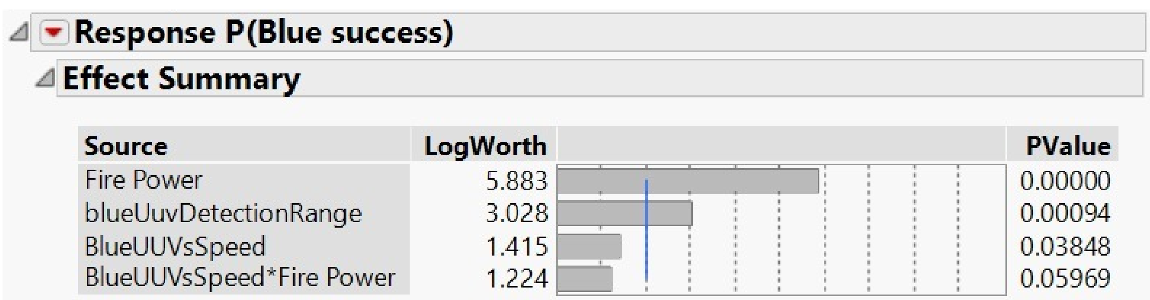
Figure 34 Partition Tree of Key Parameters

Not surprisingly the partition tree indicates that firepower is an important parameter. Scenarios with firepower above 2.56 generate an average success probability of 0.88, while those below that threshold have an average success probability of only 0.19. The detection range also has a significant impact on the battle outcome. When the detection range of Blue UUVs is 381 meters or above and firepower is greater than 2.56, P(Success) is 0.98.

The analysis indicates that firepower advantage is the most decisive factor to achieve victory. Firepower advantage comprises of 5 different factors—Blue UUV probability of hit, quantity of Blue UUV ammo carried, the number of Blue UUV, number of Red UUV and the number of hits to destroy a Red UUV. The number of Red UUV is beyond the control of the defense solution. However, the remaining parameters are within the control of Blue to some degree, and through systems development, Blue can evaluate the most cost-effective way to increase firepower.

To conclude we examine the tradeoff between firepower and speed or detection range. We first implement a stepwise regression. The response variable Y is P(Success), while the independent variables are Firepower, Blue UUV speed, and UUV detection range. Interaction terms are also included in the regression.

Figure 35 shows the effect summary of the best fit regression model. This figure ranks the coefficients in order of statistical significance. Firepower and detection range appeared as main effects with a P-value of below 0.01.



Response P(Blue success)

Effect Summary

Source	LogWorth	PValue
Fire Power	5.883	0.00000
blueUuvDetectionRange	3.028	0.00094
BlueUUVsSpeed	1.415	0.03848
BlueUUVsSpeed*Fire Power	1.224	0.05969

Figure 35 Effect Summary of Stepwise Regression

Figure 35 is a prediction profiler to provide a visual representation on how changing each of the 3 parameters settings would impacts the response variable, P(Success). It is observed that an increase in either of the 3 parameters would positively affect P(Success).

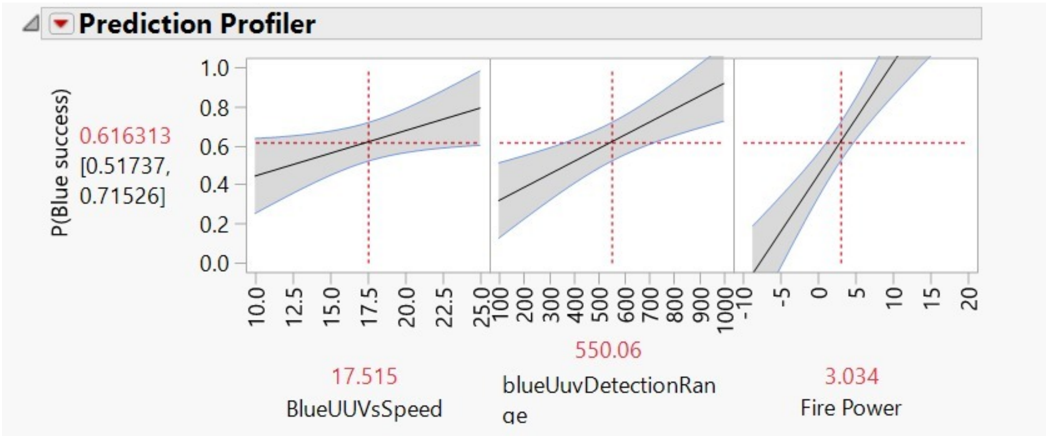


Figure 36 Effect Summary of Stepwise Regression

As detailed in (Whitcomb and Beery, 2016), contour profilers were built in JMP to investigate the tradeoff between firepower and UUV speed. Figure 37 shows the contour profile that was generated. The contour plot fixed detection range at 382 m and determines the combination of speed and firepower that will generate a predicted success probability of 0.99 (based on the regression model). These combinations appear as the white envelope in Figure 37.

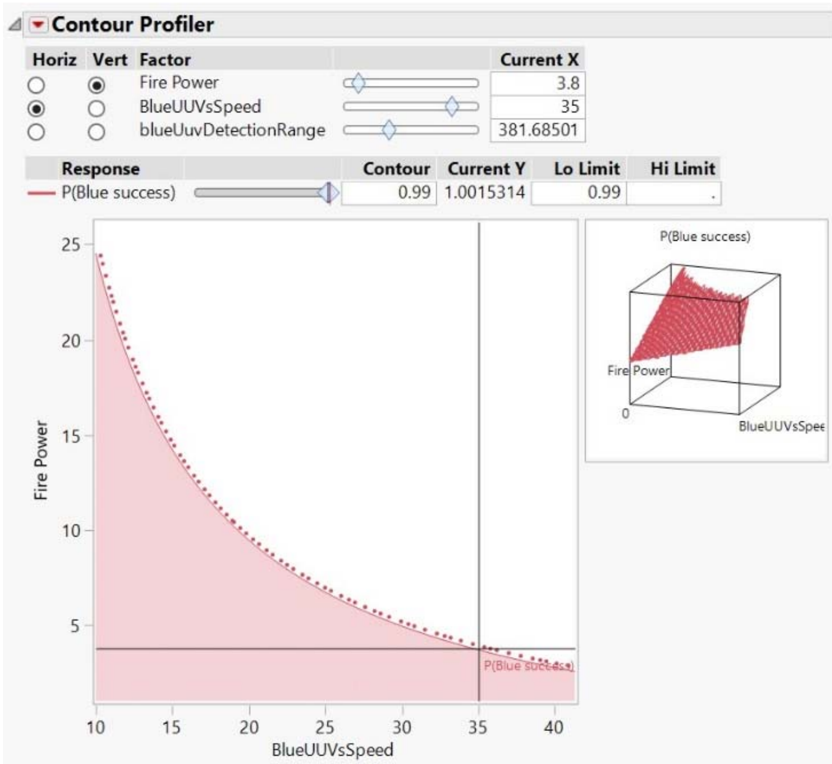


Figure 37 Contour Profile of Firepower and Blue UUV Speed

Two observations were made from the contour plot. The first observation is the confirmation of the earlier hypothesis that UUV speed is an operationally important factor for *OA* advantage, even though speed was not statistically significant at the 0.01 level in our regression. From the contour plot, a higher Blue UUV speed can be traded for lower fire power advantage to achieve the same probability of Blue mission success.

The second observation is the shape of the curve, which decreases in a convex fashion. Consequently, a slower UUV speed needs to be compensated with a much higher firepower to achieve the same P(Success). As speed increases from an initial slow level, the corresponding firepower requirement drops quickly. However, continuing to increase speed has diminishing benefits.

The contour profiler in JMP was also used to investigate the tradeoff between firepower and UUV detection range. Figure 38 shows the contour profile that was generated in a similar fashion to Figure 37. This contour plot fixed Blue UUV speed at 20 km/h, Figure 38 displays a linear tradeoff between firepower and detection range. For every additional 100m in detection range, firepower can decrease by 1.3. Figure 38 summarizes the conclusions and recommendations for the section.

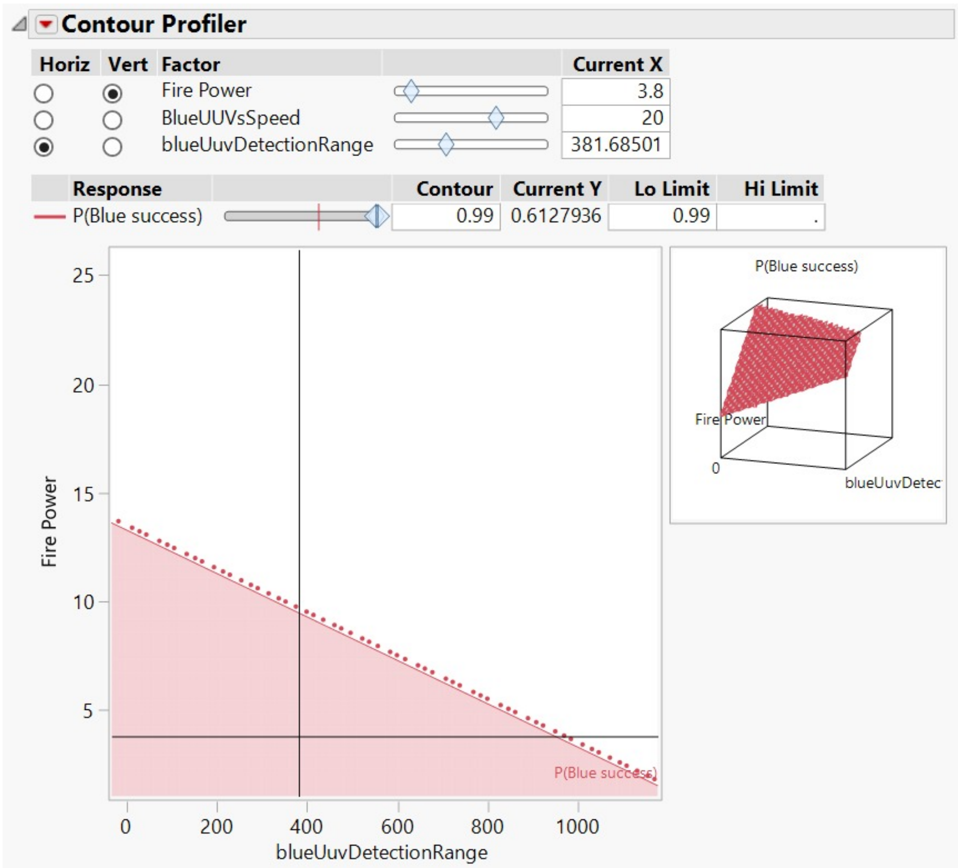


Figure 38 Contour Profile of Firepower and Detection Range

Table 11 Evaluation of Main Effects

Observation	Deduction / Recommendation
Blue Force Fire Power as a significant effect to P(Success)	The Blue Force fire power is determined to be a main effect with significant influence on P(success). The recommendation is to place emphasis on developing the 3 main constituent factors under the defender's control– Blue UUV probability of hit, quantity of Blue UUV ammo carried, and number of Blue UUV.
Blue UUV detection range has a significant effect to P(Success)	The Blue Force should place emphasis on developing technologies to allow a breakthrough in detection range at low cost; this parameter may be equally or more cost-effective compared to building UUVs at lower cost.
UUV Speed is operationally important	A slower UUV speed needs to be compensated with a much higher firepower to achieve the same P(Success).
Number of Blue Ammo is operationally significant	This parameter has similar effect to deploying more UUVs. An alternative to increasing the amount of ammo would be to increase the scale and quantity of UUV units deployed.
Blue Weapon Range is not significant	As Blue is implementing a point defense with an advancing threat, this parameter only really affects when Blue fires on Red and has very little impact on success. In other scenarios where pursuit is involved, weapon range may be a more important factor.

C. NATUNA BESAR MODEL 2 (NB2)

1. Scenario

The East Natuna Gas fields are located east of Peninsula Malaysia and west of the Natuna Islands. Extracted gas is transported to Singapore via an undersea pipeline between the gas field and Singapore. The pipeline lies along a busy shipping lane, where a significant portion of the world shipping tonnage passes through and is shown in Figure 39 and Figure 40.

Figure 39 Natuna Besar Pipeline

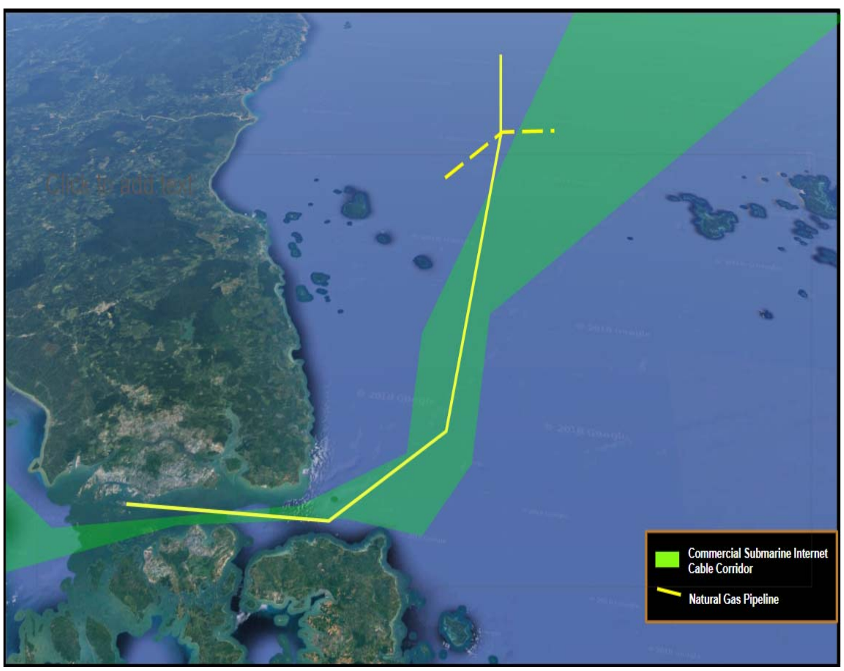


Figure 40 Natuna Besar Shipping Lane

Given that the pipes lie along a busy shipping way east of Peninsular Malaysia, many ships traverse over the pipes daily. The attack scenario focused on a Red shipping vessel releasing a UUV, whose mission is to destroy the gas pipe. The UUV attempts to achieve this objective by carrying an explosive payload to the pipe while trying to avoid defense forces. Given the overlap between the shipping lane and the gas pipe, the adversary UUV could be released as close as 4km to the pipeline. This allows the adversary to get close to the pipe, without drawing any undesired attention to itself.

Surveillance around the pipe would be provided by a sensor field to detect any intrusion by adversary UUVs. Once detected, the adversary UUV will be handled by Blue shooter UUVs. Figure 41 shows the proposed placement of the shooters. Some shooters deploy from static positions while others actively patrol.

The fixed shooter concept is a sequence of stationary pods that each contain mini UUVs used to attack the adversary UUV. The mini UUV would be armed with a warhead. Targeting information is transmitted from sensors to mini UUVs (e.g., via a wire). If the sensor field does not provide enough useful targeting information, a mini UUV could also be equipped with its own sensor. An example of such a mini UUV would be a wire-guided torpedo. Upon detection of an adversary UUV by the sensor field, a mini UUV would be launched against it. The number of UUVs that the fixed shooter pod could counter is directly proportionate to the number of mini UUVs in the pod. If there was a requirement to defend against a swarm of 5 UUVs, the pod would need to contain a minimum of 5 mini UUVs.

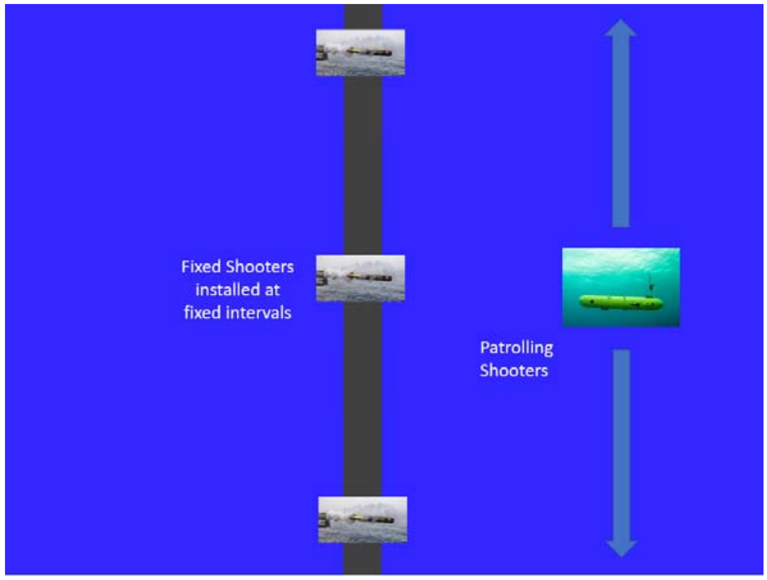


Figure 41 Proposed Defense System

Patrolling shooters are autonomous UUVs that are equipped with their own sensors. In the analysis, the patrolling shooters do not receive any exogenous information from the sensor field, and thus do not have the luxury of a global picture as the fixed shooters use. This assumption is made because of the difficulty of undersea communication across larger distances and areas which the patrolling shooters inherently need to operate in. Hence, the patrollers transverse around the area and conduct barrier searches to detect the presence of any adversary UUVs. A patroller will only detect and react to a threat UUV if the patroller detects it with the patroller own organic sensor. The patrollers are equipped with a single warhead to be used for engagement with the adversary UUVs. A patrolling shooter will be expended should it engaged with the enemy and activate its warhead.

2. Assumptions

The following assumptions are made regarding the scenario:

1. The underwater environment is free of an impediment to movement. This assumption is reasonable and conservative since the adversary would stand to gain the most from the lack of impediment. Any impediment could be utilized by the defender to harden the defense.

2. The pipe is only able to withstand a single hit. This assumption is reasonable and conservative because the pipe is not designed for blast impact and any puncture in the pipeline would cause loss of pressure and disruption of gas supply, and in the worst-case complete shutdown of supply.

3. The adversary UUV attacks the pipe and does not attack the defense forces, avoiding it altogether. This assumption is reasonable because the Red force's objective is the pipe and thus would be focused on attack. In addition, attacking any Blue UUV along the way to the pipe would alert the defender, making it more difficult for Red to execute a successful attack.

4. The adversary UUV has knowledge of the pipe position and heads in directly toward the pipe without having to search. This assumes the adversary has performed reconnaissance ahead of time, and is a conservative assumption as it gives Red an advantage

5. The scenario begins upon detection of adversary UUV by the sensor field. Recall that this information is only passed to fixed shooters; the patrolling shooters still must detect the adversary UUV on their own. This overstates the effectiveness of the system as there may be situations where the adversary UUVs are never detected by the sensor field. However, the model's primary focus is to analyze the effectiveness of using fixed and patrolling shooters in defending the pipelines. Thus, it is reasonable to assume the model starts upon detection of the adversary UUV in the area by the sensor field.

3. MANA Implementation

Map Aware Non-Uniform Automata (MANA) was selected as the simulation tool for the study. The MANA Farmer extension was used to vary the values of variables across each simulation run and collate results efficiently. The simulation focused on the number of static shooters and patrolling shooters required to defend against an adversarial UUV of varying capabilities. The results from the simulations can provide insight into how to design a cost-effective mix between static shooters and patrolling shooters.

a. Environment

The scenario is implemented in MANA as a 4km by 4km map. It is expected that the shipping vessel would release the adversary UUV within 4km of the pipeline as described in the scenario. A single time step in the model is five seconds. The battlefield is modelled from a top-down perspective and models the actions of agents in a 2-D X-Y cartesian grid. The adversarial forces are designated as Red agents, with the defense force designated as Blue agents. None of the agents are affected by either terrain or the background layers. Figure 42 shows the overview of the MANA setup.

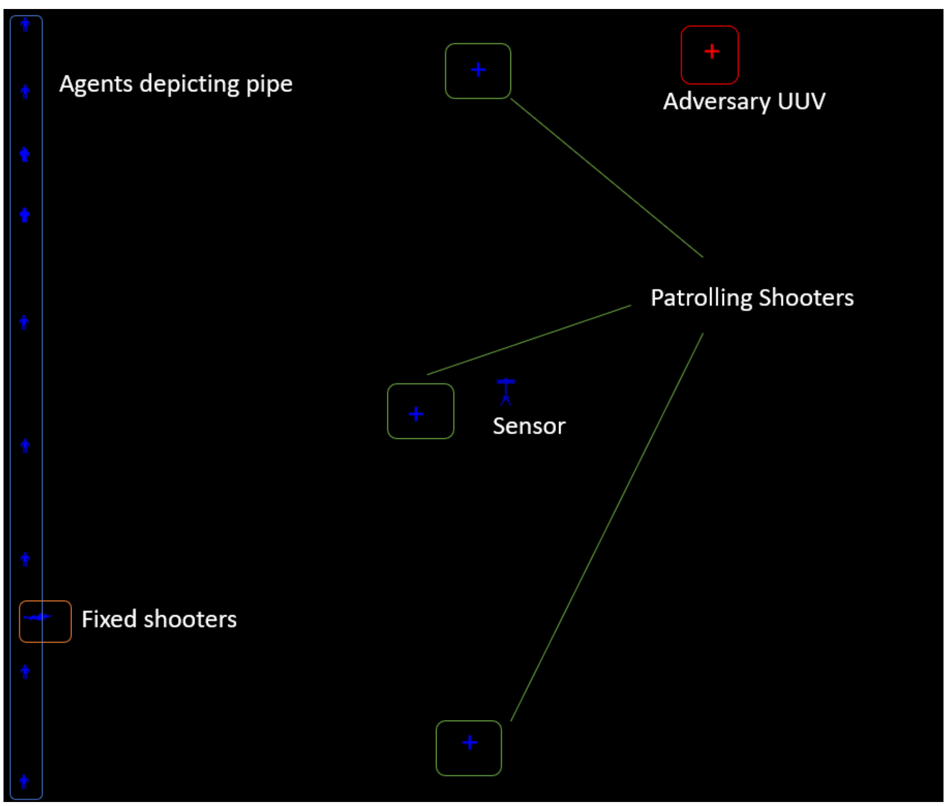


Figure 42 MANA Implementation of Fixed and Patrolling Shooters

b. Blue Agents

Four different types of agents are modelled as part of the simulation. The agents are as follows: (1) Patrolling Shooters (2) Fixed Shooters (3) Blue sensor field and (4) Pipe agents.

c. Blue Sensor Field

The sensor field is modeled as one sensor that continuously provides track information on the Red UUV's position to the fixed shooters. The sensor field does not communicate with the patrolling shooters. Recall that the model begins upon an exogenous Red detection. The sensor only provides track information after the initial detection. The sensor range covers the entire battlefield, with its probability of track varied between 0.5 and 1. The probability of track would be affected according to the capabilities of sensor used. The target information is continuously passed to the fixed shooters via wired connections.

d. Patrolling Shooters

Patrolling shooters are spawned at random locations within a designated box along the pipe as shown in Figure 43 and Figure 44. They perform a circular patrol via designated waypoints. There are multiple sets of waypoints, all of which perform a circular patrol loop. The different initial waypoints ensure that the agents do not travel together in a cluster.

The quantity, speed and sensor range of the UUVs are varied as part of the analysis. Each patrolling shooter is equipped with a single warhead. The weapon range for the patrolling shooters is kept to a minimum of 5m, which is to simulate an explosive blast. The patrolling shooters cease any further operations upon exploding with an adversary UUV.

Each patrolling shooter is also equipped with an onboard sensor to enable it to detect and track adversary UUVs; this organic sensing capabilities is necessary as the patrollers do not receive any detection or tracking information from the sensor field.

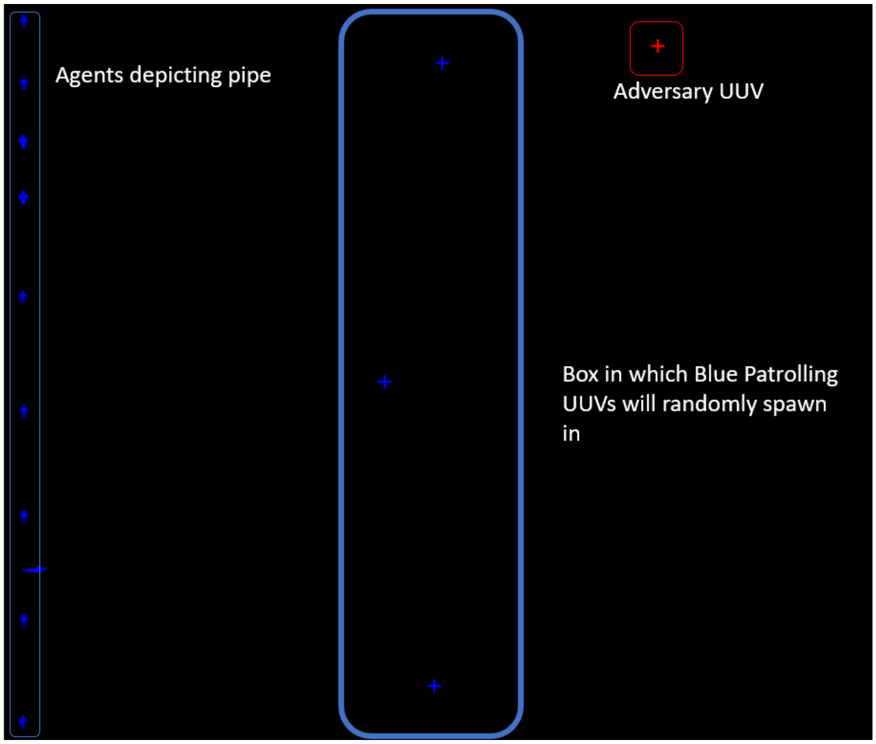


Figure 43 Spawn Point Location in MANA

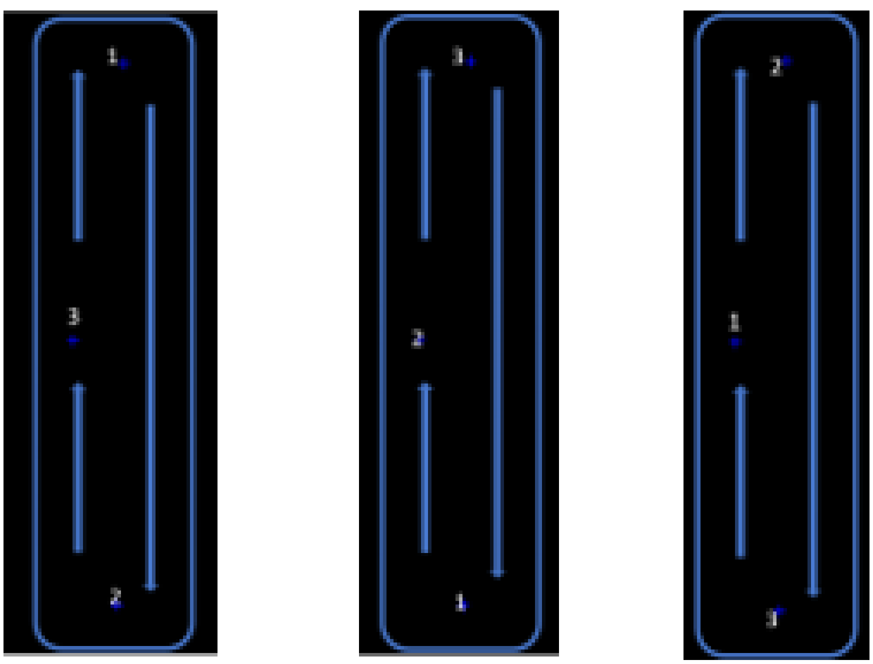


Figure 44 Variety of Waypoints Used to Set the UUV's Patrolling Path

e. *Fixed shooters*

The fixed shooter UUVs are guided to the Red agent via the information provided by the Blue sensor field. A single shooter UUV will be deployed to intercept each Red UUV that breaks through.

The fixed shooter pods are spaced equally along the pipe. The distance between pods was varied in the analysis to determine the maximum distance beyond which the fixed shooter is unable to intercept the Red agent. This provides an insight into the number of shooters that are needed to be placed along the pipeline to provide full coverage against a single Red agent.

Similarly, the quantity, speed and sensor range of the UUVs are varied as part of the experiment. Weapon range for the agents is kept to a minimum of 5m, which is to simulate an explosive blast. Once a fixed shooter agent detonates, it ceases any further operations and does not participate in any further interaction with the rest of the simulation.

The fixed shooters also have their own sensors. Given that sensor field is not perfect, the fixed shooter agent is given its own sensor (which was also varied in quality) to localize the adversary UUV if the sensor field is unable to properly track the adversary UUV.

f. *Pipe Agents*

Pipe agents are placed along with the position of the pipes and serve as a target point for the Red agent.

g. *Red Agent*

The Red agent consists of a sole agent, representing an enemy UUV. The objective of the Red agent is to attack the pipe while avoiding contact with any Blue UUVs en route. This is modelled using personalities in the MANA simulation, with a small priority for reaching the pipe. The speed of the Red UUV and the distance of its sensor range are varied to test the capabilities of the defense system.

Initial simulations showed that Red's initial detection point is important. The closer Red is detected to the pipeline, the less time Blue can react with shooters. Adjusting the detection point was used to evaluate how far the Blue sensor field needs to provide surveillance coverage to ensure the defending forces can react and intercept the incoming threat.

h. Design of Experiment

Due to the limitation in Mana Farmer on accepting zero agents as a valid entry, three separate simulations were conducted.

Table 12 Blue Assets Allocation per Simulation

	Simulation 1	Simulation 2	Simulation 3
Sensor Field (linked to fixed shooter)	√		√
Fixed Shooter	√		√
Patrolling Shooter		√	√

The first simulation primarily serves to establish the maximum distance that the fixed shooter pods can be placed apart from each other on the pipe while still providing adequate defense coverage. This inter-UUV spacing is directly related to how many UUVs are required to defend an area of interest. The second simulation studies the impact of varying the number of patrol shooters. The third simulation with both patrol UUVs and fixed shooters determines the ideal mix of Blue agents.

The following variables are selected for further investigation in the design of experiment analysis.

Table 13 MANA Farmer Parameter Configuration

Agent	Parameters	Description	Units	Min	Max
Fixed Shooter	Inter-UUV spacing	Half Distance between Blue Fixed Shooters.	meter	100	4000
	Speed of Blue Fixed UUV	Speed of the wired UUVs launched by the Fixed Shooters	km/h	10	40
	Blue Fixed UUV Detection range	Fixed UUV sensor detection range	meter	100	300
Patrolling Shooter	Number of Blue Patrol UUVs	Number of patrolling UUVs	-	0	40
	Speed of Blue Patrol	Speed of patrolling UUVs	km/h	10	40
	Blue Patrol UUV Detection range	Patrolling UUV sensor detection range	meter	100	300
Sensor Field	Probability of Detection	Detection probability of the sensor	-	0.5	1
Red UUV	Speed of Red UUV	Speed of Red adversary UUV	km/h	10	40
	Red Detected Pt	Distance away from pipeline the Red UUV was detected	meter	500	4000
	Red UUV Detection range	Red UUV sensor detection range.	meter	100	300

The inter-UUV spacing is presented as the half the distance between Blue fixed shooters because the worst case for Blue is if Red approaches halfway between two pods as shown in Figure 45.

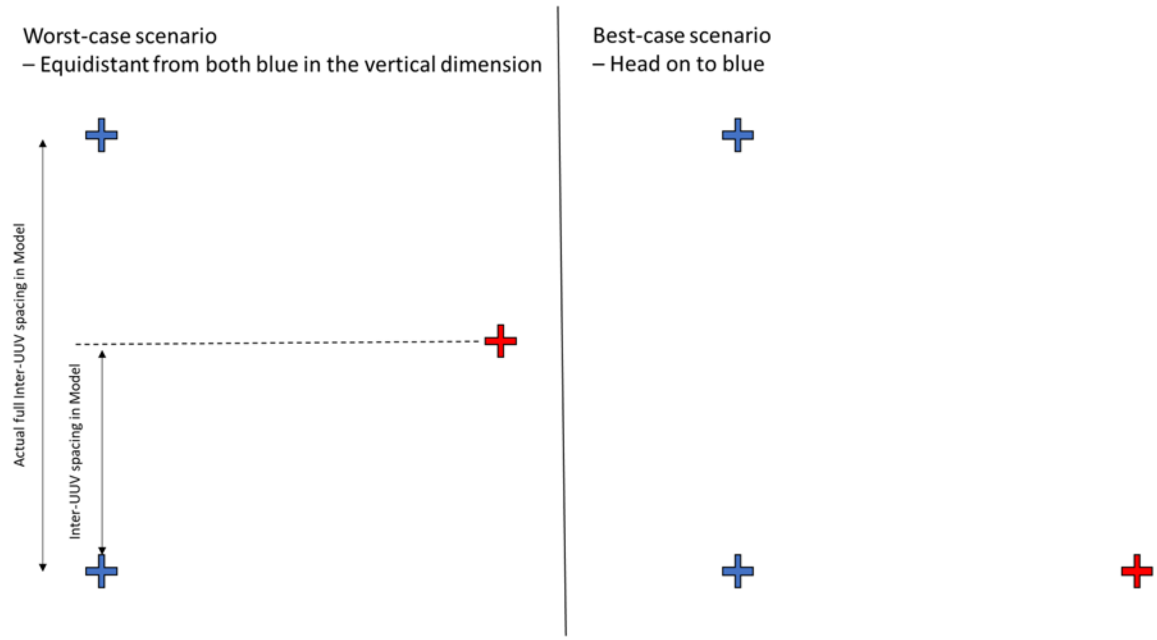


Figure 45 Inter-UUV Spacing

A design of experiments generator was used to define 33 design configurations. To account for model variability each design configuration was replicated 30 times, resulting in a total of 990 total model runs.

D. ANALYSIS

JMP was used to analyze the data produced by the MANA simulations. Stepwise regression and least square regression analysis were performed on the simulation results. Stepwise regression was initially conducted to filter out the important factors and relationships (such as polynomial, factorial). A model with good adjusted R-square value and a reasonable number of factors was then put through least square regression analysis. Analysis for each of the three scenarios listed in Table 12 is presented separately.

1. Fixed Shooters

In this scenario, the Blue forces only consist of the sensor field and fixed shooters to defend the pipeline against a single Red adversary; there are no Blue patrolling shooters. Table 14 shows the parameters used for the stepwise analysis. Each variable was included as both a linear and quadratic term. The interaction terms were also included in the initial regression.

Table 14 Parameters of Stepwise Analysis

Y Variable (Measure of performance)	P(Blue Success): Probability of Blue successfully defending the pipe
Parameters	Red Detected Pt Speed of Red UUV Red UUV Detection range Blue Inter-UUV Spacing Speed of Blue Fixed UUV Blue Fixed UUV Detection range Buoy Sensor Detection Probability

Based on the stepwise analysis, Table 15 shows the relevant factors that were used to generate the final model for the least square regression, where the selected model has an R-squared value of 0.86. The R-squared value is a measure of the fraction of variance explained by the model, so the closer to one implies a better model.

Table 15 Parameters of Least Square Regression

Y Variable (Measure of performance)	P(Blue Success): Probability of Blue successfully defending the pipe
Include regression variables	Speed of Red UUV Speed of Blue Fixed UUV Blue Inter-UUV Spacing Red Detected Pt Red Detected Pt* Blue Fixed UUV Detection range Blue Fixed UUV Detection range* Blue Fixed UUV Detection range Blue Fixed UUV Detection range

The regression results are shown in Figure 46, which shows both the Predicted Plot and the Effect Summary. The Predicted Plot shows the difference between the actual success probability and the predicted probability from the model. The Effect Summary shows the logworth of each coefficient in the regression model. Variables with a higher logworth have a more statistically significant impact on the probability of success. The results reveal the main factors that have a statistically significant impact on the mission success are speed of the adversarial UUV, speed of fixed shooter, Blue inter-UUV spacing, distance from the pipe when the Red UUV is first detected and the Blue Fixed UUV detection range.

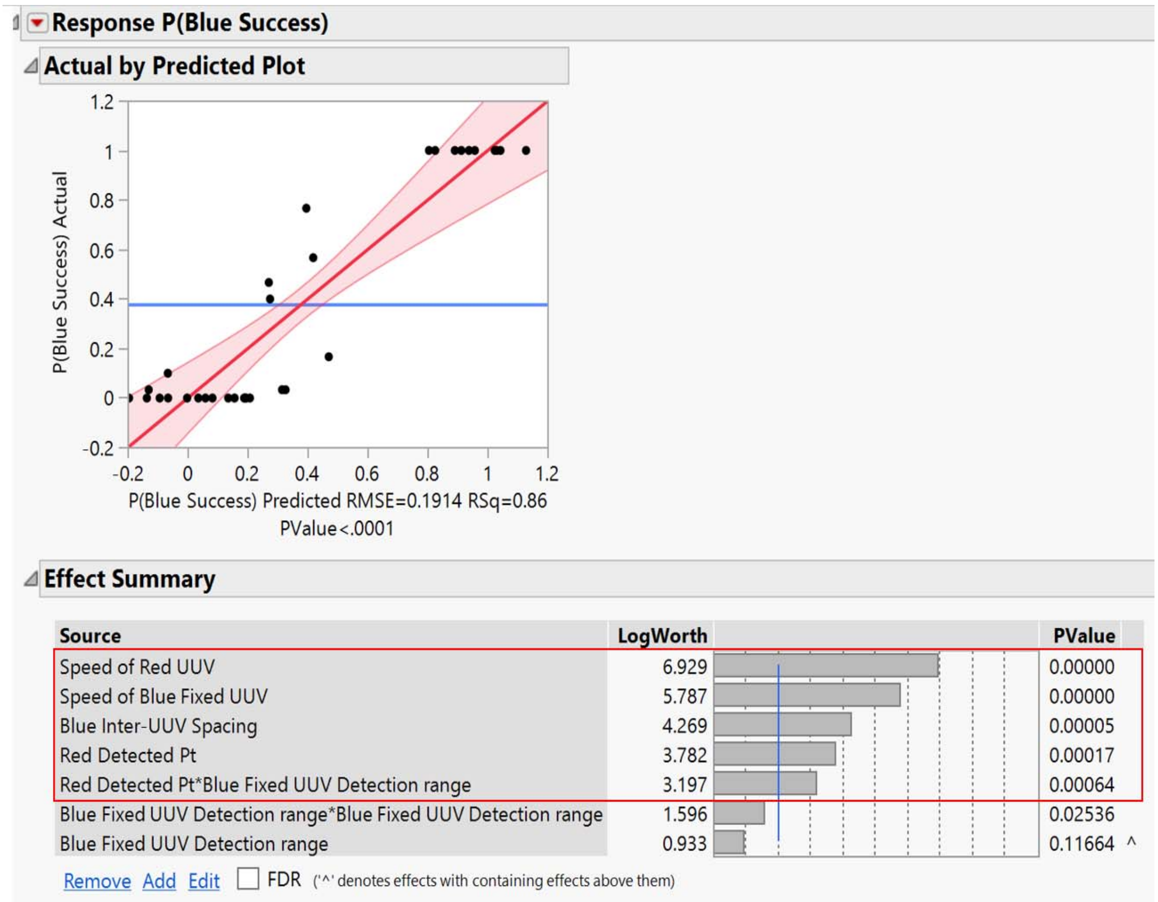


Figure 46 Predicted Plot and Summary for Fixed Shooters

Figure 47 shows the prediction profiler for the model. The figure shows how each individual parameter affects the probability of success holding the other variables constant. For example, an increase in the speed of the Red UUV or a decrease in Red's detection distance results in a decrease in the success probability. A Red UUV with a higher speed is more difficult to chase and interdict, and the closer an adversary UUV is first detected to the pipeline, the less time for the shooters to react. For the parameters affecting Blue UUV, an increase in the speed of Blue UUV or a decrease in Blue inter-UUV spacing increases the probability of defending the pipe. Higher speed allows the Blue UUV to more easily chase the adversary, and a closer launch point allows the Blue UUVs to better handle shorter response times. An increase in Blue detection range also initially increases the success probability; however, it exhibits diminishing improvement after 200m.

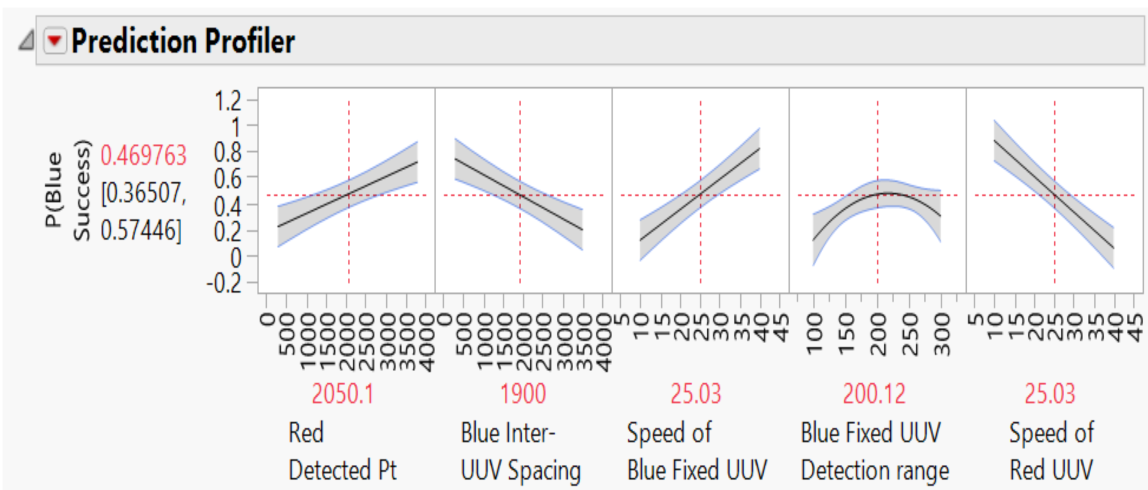


Figure 47 Prediction Profiler for Fixed Shooters

Commanders want a very high probability of success, and therefore parameter combinations that generate a success probability of 0.95 were examined. Two parameters were varied simultaneously while holding the other ones fixed. The parameters are listed in Table 16.

Table 16 Fixed Shooters Contour Plot Parameters

Parameters of interest	Values
Blue Fixed UUVs inter-spacing distance	100–4000 meters
Blue fixed UUV speed	10–40 km/h
Fixed Parameters	**Values**
Red UUV detected point	3500 meters
Red UUV speed	20 km/h
Blue fixed UUV detection range	200 meters

Figure 48 presents a tradeoff plot that specifies the speed required for a certain spacing to generate a predicted success probability of 0.95. For example, if the spacing between fixed shooter pods is 1000m, then the UUVs need to travel at speed of 24km/h or greater to achieve a 0.95 success probability. This assumes the other parameters are fixed as in Table 16

The inter-UUV spacing directly relates to the number of Blue fixed UUVs required in a specific operation area. Figure 48 shows the feasible solution region in white and the infeasible solution region in red. The estimated gradient of the limit boundary line is 0.0075. This implies that for every additional 1000m inter-UUV spacing, the Blue UUV requires an increase of 7.5km/h to maintain the system's rate of mission success. This provides useful information in performing a cost-benefit analysis of many lower-speed Blue UUVs, with shorter inter-UUV spacing, versus fewer faster UUVs with greater spacing.

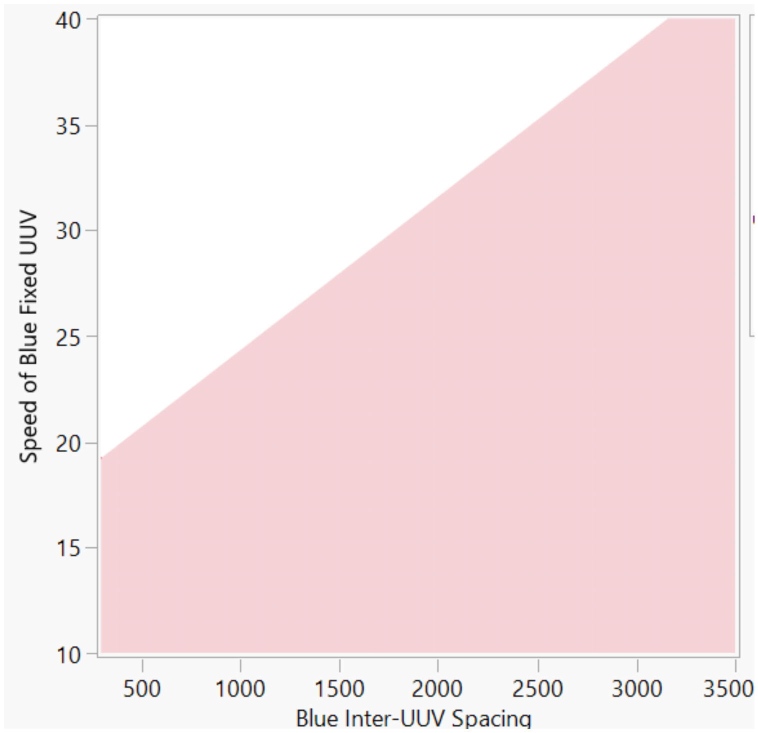


Figure 48 Blue UUV Speed vs. Spacing Results

The regression results assume a linear relationship, however inspection of the predicted plot in Figure 46 and the partition plot in Figure 49 reveals many extreme outcomes of close to 0 and 1. The results of the simulation are fairly binary, with many design points producing near certain success of failure. Next, the Partition tool in JMP was used to formulate classification trees based on the success probability. This provides insight into whether a certain threshold of factors exists in affecting the success probability. Results were partitioned by Blue inter-UUV spacing followed by Blue UUV speed. These two factors were chosen based on the results in Figure 47 and Figure 48. The Red factors were not considered because they are not within the defender's control.

The partition results suggest a threshold of 1600m for the inter-UUV spacing. 14 out of 20 models with values above 1600m produced almost zero success probability and 8 out of 13 below 1600m had probability 1. Further partitioning on Blue speed, results show that when spacing is below 1600 and Blue UUV speed is above 26 km/h, 6 out of 8 models produced near 1 success probability. Examining the contour plot in Figure 48, a spacing of 1600m requires a speed of 29km/h and above to produce near certain success. Thus, the two different analyses generate similar results and insights.

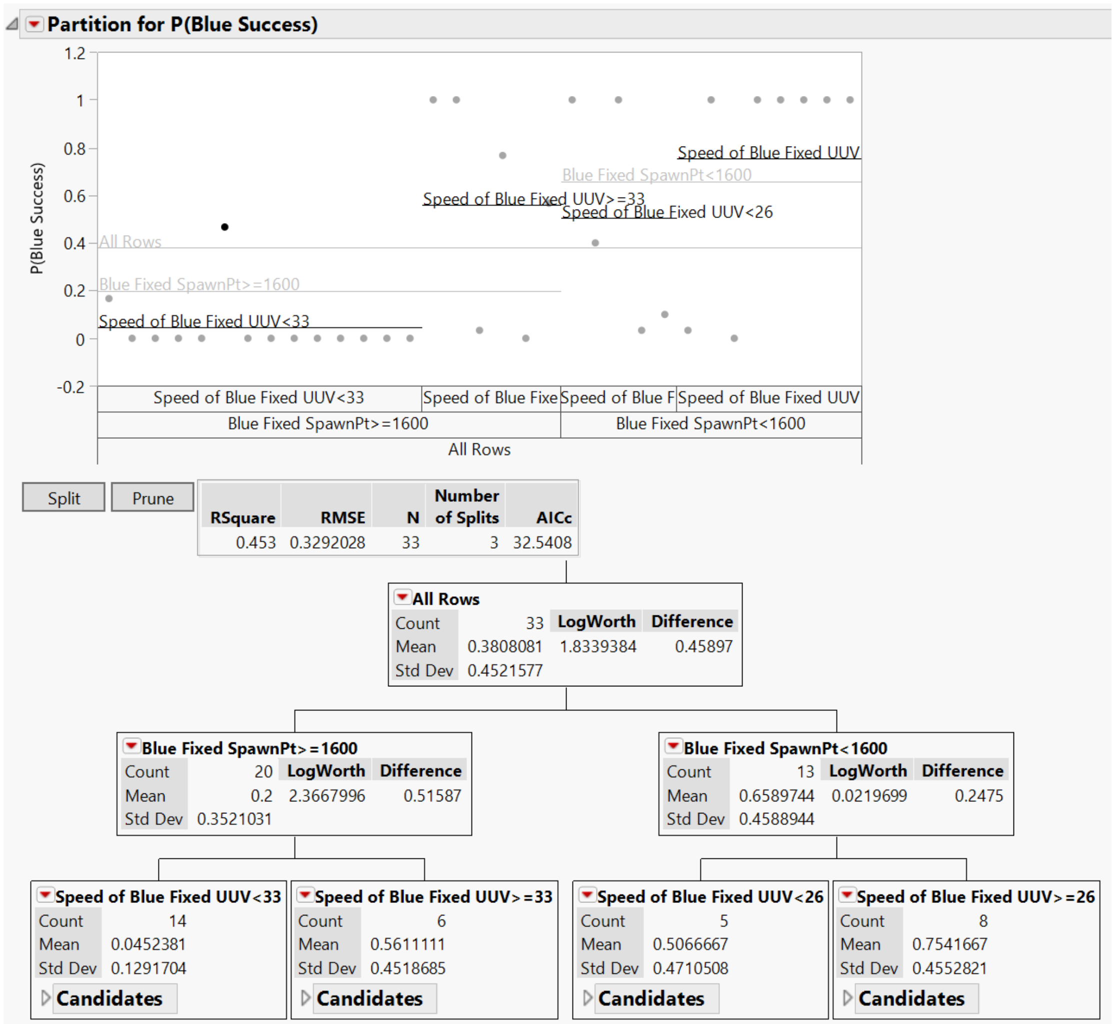


Figure 49 Partition Tree of Inter-UUV Spacing and Speed

Finally based on the regression results, combinations of variables that produce predicted success probabilities near 0.5 or 0.7 were generated. These points were generated randomly based on the predicted regression equation; that is using plots similar to Figure 2 but using 0.5 and 0.7 rather than 0.95. Multiple parameter values close to the boundary of these two limits were sampled and then the scenario was simulated in MANA. Based on the simulations, the models of 0.7 limit yielded results near probability of 1 while models of 0.5 limit yielded results near probability of 0. This suggests that the success probability might be closer to a piecewise constant function in relation to the input factors. The configuration of factors that predicts a probability of 0.7 or more in the linear regression actually achieves close to probability 1 in reality. While those predicting a probability of 0.5 or less in the linear regression actually achieves a success probability close to 0.

2. Patrolling Shooters

The second scenario only incorporates patrollers with no fixed shooters. Figure 50 illustrates the set up in MANA. The patrolling shooters do not get any sensor information from the sensor field and are dependent on their on-board sensors. A Red UUV is only detected by the patrolling shooters when it comes within range of the on-board sensor. The patrolling shooters main tactic is to transverse the area and conduct barrier searches. A patrolling shooter will detect and attempt to interdict any adversary UUV that crosses the patroller sensor footprint. The aim of the simulation is to determine the appropriate number of Patrolling shooters to defend the pipe.

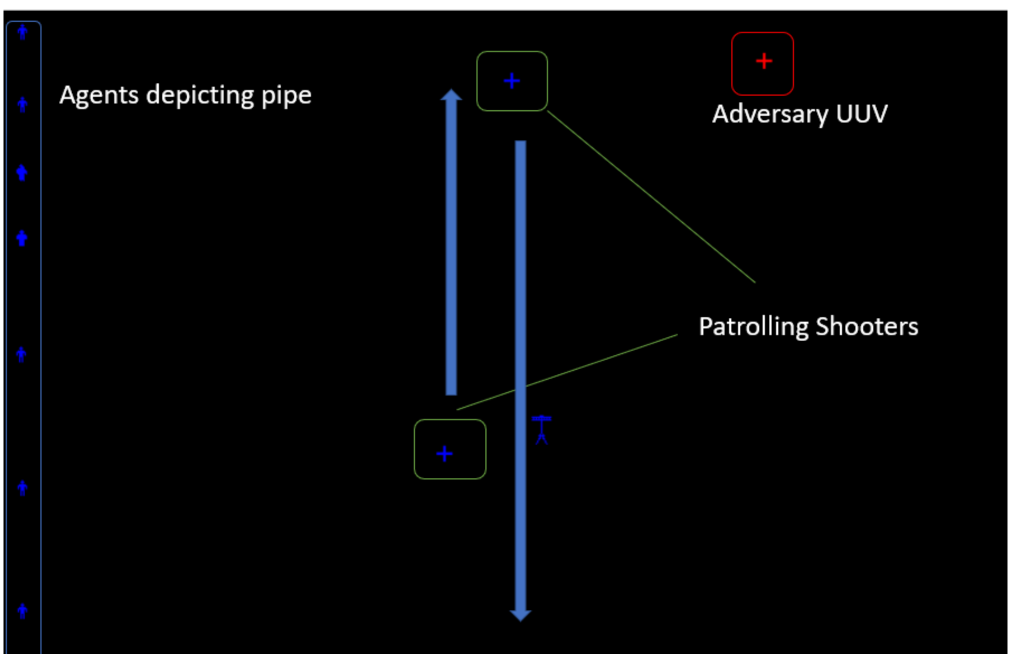


Figure 50 Patrolling Shooters MANA Simulation

Stepwise analysis was conducted to choose the variables for regression. The following parameters were included as design variables:

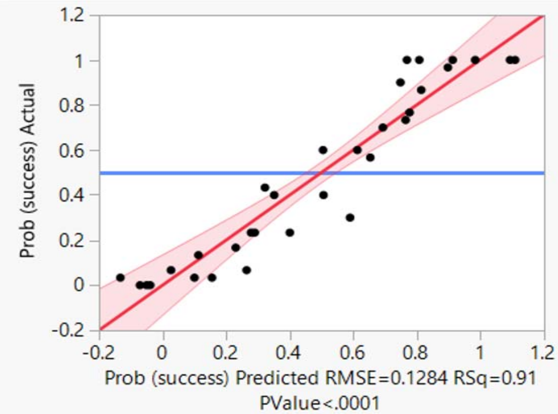
1. Speed of Red UUV
2. Red UUV sensor range
3. Number of Blue shooters
4. Speed of the shooters
5. Sensor range of shooters

Linear and quadratic terms were added for these inputs as well as their interaction terms. The selected model using Standard Least Squares and has an R squared value of 0.91. The variables in the final model appear in Table 17.

Table 17 Patrolling Shooters Least Square Regression

Y Variable (Measure of performance)	P(Blue Success): Probability of Blue successfully defending the pipe
Construct Model Effects	Speed of Red UUV Speed of Blue Patrol Shooters No. of Blue Patrol shooter Red UUV Sensor range Speed of Blue Patrol Shooters*Red UUV Sensor range No. of Blue Patrol shooter*Red UUV Sensor range Blue Patrol Shooter Sensor range

Figure 51 summarizes the main effects of the fitted model. The speeds of both Red and Blue have the most statistically significant impact on the success probability. The success rate is also affected to a smaller extent by the number of Blue patrolling shooters and Red's detection range.



Effect Summary

Source	LogWorth		PValue
Speed of Red UUV	11.107		0.00000
Speed of Blue Patrol Shooters	8.098		0.00000
No. of Blue Patrol shooter	3.803		0.00016
Red UUV Sensor range	3.544		0.00029
Speed of Blue Patrol Shooters*Red UUV Sensor range	1.596		0.02533
No. of Blue Patrol shooter*Red UUV Sensor range	1.167		0.06802
Blue Patrol Shooter Sensor range	1.037		0.09173

Figure 51 Predicted Plot and Effects Summary for Patrolling Shooters

Figure 52 shows the prediction profiler where the impact of success probability against one variable at a time was evaluated. The main take away is that the speed of Red or Blue is also operationally very important. The faster the speed of Red, the lower the probability of Blue success. The speed of Red UUVs would have to be mitigated by a combination of both higher speed and quantity of Blue patrollers.

This is further illustrated by Figure 53, which presents the trade-off between the speed of the Blue patrollers versus the number of Blue patrollers. The plot displays the combination required to generate a 0.95 success probability with detection ranges and Red UUV speed remaining constant as shown. With the speed of Red UUV fixed at 15 km/h, only 1 Blue UUV is required when the Blue UUV's speed is 40km/h. On that other extreme, 40 UUVs are required when the speed of the UUV is only 25 km/h. Depending on the technological cost of having a UUV with faster speed, versus simply many slower UUVs, a decision can be made on the optimum mix between speed and quantity.

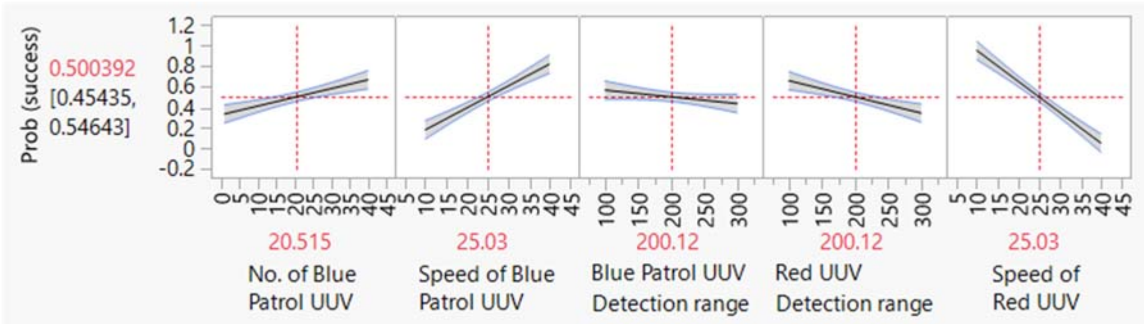


Figure 52 Prediction Profiler for Patrolling Shooters.

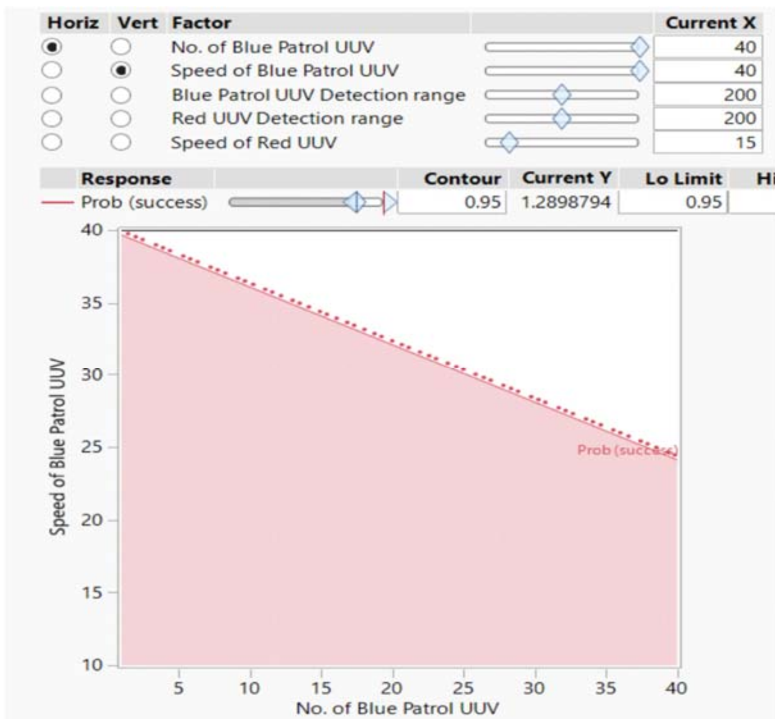


Figure 53 Speed Versus Number of Blue Patrollers

3. Fixed and Patrolling Shooters

The final scenario included both fixed and patrolling shooters. To study the combined contribution of fixed and patrolling shooters in greater detail, the range of parameter values for both are selected from design points that produce a 0.50 and below success probability in the respective scenario above. The main objective was to determine if two relatively poorly performing defensive approaches could combine to enhance the overall effectiveness. The range of values defined for this scenario is shown in Table 18.

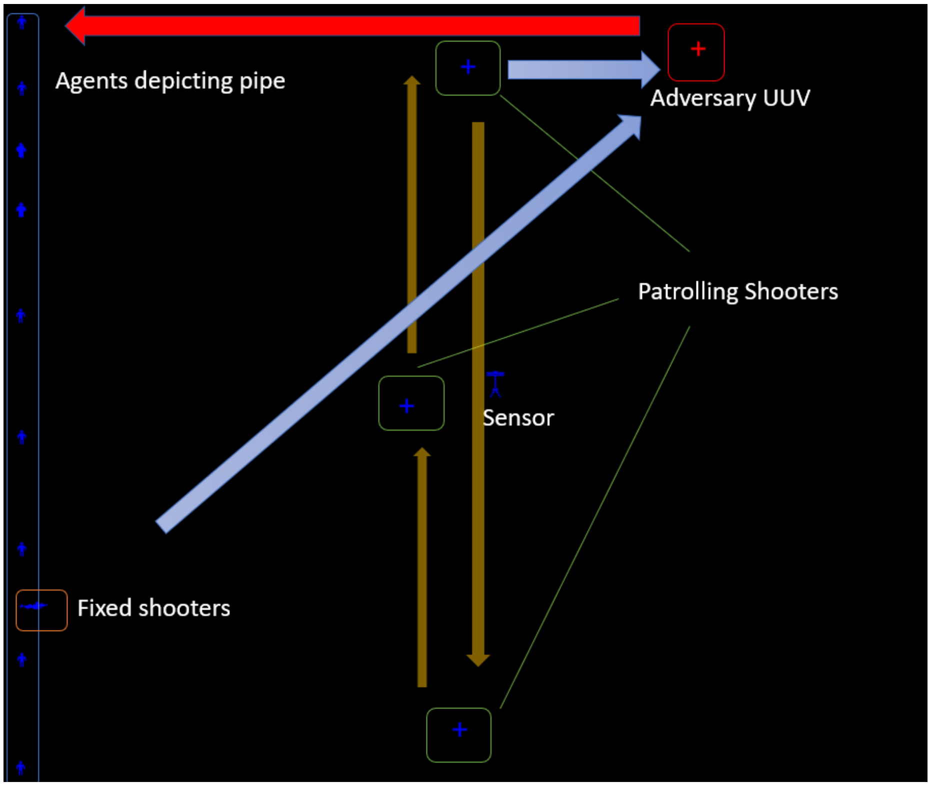


Figure 54 Fixed Shooters and Patrolling Shooters

To better isolate and extricate the effect in using combination of fixed shooters and patrollers, less variables are chosen to vary in this scenario. The speed of the Red UUV was fixed at 20 km/h and the Red Detection Point was fixed at 3500 m.

Table 18   Simulation 3 Variables

Agent	Description	Units	Min	Max
Fixed Shooter	Inter-UUV spacing (Blue Fixed SpawnPt)	meter	2000	4000
	Speed	km/h	11	21
Patrolling shooters	Number of UUVs	-	15	25
	Speed	km/h	14	24
Red UUV	Sensor Range	meter	100	300

The results did not reveal synergies and improved overall performance; the best result still only generated a success probability of around 0.5. In general, the results of the combined system closely resembled that of the patrollers only scenario. This suggests that the success probability in this combined scenario is mainly attributable to the patrolling shooters. Recall from the earlier discussion of the fixed-shooter-only scenario: design points that generated a predicted probability of 0.5, were often closer to 0 in reality. Therefore, the parameter combinations that were considered in the combined scenario produce fixed shooter defenses that are nearly worthless.

In Figure 55 and Figure 56, the black lines indicated the parameters which had a predicted probability of success of 0.5 from the fitted model in the simulation with just patrolling shooters. This sits closely near to the magenta division, which indicated the region where the probability of success was less than 0.5 for the combined scenario.

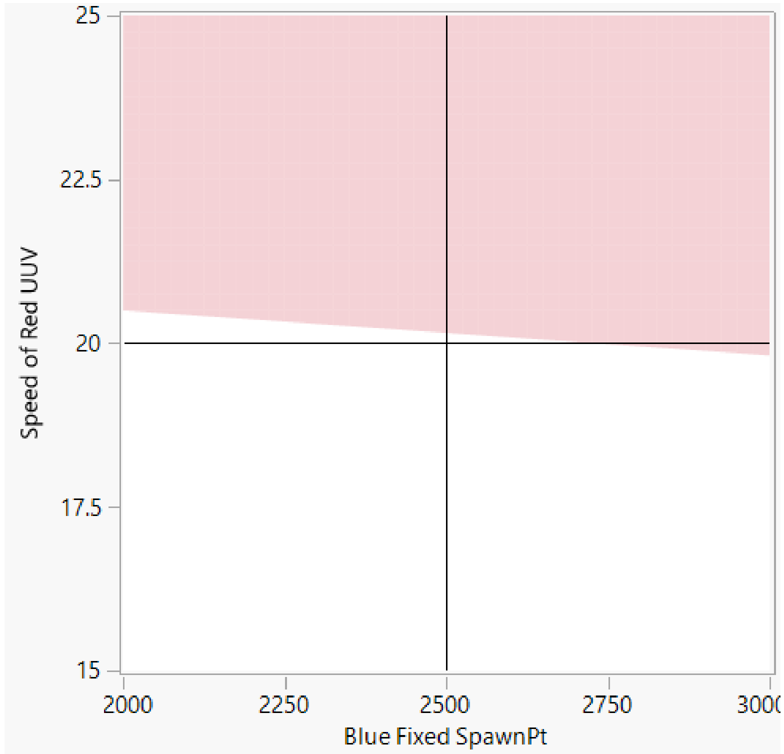


Figure 55 Speed of Red UUV vs Blue Spawn Point

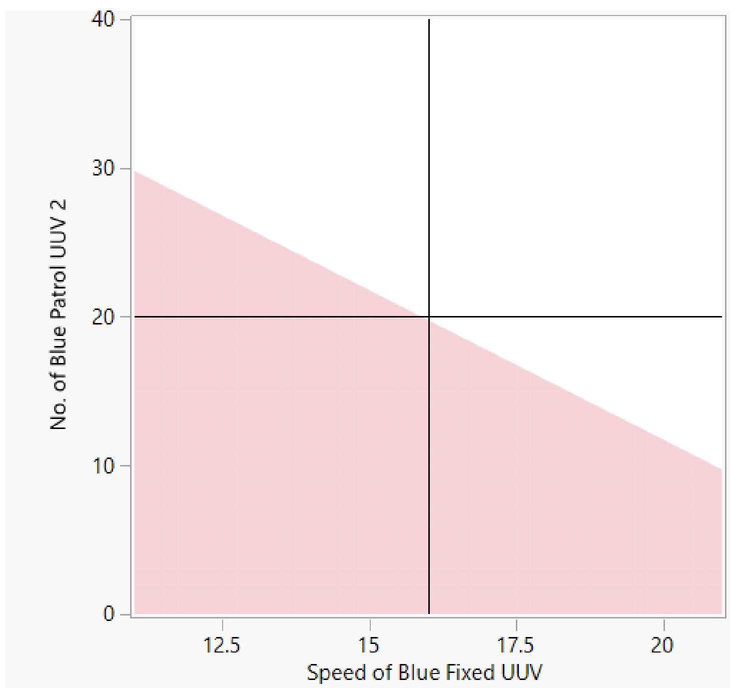


Figure 56 Number of Blue Patrollers vs Speed of Fixed UUVs

4. Conclusion

The results from Natuna model 2's three simulations provided insights for the composition of a defense system along the Natuna gas pipeline. The first simulation modeled the use of only fixed shooters only, the second modeled the use of patrolling shooters only, while the third simulation modeled the use of both types of shooters.

Based on the overall results from the three simulation scenarios, it is not recommended to deploy a combination of fixed shooters and patrolling shooters. This follows from the binary nature of the fixed shooters. If the fixed shooters are capable enough to defend, then the fixed shooters alone would effectively defend most Red attacks and adding patrolling shooters would provide little benefit. On the other hand, if the fixed shooters are not capable, the fixed shooters would fail against most Red attacks; in this case it would be more cost effective to just deploy patrollers. Instead, the two assets could be thought of as two separate layers of defense. The patrolling shooters could deploy much further out beyond the wired-guided fixed shooter defense range, so that the patrollers perform a separate role of early elimination of threats. The fixed shooter can only engage targets close to the pods near the pipe due to its guide wire length limitation.

The speed differential between Blue and Red is the crucial parameter for both the fixed shooter and patroller scenarios. Knowledge of the speeds can provide insight into other parameter requirement, such as the spacing in the fixed shooter scenario. For example, assuming that the adversary could be detected 3.5km away from the pipe and had a speed of 20 km/h, and the fixed shooter had a speed of 26 km/h, an inter-spacing of 3.2km is required between each fixed shooter.

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V. UNDERSEA INFRASTRUCTURE DEFENSE: GULF OF MEXICO

A. INTRODUCTION

As discussed in Chapter III, two distinct analyses of undersea infrastructure defense in the Gulf of Mexico were conducted. Each analysis utilized an agent-based simulation program called Map Aware Non-Uniform Automata (MANA). The first analysis (Gulf One) focused on an in-depth examination of micro level considerations for the deployment of an undersea sensing array with supporting UUV systems. The second analysis (Gulf Two) focused on a macro level examination of a multi domain undersea infrastructure defense system.

B. GULF ONE—MICROSCALE EXAMINATION OF SENSOR ARRAYS AND UUVS

1. Micro Scale Scenarios

The Gulf of Mexico contains an abundant amount of critical natural resources that are extracted by an elaborate network of infrastructure consisting mainly of oil / gas pipelines and oil rigs. Multiple courses of action are plausible in which a given threat could potentially attack the infrastructure via subsurface, surface, or air.

The scenario we focus on, based on its potential destructiveness, feasibility and likelihood, is an enemy launch of a threat Red UUV from a commercial container ship. The commercial container ship, which can carry thousands of cargo containers, would have a route charted for a country other than the United States. The ship would stay outside the U.S. Economic Exclusion Zone in international waters (to achieve maximum covertness) and deploy pre-programmed Red UUVs with target coordinates being oil platforms in the Gulf of Mexico. Figure 57 represents the enemies COA.

Figure 57 Enemy Course of Action in the Gulf of Mexico

Phase I shows the container ship en-route to a drop zone. Phase II shows the ship reaching the drop zone followed by phase III.a where the UUVs are deployed from a container and move toward the target zone. Finally phase III.b shows the ship en-route to a port to offload its commercial cargo with no one suspicious that the cargo ship had just deployed Red UUVs.

Figure 58 displays a multi layered defense network that could potentially combat against this specific threat.

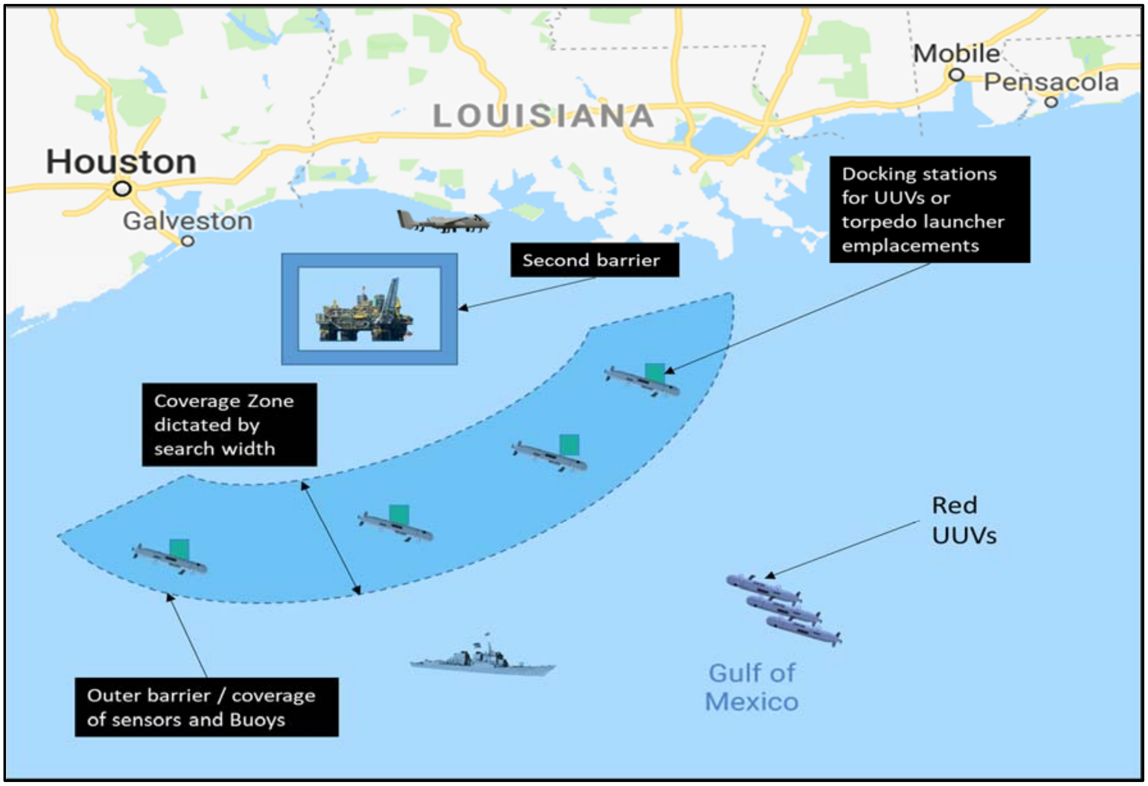


Figure 58 Conceptualized Defensive Network

While the enemy mother ship carrying Red UUVs could be intercepted in international waters before launch (this is explored in the Macroscale examination later in this chapter), this scenario assumes the enemy has launched the Red UUVs and the UUVs are approaching the defense network. While Coast Guard, Navy ships, and aircraft may be in the area to provide detection and interdiction capabilities, an electric UUV moving very slowly would be extremely hard to detect from a surface or air-based platform. Consequently, we do not consider surface or air assets in this specific scenario. An underwater sensor detection grid with a deployable munition (Blue UUV) provides a higher degree of protection against an underwater covert attack by Red UUVs. Figure 58 shows an area of coverage where a sensor field is monitoring a swath of the ocean in the general area containing undersea infrastructure, with additional sensors deployed around specific oil platforms. The outer barrier and second barrier around the oil rig represent multiple layers of sensors which may or may not be stationed in this manner. With that said, this scenario will be modeled by Blue forces consisting of a defensive sensor network that can deploy Blue UUVs from UUV docking stations or "pods" that will intercept and counter the Red UUVs.

2. Scope

This model represents a very small portion of the Gulf of Mexico and is intended to represent a single enemy Red UUV against a defensive system defending a single oil platform as shown in Figure 59. The oil platform is in the top of Figure 59 and Red approaches from the bottom. Red must traverse through a sensor field, represented by + signs in Figure 59. If a sensor detects Red, then interdiction UUVs are deployed from the pod slightly north of the field to intercept and destroy the Red threat. The oil field network in the Gulf of Mexico extends hundreds of kilometers long, with varying distances from the U.S. coastline. This model will only examine a 20-kilometer swath of the Gulf of Mexico with a single Red UUVs inbound to a single oil platform defended by a defensive network.

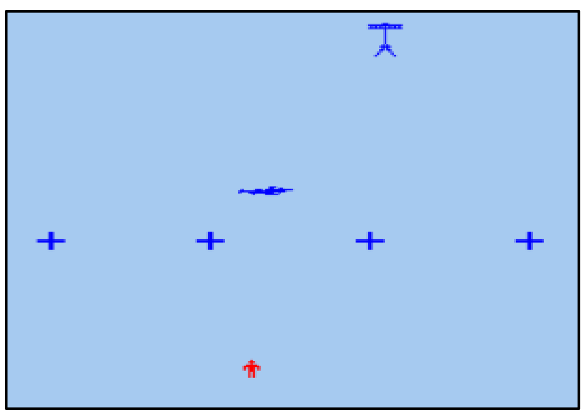


Figure 59 Scope of Scenario

The technology to detect, track, engage, and kill a Red UUV is available today and will be more advanced in the 2030 timeframe. The modeled defensive network was conceived based on how these current technologies work today. For detection technology, acoustic sensors are primarily used. There are many different types of acoustic sensors and ways to deploy them. For instance, we know that an underwater sensor can listen / detect noise in a spherical manner depending on placement in the ocean. For example if the sensor is placed on the ocean bottom it will get a half sphere of detection, but if the sensor is tethered and suspended in the water column it can establish a full sphere of detection. This report uses more general terms such as “sensor” instead of something specific like “passive hydrophone” to avoid presenting an unnecessarily limited defensive system.

Communication between sensors and the transmission of data to oil platforms, shore-based facility, and UUVs is an important part of an undersea defensive network. Such communication can be accomplished in a variety of ways such as underwater transmitters, cabled communications, tethered transmitting buoys, and wire guided UUVs. For this reason, the model is set up so that the sensors communicate the position of a Red UUV to Blue interdiction UUVs. Underwater detection by UUVs is also possible today, and thus the Blue UUVs are given a short-range organic detection sensor for localization of the Red UUV. Destruction of the Red UUV can only be achieved by the Blue UUV, and for modeling purposes, we view the Blue UUV functioning like a torpedo in which it has to close within a certain distance of the Red UUV to achieve destruction. If the Blue UUV ever loses track of the Red UUV (e.g., because the Red UUV left the sensor field), the Blue UUV will terminate its pursuit.

The paragraphs above show how we have scoped this problem and how it is possible to model the system and implement a simulation in an environment such as MANA. The model includes a stationary underwater sensor field with Blue UUVs as the defensive munition protecting an oil rig from and inbound Red UUV. The objective of this model is to determine the probability of kill for one Red UUV against a defensive system protecting an oil platform. This model is built on four principal agents: the Red UUV, Blue UUV, Blue sensor, and the Blue platform. The characteristics of these agents will be varied to determine which type of defensive setup is necessary in defending the platform.

3. Assumptions

Based on UUV and Sensor characteristics previously discussed, certain assumptions and conclusions are made to build a realistic MANA model.

- Red UUV is fire and forget (a one-time use weapon not intended to survive or return)

- Red UUV is modeled at 10kph (5.4kt)

- Red UUV knows the location of the Oil platform

- One platform will be protected by a 20km linear barrier of sensors

- Each sensor has a maximum detection radius of 1000m

- Each sensor has the same Gaussian detection characteristics where the sensor has a probability of detection of 0.5 at 500m.

4. MANA Implementation Details

This section provides information about the simulation implementation in MANA. It primarily defines the key variables examined.

a. Initial setup

To build this scenario in MANA, every aspect of every agent is explored. Figure 60 is one defensive representation in which a 20-kilometer swath of water has 40 sensors equally spaced 1000 meters apart in two rows and three Blue stationary UUV pods are equally spaced. The UUV hold Blue UUVs that launch when the Red UUV is detected by the sensor network. We randomly generate the initial position of the Blue platform and Red UUV on either side of the sensor field.

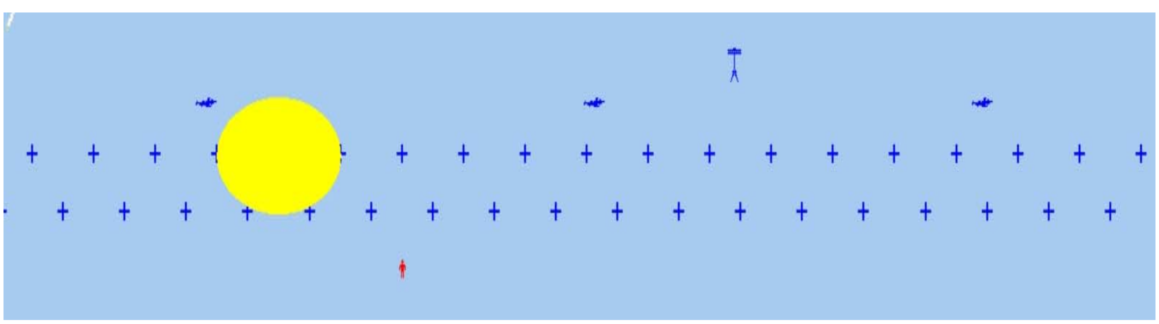


Figure 60 MANA Implementation of Scenario

Several parameters are varied in our analysis to determine their impact on the success probability. These include the number of UUV Pods, spacing of sensors, characteristics of the Blue UUV (such as speed), and number of rows of sensors. Exploring these model parameters allows for the determination of a base case that can yield valuable results.

b. Sensor Field

A sensor's detection capabilities with respect to distances are normally distributed and have a probability of detection of 0.5 at 500 meters. At zero meters from the sensor the probability of detection is one, and the detection probability drops off the further a target is from the sensor according to Figure 61.

Sensor Ranges (metres)

Detect	Range, R	0	100	200	300	400	500	600	700	800	900	1000
	Avg Time Between Detections (r<=R) (seconds)	0.999	0.887	0.841	0.748	0.631	0.5	0.369	0.252	0.159	0.091	0.048
Classify	Range, R	0	100	200	300	400	500	600	700	800	900	1000
	Prob/Turn (r<=R)	0.999	0.887	0.841	0.748	0.631	0.5	0.369	0.252	0.159	0.091	0.048

Figure 61 MANA Sensor Characteristics

The yellow circle in Figure 60 represents the sensor coverage of one sensor. The radius of the yellow circle is 1000 meters (which is double the 0.5 detection probability radius). This sensor field is constructed so that the distance between sensors is 1000 meters and there is significant overlap in the sensor footprints.

The sensor overlap increases the overall detection probability of a threat at every range. For example, if the threat is 400 meters from Sensor A, sensor A will detect with probability of 0.631. However, if the threat is also 600 meters away from adjacent Sensor B, then the overall detection probability is 0.767 = 1-(1-0.631) *(1-0.369). We next explore the importance of this overlap.

Assume the two circles in Figure 62 represent two sensors. As the circles move away from each other, the overlap degrades, and the combined sensor advantage is reduced. Of course more overlap requires more sensors and more cost.

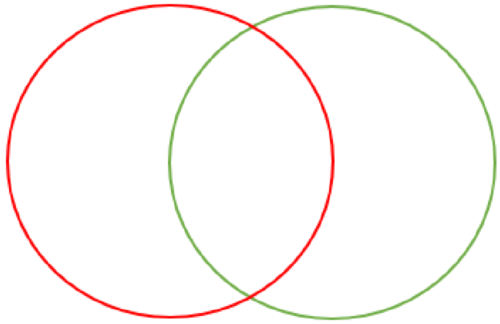


Figure 62 Significant Overlapping Sensors

Though the probability of detection is increased by having overlapping sensors, detection and interception of a Red UUV is more likely to occur if the Red UUV spends more time in the sensor network. We assume the sensors have an independent detection opportunity every second. Even a cookie cutter sensor with only 0.25 detection probability would detect a threat with 0.95 probability after 11 seconds in the sensor footprint $(1-(1-0.25)^{11})$.

Without significant overlap, there will be quasi gaps where a threat could traverse between two sensors and spend little to no time in the sensor field. Figure 63 illustrates an extreme example where two sensors are spaced so the footprints barely touch. If a threat traversed right between the two sensors, it would be nearly impossible to detect it.

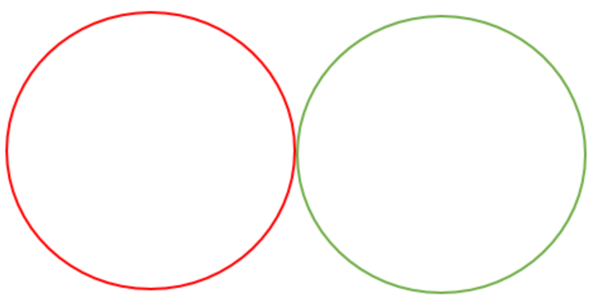


Figure 63 Non-Overlapping Sensors

Having overlapping sensors significantly increases the probability of detection and interception due to the amount of time a Red UUV spends in the sensor field or network.

In a two-row sensor network of overlapping sensors, the effective configuration to counter a threat approaching from any direction could look like Figure 64.

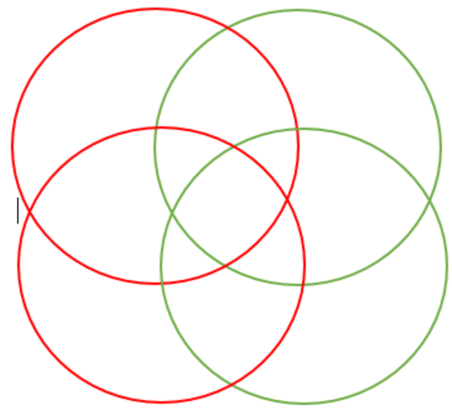


Figure 64 Two Rows of Overlapping Sensors

In our case we know a threat would approach from south to north, and thus we only need to overlap east to west as shown Figure 65.

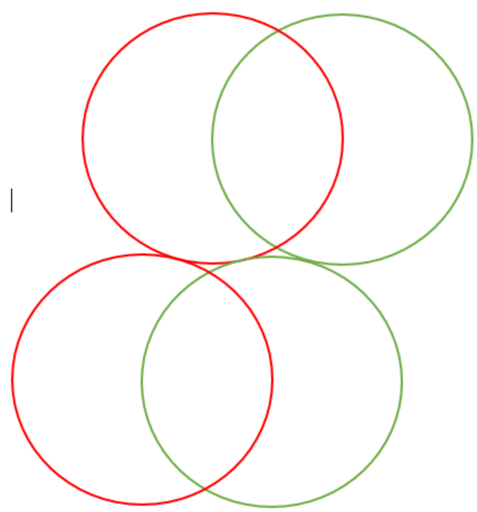


Figure 65 Two Row Staggered Sensors

Overlapping sensors not only provide enhanced detection capabilities, they also transmit tracking information to the interdiction UUV for a longer period of time. In Figure 62, a Red UUV would have to traverse over 1700 m in a one row field based on sufficient overlap. This number comes from the intersection of two circles. A Red UUV capable of traveling at 9.2 kph (5kt), traverses 1700 m in slightly more than 11 minutes. The interdiction UUV must arrive to the Red UUV within this time, or else the system will lose track or the Red UUV. With two rows of overlapping sensors as in Figure 65, the interdiction UUV has over 22 minutes to respond. In the implementation when there are two sensor rows, we allow the overlap to vary between the situation illustrated in Figure 64 (which corresponds to a total sensor field width of 3000m) and the situation illustrated in Figure 65 (which corresponds to a total sensor field width of 4000m).

The MANA models created for this scenario only consider one or two rows of sensors. We found that having more than two rows of sensors did not provide much additional benefit; improving interdiction speed and sensor characteristics made a greater difference. More details appear in the analysis section.

c. Number of Blue UUVs

We next turn to the remaining parameters we vary in the model. The number of Blue UUV pods varied from three to six in the analysis. We chose a minimum of three because the preliminary analysis using only one or two pods produced a success probability of less than 0.5. Using three pods the probability increased to 0.8. Even though a 0.8 success probability is lower than most commanders would want, other factors such as Blue UUV speed, weapons range, and communications latency can push the success probability even higher. The number of UUVs in each pod varies from 1 to 6. When the sensor field detects a threat and communicates that back to the pod, all UUVs in the pod are deployed to hunt for the threat. The number of UUVs per pod has a negligible impact on the results for this model because there is only one threat. However, it is important to consider systems that include multiple UUVs per pod to counter more sophisticated attacks such as swarms. One such swarm scenario appears in Chapter Five.

d. Starting point of Red UUV and Blue platform

The model assumes the Red UUV has been launched and is traveling toward the platform. Since the location of oil rigs are known in the Gulf of Mexico the Red UUV already has the coordinates and is using onboard navigation to arrive at those coordinates.

The initial point (called spawn point) where the Red UUV enters the area of interest near the sensor field is uniformly generated. Similarly, the spawn point for the oil platform is uniformly generated on the opposite side near the pods. The randomness of the spawn points adds to the realism of the model because in practice the angle of approach will be unknown. Given the attack is covert in nature, we assume the Red UUV will move slowly and as quietly as possible directly from its launch point towards the oil platform with no type of deception or sprinting.

e. Interaction between sensor field and Blue UUVs

The Red UUV enters the defensive sensor network at the start of scenario and the Blue UUVs are not deployed until the sensor field detects the threat and communicates the information back to the Blue UUVs. Figure 66 demonstrates which Blue sensors interact with which Blue UUV.

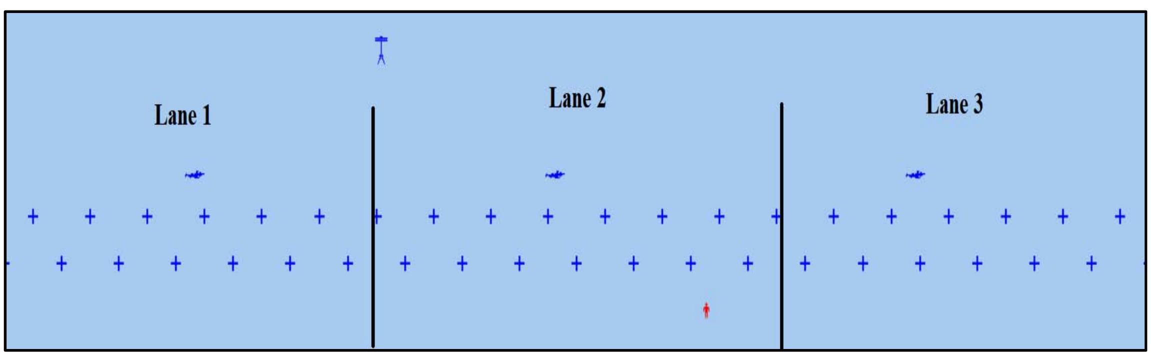


Figure 66 UUV and Sensor Communication

In each MANA model, the Blue sensors communicate with the Blue UUVs to transmit the Red UUV's location as shown in Figure 66. Each UUV only communicates with sensors in its designed area because that is where interception is possible. The interception UUVs in lane 1 could not possibly intercept a Red UUV in lane 3 before the Red UUV finishes traversing the sensor field. Recall that interception must occur in (or very close to) the sensor field. Once the threat leaves the sensor field, it will be very difficult for a Blue UUV to detect the Red UUV again with its own organic sensors.

Communication between the sensor field and Blue UUVs is not perfect. We define a communications reliability percentage in the model that tracks the probability each message is successfully transmitted. The communications reliability varies between 90 to 100 percent. Furthermore, there can be delays in the transmission of a message from the Blue sensor to the Blue UUV. This sensor latency was varied from zero to ten seconds

The vertical distance between the location of a Blue UUV pod and the sensor field is a parameter we also vary in the model. This distance ranges from 1 to 3 kilometers.

f. UUV Characteristics

The Blue and Red UUV characteristics were modeled based on the information provided in Chapter II. The remaining Blue UUV parameters are organic sensor range of a UUV, UUV organic sensor aperture angle, UUV speed, and weapons range. The UUVs speed varies from 10 to 25 kph. The Blue UUV sensor aperture is part of the organic sensor onboard the Blue UUV and is varied from 90 to 180 degrees; this was to analyze the effects of the UUVs' field of view while closing in on the Red UUV. The Blue UUV organic sensor range is varies from 50 to 200 meters. Finally, the warhead blast range of the Blue UUV varies from 3 to 10 meters. Figure 67 shows how characteristics in MANA are manipulated.

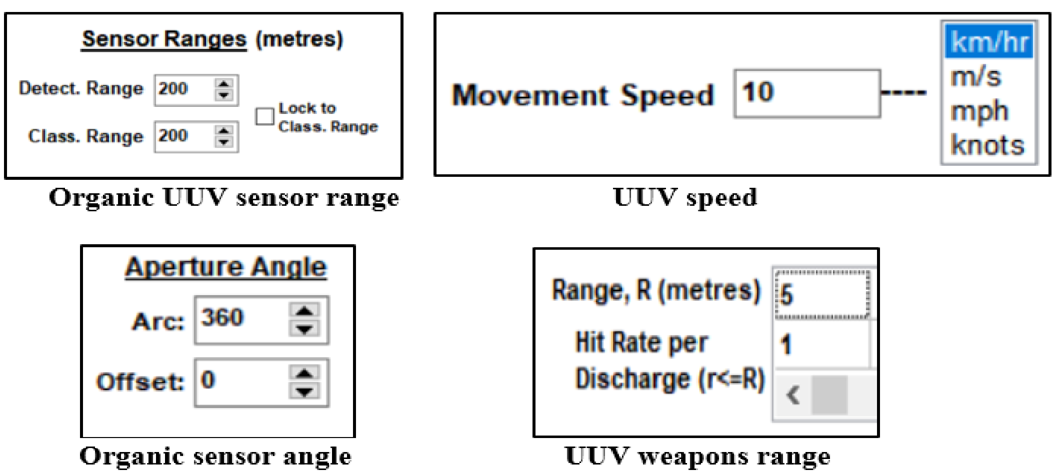


Figure 67 Varied UUV Characteristics

g. Summary

The parameters described in the last several subsections appear in Table 19.

5. Design of Experiments

A design of experiments approach was used to vary the parameters described in the previous section. A nearly orthogonal latin hypercube (NOLH) design was used, and a sample of the design points appear in in Table 19. Our measure of effectiveness is the probability of Blue mission success; that is will Blue be able to successfully kill Red before Red reaches the defended objective. The underlying assumption is that considerable damage will be inflicted on the defended objective once the Red UUV reaches it. The NOLH model generated 260 design points for exploration.

Table 19 Performance Effects Parameters

S/No.	Parameter	Mini value	Max value
1	Number of docking stations	3	6
2	Blue UUV Sensor Aperture (field of view in degrees)	90	180
3	Blue UUV Sensor range (meters)	50	200
4	Number of Blue UUVs per docking station	1	6
5	Blue UUV speed (km/hour)	10	25
6	Number of sensor layers	1	2
7	Communications reliability (%)	90	100
8	Sensor latency (sec)	0	10
9	Distance of docking station from sensor layer (km)	1	3
10	Sensor layer width (km)	3	4
11	Warhead blast range (m)	2	10

42 of the 260 design points performed exceptionally well, producing Blue success in all simulation runs. The details of these 42 design points appear in Table 20.

The next section describes the analysis performed on the 260 data points from the design. This analysis generates insights on the influencing factors that lead to good performance of the system.

Table 20 Successful Design Points

# of Pods	Blue-UUV-Sensor-Apreture	Blue-UUV-Sensor-Range	Number-Of-Blue-UUVs-per-Pod	Blue-UUV-Speed	Blue-Sensor-COMMS-Reliability	Blue-Sensor-COMMS-latency	Blue-Pod_Range from-Sensor ©	Sensor Layer Separation	Blue-UUV-Blast-Radius	Sensor Layer
6	177	153	3	21	90	3	1156	3375	8	2
6	143	200	5	16	97	5	1844	3219	10	2
6	169	148	6	23	97	6	1187	3672	8	2
6	158	144	2	25	98	2	1719	3359	6	2
6	134	198	1	17	98	6	1625	3313	10	2
6	105	170	4	24	90	6	1031	3297	8	2
6	132	62	5	18	98	3	1281	3141	4	2
6	108	76	6	23	95	3	1969	3109	9	2
6	150	137	4	21	91	10	1000	3563	6	2
6	114	141	3	21	92	1	1062	3594	6	2
6	149	69	5	18	100	4	1469	3766	9	2
6	94	92	5	19	97	8	2094	3250	5	2
6	125	90	2	24	95	8	1875	3828	4	2
6	146	88	1	19	98	7	1125	3156	4	2
6	100	146	1	22	97	1	1312	3547	7	2
6	122	66	2	18	99	6	1531	3734	9	2
6	152	55	1	22	94	6	2219	3094	9	2
6	174	95	2	19	96	2	2187	3078	5	2
6	111	172	3	25	98	7	2781	3578	9	2
6	160	132	3	23	93	10	2906	3000	7	2
6	141	179	2	15	96	5	1344	3797	6	2
6	139	83	3	20	94	5	2625	3281	10	2
6	103	134	4	23	93	0	2562	3031	6	2
6	172	177	4	22	99	3	2750	3656	8	2
6	179	127	4	24	92	1	2250	3813	5	2
6	135	125	4	18	95	5	2000	3500	7	2
6	115	193	4	20	99	2	2594	3516	3	2
6	142	99	5	24	94	2	2062	3938	4	2
6	138	188	2	17	92	7	2719	3859	9	2
6	107	85	1	20	96	1	2406	3984	8	2
6	127	50	2	19	93	5	2156	3781	3	2
3	107	85	1	20	96	1	1031	3297	8	2
3	172	177	4	22	99	3	1687	3125	8	2
3	166	64	5	22	95	9	1094	3328	8	2
3	179	127	4	24	92	1	1375	3375	5	2
3	115	193	4	20	99	2	1969	3203	3	2
3	139	83	3	20	94	5	2437	3188	10	2
3	97	130	5	25	99	8	2219	3750	6	2
3	103	134	4	23	93	0	2937	3219	6	2
3	125	90	2	24	95	8	1344	3563	4	2
3	142	99	5	24	94	2	1125	3469	4	2
3	100	146	1	22	97	1	1906	3844	7	2

6. Results

We first examine the impact of the number of sensor layers. The sensors provide the initial detection of Red. However as discussed previously the sensor field plays another critical role: by constantly tracking Red and communicating Red's position to Blue UUVs, the sensor field provides Blue with the ability to effectively respond to the threat over a period of time. The more layers in the sensor field, the more time Blue has responds. The decision tree shown in Figure 68 illustrates the impact of one vs. two sensor layers. Over all 260 design points, the success probability is 0.46. When we consider the 130 design points with two layers of sensors, the success probability significantly improves to 0.78. Furthermore, the 42 design points shown in Table 20 that generate success in all simulation runs all had a configuration with 2-layers of sensors. The single layer design points perform poorly: the average success probability is 0.15. This leads to the conclusion that a single sensor layer in this concept of operations will not be effective. Therefore, the remaining analysis will focus on 2-layer sensor design point.

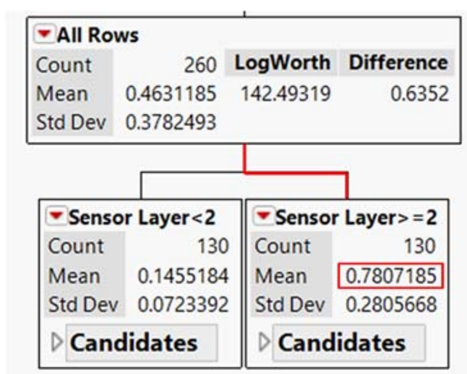


Figure 68 1st Sub-branch of the Decision Tree

a. Stepwise Regression Control and Least Mean Squares

The next step is to perform a stepwise linear regression analysis using the 11 independent variables Table 19 as input, except for the sensor layout. This produces a dataset with 130 points. We include main effects and two two-way interactions in our model. The dependent variable is the success probability. The significance level for the analysis is α = 0.05.

Figure 69 presents the coefficients ranked in order of statistical significant. It gives a plot of the LogWorth (defined as $-\log_{10}$(p-value)) values for the effects in the model. The LogWorth transformation adjusts p-values to provide an appropriate scale for graphing purposes. The vertical blue line in the bar chart represents the threshold for significance at the α =0.05. This figure shows that Blue UUV speed, number of pods (i.e., docking stations) and distance between the pods and the sensor field are statistically significant parameters.

Effect Summary

Source	LogWorth	PValue
Blue-UUV-Speed	64.755	0.00000
Blue-UUV-Speed*Blue-UUV-Speed	25.777	0.00000
# of Pods	11.916	0.00000
Blue-Pod_Range from-Sensor ©	11.273	0.00000
Blue-Pod_Range from-Sensor ©*Blue-Pod_Range from-Sensor ©	7.942	0.00000
Blue-UUV-Sensor-Range*Blue-UUV-Speed	7.523	0.00000
Blue-UUV-Sensor-Range	6.710	0.00000 ^
Blue-UUV-Speed*Blue-Pod_Range from-Sensor ©	5.216	0.00001
# of Pods*Blue-UUV-Speed	4.711	0.00002
Sensor Layer Separation*Blue-UUV-Blast-Radius	2.775	0.00168
Blue-UUV-Speed*Blue-Sensor-COMMS-Reliability	2.520	0.00302
# of Pods*Blue-Pod_Range from-Sensor ©	2.169	0.00678
Blue-Sensor-COMMS-Reliability	1.943	0.01141 ^
Sensor Layer Separation	1.464	0.03434 ^
Blue-UUV-Speed*Sensor Layer Separation	1.411	0.03882
# of Pods*Blue-UUV-Sensor-Range	1.407	0.03918
Blue-UUV-Blast-Radius	0.401	0.39701 ^

Figure 69 Summary of Significant Factors and Two-way Interactions on P(Success)

b. Main Effects Profiler

We next present a profiler plot, which illustrates how the success probability changes as we vary one parameter at a time; the remaining parameters are fixed at their mean values. The team observed that the Blue UUV speed and distance between Blue Pod and sensor field have an operationally significant impact on the results. Note these relationships have diminishing returns. The number of pods and UUV sensor range have a slight operational impact.

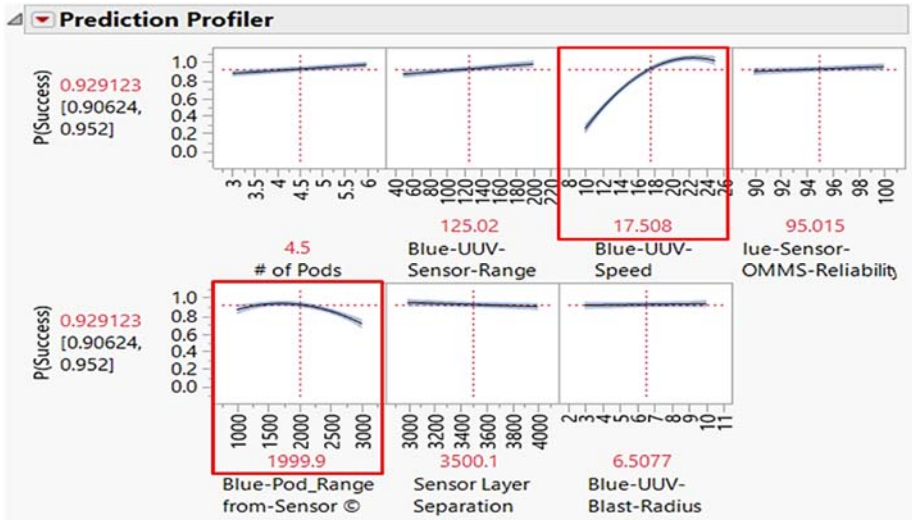


Figure 70 Main Effects Plot

<u>Effects from speed of Blue UUV</u>. The probability of success increases with the Blue UUV speed. With greater speed, the Blue UUV will have a higher chance of intercepting the Red UUV. However, it is important to note that relationship is increasing at a decreasing rate. This implies that at high values of UUV speed, the investment into UUV speed will not yield as significant an impact as the initial improvements. The insight here is that Blue needs sufficient speed to get into position in the sensor field to intercept Red before Red leaves the sensor field. Having additional speed beyond this level, does not provide additional benefit.

<u>Effects of distance of Blue Pods from Sensor field</u>. As the distance between the Blue UUV docking stations (pods) and the sensor field increases, the probability of success decreases. This longer distance translates to a longer travel time for Blue to reach the sensor field. If Blue does not reach the sensor field by the time Red leaves the field, Blue will have very little opportunity to reacquire Red with Blue's own organic sensors. The implication is the same as speed: the faster Blue can arrive to the sensor field in effective intercepting position, the better

<u>Effects of Number of Pods</u>: the more pods, the better Blue performs, although the relationship is small compared to the prior two variables. The number of pods has a similar impact as the distance from pods to sensor field. The more pods there are, the less pipeline

each pods is responsible for, and the easier it is for Blue UUVs to reach the pipeline before Red leaves the sensor field.

Effects of Blue UUV Sensor Range: as with the number of pods, Blue UUV sensor range has a small positive impact on success probability. UUV sensor range is important for two reasons. First, it allows Blue to potentially detect and localize the threat after the Red UUV has left the sensor field. Second, even if Red is still in the sensor field, Blue has a greater margin for error in where it needs to position itself when it arrives to sensor field to successfully intercept Red.

c. Decision Tree Analysis

Based on the importance of speed, distance between pod and sensor field, number of pods, and UUV sensor range, we create a decision tree to further examine their impact on mission success. Recall this analysis assumes two layers of sensors. Figure 71 further confirms the importance of Blue UUV speed. When the speed is less than 12 kph, the probability of mission success drops from 0.78 to 0.22. When speed is 17 kph or greater, the probability of success increases from 0.78 to 0.96 At the bottom of the tree, we see the other factors can make a nontrivial impact. At moderate speeds, having more pods and/or deceasing the range from the pods to the sensor field can make a significant impact. At very slow speeds a larger blast radius can increase the success probability by nearly 0.3. This highlights that decision makers should focus most of their efforts and resources into improving the UUV speed. After that they should take measures to reduce the distance from the pod to the sensor in the most cost-effective manner: either adding more pods, or placing the pods closer to the sensor field.

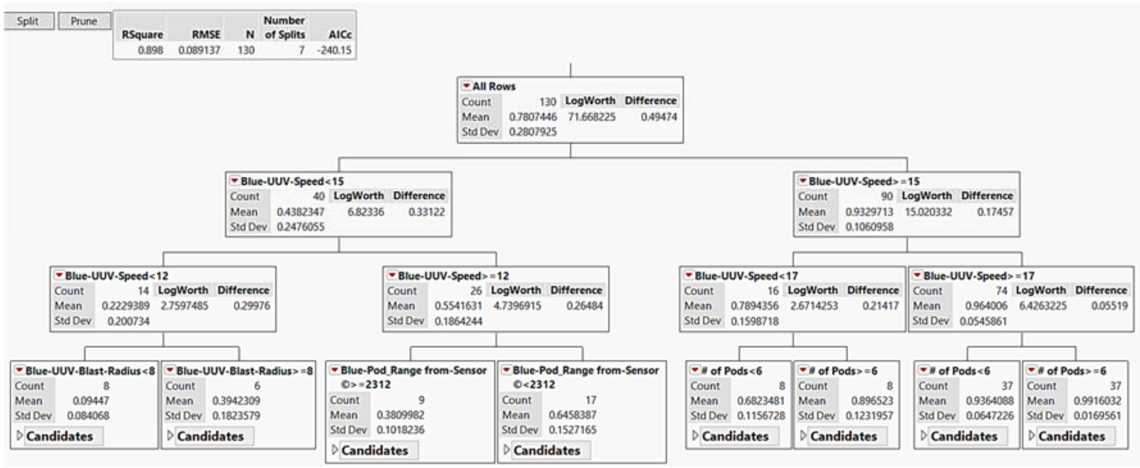


Figure 71 Decision Tree Analysis on Factors of Significance.

Clearly Blue UUV speed is the most important factor. However, our last analysis examines a tradeoff of speed vs. number of UUVs. In reality, it might be more realistic or cost effective to deploy more, slower UUVs than fewer, faster UUVs. The number of pods is proportional to the number of UUVs and hence is our proxy for number of UUVs. Figure 72 displays a contour profile based on predicted probability of success from the regression model. We fix all parameters except for Blue speed and number of Pods. We then examine the combination of those two parameters that produce a success probability of 0.99 (red envelope). The plot shows that an increase in the number of docking stations can reduce the Blue UUV speed requirements. A feasible design point exists even for the low-end scenario where only 1 docking station is modelled within the defended area. Hence, having a speed advantage can compensate for a reduction in dispersion of Blue UUV forces. The analysis is predicated on a 2-layer sensor field and a nominal Blue UUV speed of approximately 21kph. The plot also illustrates that even with a significant number of UUVs, there still is a relatively high floor on the speed required (over 17kph with 6 pods).

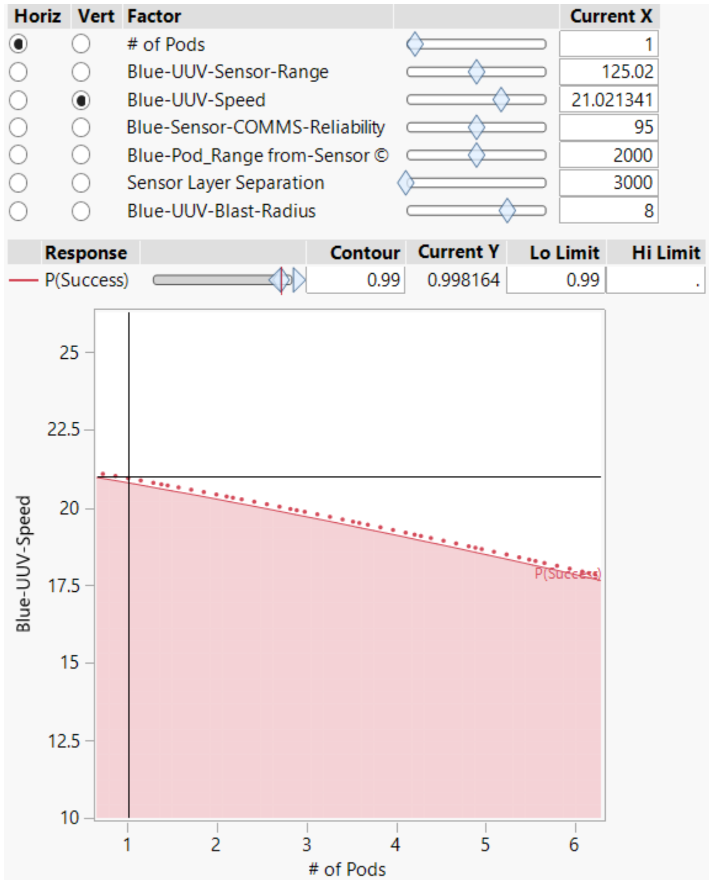


Figure 72 Contour Profile Plot for Blue UUV Speed and # of Pods

7. Conclusion and Recommendations

In conclusion, there is need for a dense effective sensor field that can detect, localize, and track the threat and guide the interceptor. It is also important for the interceptor be able to effectively navigate into position to destroy the threat. Speed is the most effective way for Blue to reach the sensor field quickly, although increasing the number of pods and positioning the pods closer to the sensor field also make a positive impact. We recommend At least 3 UUV pods be deployed in a 20km frontage to defend against a single Red UUV attack. Table 21 summarizes the recommendations.

Table 21 Summary of Recommendations

Factors	Observations	Recommendations
Blue UUV Speed	A speed advantage over adversary UUV is required for mission success.	A 2x speed advantage over Red UUV is recommended.
Sensor Layer	Given an assumed detection range of 1km, a minimum of 2 layers are required for mission success.	A 3km-wide sensor field comprising 2 parallel layers of sensors is recommended.
# of Pods	A minimum of 3 Pods (docking station) are required.	The recommendation is to increase the number of docking stations or capacity of pods for future expansion of infrastructure defense capability.
# of UUV	A minimum of 1 UUV per Pod is required to defend an area spanning 20km in length.	Requirements can be extrapolated to meet other Red CONOPS.
Sensor overlap	Increasing sensor overlap, increases the probability of success.	The recommendation is to achieve 100% overlap, i.e., adjacent sensor layers are placed apart at a distance equal to their maximum range.

C. MODEL 2: THEATER-WIDE DEFENSE IN DEPTH

1. Scenario

The layout of the region with an overview of the locations of pipelines and proposed defense barriers is shown in Figure 73.

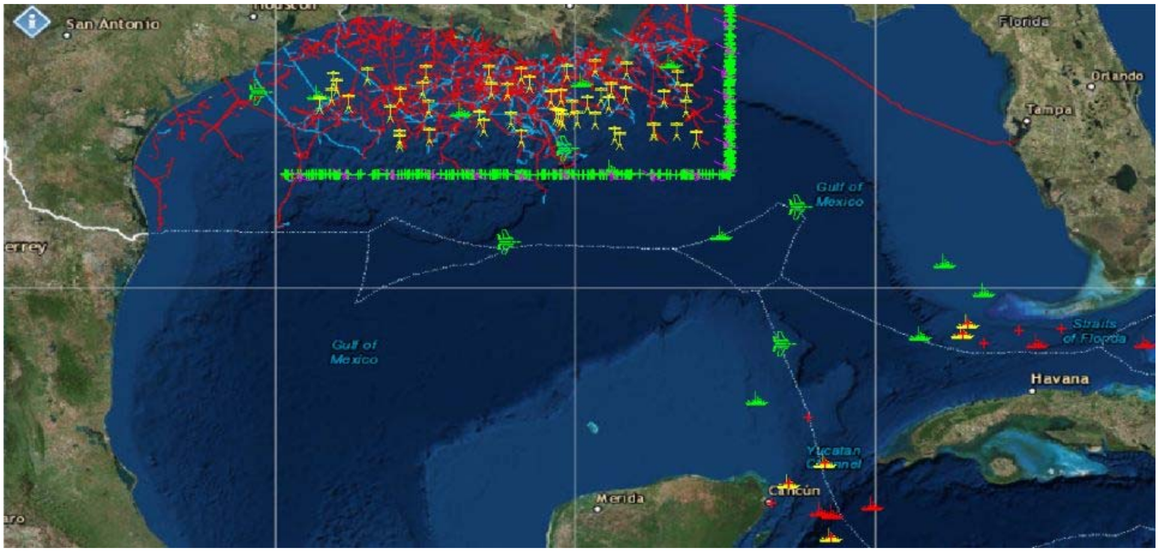


Figure 73 Gulf of Mexico Pipelines

While Model 1 examined the barrier defense concept to determine feasibility for defeating UUV attempting to enter a restricted area, Model 2 examines the problem from a theater wide view, focusing on a larger range of threats that might present themselves and incorporating variations of defense in depth to determine how they might be dealt with.

The lower fidelity nature of the individual unit interactions in a model of such large scale requires the analyst to look beyond the technical feasibility of some aspects of the model design. In certain cases, feasibility issues are examined and the rationale for using the model configuration chosen is explained in more detail. The intended effect is to allow the analyst and decision maker to look beyond the proverbial trees so as to try and get a sense of the forest. This will admittedly have an effect on the cost estimation and model analysis in later chapters, and so should be considered when discussing the level of accuracy of the model's results.

a. Defending Assets

The scenario model is based around the defense of 100 key infrastructure nodes within an area which encompasses the bulk of the Gulf of Mexico's underwater infrastructure. The decision to focus on key nodes rather than the full extent of infrastructure in the region is based on several points.

First, from a practical standpoint there is too much infrastructure to possibly fit in a single model, especially once the tens of thousands of miles of pipeline are added to the thousands of potential platform targets. Second, the alternative to focusing on a limited number of target nodes would be to count threat units that navigate successfully into the threat area as a successful attack; this is an imprecise measure of attack success as it fails to allow for the possibility that attackers would be defeated by point defense or area defense weapons operating within the threat area. Thirdly, based on analysis previously explored in chapters two, this model assumes that attacking forces would most likely focus on attacking high priority nodes which are more limited in number and would be uniquely damaging to the environment or economy. These nodes may or may not be known by the defender, and as such the defender may or may not be able to incorporate point defense at the nodes; both possibilities are included in the model.

b. Defending Assets: Overview

To defend these nodes, the model analyzes the use of different combinations of Blue platforms to defeat attacking enemy forces. This range of delivery platforms allows for examination of a broad spectrum of defensive approaches, varying from the singular method of point defense of critical nodes to more holistic approaches involving multiple layers of defense in depth.

Blue assets can be broken into three categories; point, barrier, and area defense. Point defense is defined as an attempt to protect a singular position from a threat. Barrier defense is an attempt to maintain some sort of security perimeter so as to ensure that any position inside the region of the barrier is protected to a larger degree than one outside it. Area defense shares with Barrier defense the same goal of improving the security of various positions within region, but is differentiated by the fact that it is not limited to activity within the confines of specified barriers.

c. Defending Assets: Weapons

The weapon of choice for engaging adversary forces underwater is an idealized Blue UUV, which is represented in the model in the form of a line-of-sight kinetic weapon fired from a range of platforms. This Blue UUV is theoretically similar to a torpedo, with a range upwards of 10km and is capable of both organic and inorganic target acquisition and guidance. The platforms capable of firing this weapon include underwater UUV docking stations arranged in either point defense or barrier defense schemes, as well as ships and aircraft which perform area defense patrols. Of note, the actual execution details of a UUV intercept against a threat would be different than the way this model presents it; Model 1 provides a more accurate assessment of how such an engagement might take place. From a theater wide perspective, this inconsistency can be overlooked as modeling a torpedo-like engagement at this large scale is impractical given the technical constraints of the modeling program, hence the use of the line-of-sight kinetic weapon.

The weapon of choice for engaging adversary forces on the surface is the Blue surface ship boarding team. The selection of the surface ship as the sole means of stopping enemy surface forces is based on several considerations. First, the model assumes that, given the amount of civilian traffic in the Gulf of Mexico, it is imperative that Blue forces are able to visually assess a surface contact as being a hostile contact. Second, the model assumes that all aircraft and underwater nodes (defended assets) are armed solely with Blue UUV so as to maximize their ability to counter enemy UUV threats operating in large numbers. Third, we have selected physical boarding of the threat ship as the means of stopping an enemy surface ship. This is based on a realization that the political risks associated with attacking a critical contact of interest with lethal force without having first proved outright hostile intent is too high. Of the units involved in the model, only Blue surface ships have the capacity to perform this role. They do so without the aid of helicopter based boarding teams since that is a specialized mission set that is not typically included on most surface vessels.

d. Defending Assets: Sensing and Targeting

In order to prosecute engagements, a variety of sensor equipment is utilized by Blue platforms. Surface ships were assigned surface sensing ranges out to 20km and subsurface sensing ranges out to 1km. Aircraft were assigned 100km surface sensing ranges and 100m subsurface ranges (this 100m subsurface range was required as a work around within MANA software because aircraft were otherwise unable to fire on subsurface contacts provided by other defending assets, a critical component of this model). The point defense underwater sensor had a subsurface detection range of 2km and the underwater docking stations had detection ranges varying from 500 to 1500m.

Of note, the model assumes that all sensors utilize a step-function approximation to the lateral range curve, also known as "cookie cutter" methodology to establish sensor range or "sweep width." This means that all areas within the sensor range have equal probability of detection, as opposed to a distribution-based methodology in which probability of detection would increase or decrease depending on exact distance to the sensor node. Using the "cookie cutter" methodology is commonplace in naval operations analysis.

Another major characteristic of the sensors is that the model assumes that all sensors have communication with the all other assets, and once a sensor detects a threat UUV it is able to send fire control quality targeting information to a Blue Force asset which can then deploy a weapon to neutralize the threat. The assumption made here is that once the Blue UUV has been launched, it will continue to attempt to interdict the target utilizing organic targeting systems even if the original detection platform has lost contact.

e. Enemy Threats

While there is a wide array of threats that could potentially exploit underwater oil and gas infrastructure in the Gulf of Mexico, they can be generally broken down into four categories, only three of which can be adequately modeled for the purposes of this project. The first threat is an underwater asset that is able to travel long distances under its own power and attack a singular position without coordinating with any other units. This has been termed the "Lone Wolf UUV" for the purposes of this model, but it serves to represent any type of underwater vehicle with a similar concept of operations. The second threat is a Deceptor Cargo Ship capable of carrying multiple UUVs within close proximity of its intended target before launching them. This enables the UUVs to bypass the majority of the barrier and area defenses that the Lone Wolf UUVs would have had to pass through. The third threat is a "Bomber Ship," which represents any surface vessel that might directly attack the underwater targets, either by dropping explosives on top of the target or by dropping or dragging an anchor to cause damage. The low number of Deceptor Cargo Ships and Bomber Ships incorporated in the model reflects the assumption that these attacks would be carried out by large and expensive cargo ships, for which the logistical costs of acquiring and operating more than a few would be prohibitive for most potential adversaries.

It is worth noting that hostile aircraft would be able to perform the second and third threat roles to varying degrees of success. The reasons that they were not included is several fold. First, the level of threat these aircraft would be able to present is generally lower because of the payload limitations associated with aircraft, especially considering the size and weight of the UUV or explosives that would most likely be required to accomplish these missions. Second, the existence of an Air Defense Identification Zone around the United States, and its ensuing air superiority capabilities, already provides some level of defense against such an attack. Finally, the effects of cargo or bomber aircraft can be presumed to correlate at least approximately with the effects of Deceptor Cargo Ships or Bomber Ships.

The fourth threat category is the insider threat. This could be anything ranging from a disgruntled employee with access to key control subsystems or weak points, cyber attackers who manipulate those targets remotely, or saboteurs who force entry to targets. In any case, data surrounding those activities is scarce and as such they cannot be adequately modeled in MANA with any degree of accuracy.

f. Enemy's Intended Outcome

The intended enemy outcome is the destruction of as many infrastructure nodes as possible. During each run, the number of nodes destroyed is tracked. By analyzing the casualty rates for infrastructure nodes against a wide combination of defenses and threats, the model may aid in the identification of trends that might provide valuable insights for future decision makers. Two primary models were developed—one which looks at the employment of various systems with a point defense concept in place and another without it.

2. Factor Selection and MANA Implementation

The combinations of defenses and threats vary according to a total of 14 factors that were varied between high and low extremes through a large number of trials. Of these 14 factors, 8 were attributed to Blue Forces and 6 to Enemy Forces. These factors will now be discussed in further detail, a full list is shown below in Table 22.

Table 22 Gulf Model 2 Scenario Factors

		Levels	
	FACTOR LIST	min	max
1	Weapon Pk	0.5	0.8
2	Number of Blue Ships	2	20
3	Number of Weapons per Ship	8	20
4	Number of P-8 Airborne	1	7
5	Number of Weapons per P-8	2	6
6	Range of Barrier Sensor (m)	500	1500
7	Number of UUVs per Docking Station (Barrier)	2	6
8	Number of UUVs per Docking Station (Point)	2	6
9	Speed of Threat UUV (kph)	4	20
10	Number of Threat Deceptor Cargo Ships	0 (1) *	5
11	Number of Threat UUVs per Deceptor Cargo Ship	1	5
12	Number of Lone Wolf UUV	1	30
13	Number of Threat Bomber Ships	1	5
14	Speed of Bomber Ship (kph)	10	37
*MANA Limitation, explained in Deceptor Cargo Ship Section Below			

a. Blue Weapon Pk

All the Blue assets incorporated in this scenario use Blue UUVs as the weapon to kill the Threat UUVs. The first factor was the Pk of Blue Force weapons. The Pk ranged from 0.5–0.8. Blue Weapon Pk for surface ships against enemy surface ships is set at 1.0, based on the assumption that once the boarding team has embarked the target they will successfully stop it.

b. Blue Surface Ship #s

The surface ships utilized are not class specific. Any ship capable of achieving a cruising speed of 40 kph that could be outfitted with sonar and a means to deploy Blue Force UUVs could be used. This includes Navy DDG, LCS, and the Coast Guard National Security Cutter (NSC). These ships are responsible for conducting area searches to detect threat UUVs, looking for suspicious surface vessels to board, and responding to detections made by other units. The surface ships are placed on random patrols in the Gulf of Mexico between Cuba and the pipelines targets, and are designed to look for surface and subsurface threats and to respond to threats identified by Blue sensor systems including air and subsurface sensors. Once a UUV threat is detected either organically or inorganically, ships can launch Blue UUVs to destroy the attacker. The number of ships used in the model ranged from a minimum of 2 ships to a maximum of 20.

c. Blue surface ship ammunition

Each of these ships carried 8–20 UUVs for intercepting enemy UUVs and unlimited ammunition for intercepting enemy surface vessels.

d. Blue Aircraft #

The P-8 Poseidon is the air asset of choice for our scenario because of its subsurface capabilities, on station time, cargo capacity, cruising speed, and general fleet availability. The P8s in the model are assigned to various patrol patterns from which they can break away to respond to enemy UUV threats detected by point and barrier defense sensors and Blue ships. When they are within range, they launch their Blue UUVs to attack the enemy UUV.

e. Blue Aircraft Ammunition #

The amount of ammunition available to each P8 ranged from 2 to 6 UUVs interceptors. They are not outfitted with any air to surface weapons and as such cannot target any enemy shipping. This is an acknowledged weak point of the model in that any theater commander anticipating a surface ship threat would very likely order the P8 or any other available assets to include air to surface weapons to its weapons payload. Even so, this model is designed to be optimized against underwater threats and the assumption moving forward is that intelligence about the surface threat doesn't exist in time for the P8 to change its payload.

f. Blue Underwater Sensors: Detection Range

The model examines the effectiveness of point defense and barrier defense sensors of varying ranges. The point defense sensors are assigned to each Blue target node and the barrier defenses are arranged in two lines of sensors. One ran from west to east for approximately 194 KM and a second south to north for a distance of 155 KM. For the purposes of our model, sensors are arranged along the barrier in a configuration that produces an effect similar to the barrier investigated in GM Model 1. The detection range of the individual defensive sensors varies between 500–1500 m as a variable for model analysis. These sensors provide initial targeting information for the Blue UUV that are housed by the UUV docking stations. Collectively, they are represented by the green lines in Figure 74.

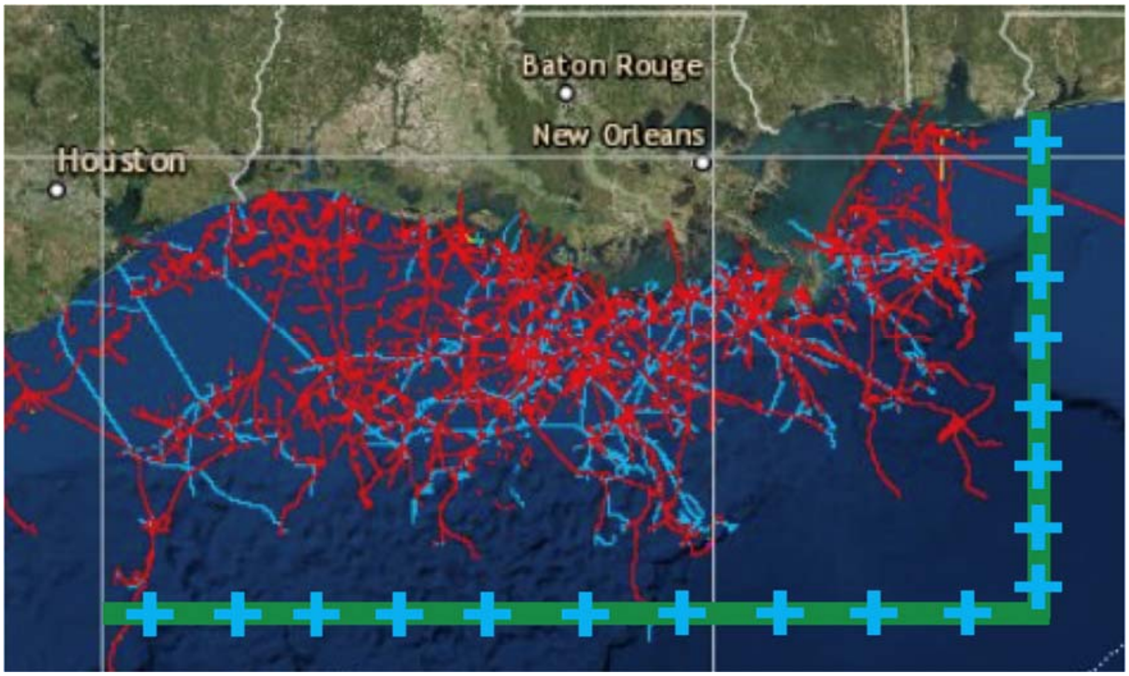


Figure 74 Gulf of Mexico Pipeline Sensor Fields and UUV Docking Stations

g. Blue Underwater Barrier Docking Station: Number of defensive UUV

In addition to the sensors, the barrier also has UUV docking stations which are placed every 20 km along the barrier. These are represented by the blue (+) symbols in Figure 70. Each docking station has between 2 and 6 Blue UUVs, each of which is able to intercept an incoming enemy UUV once a preliminary detection is made by one of sensors in the barrier. This interception is simulated by a kinetic weapon that fires at the target detected by a sensor with a probability of kill based on the previously described Weapon Pk. The UUV docking stations are programmed with a short delay in between each attempted intercept to ensure time for the Blue forces to evaluate the effectiveness of each salvo prior to firing a follow-on salvo.

h. Blue Underwater Point Defense Docking Station: Number of Defensive UUV

In the point defense, each node has a docking station that has between 2 and 6 Blue UUVs. This interception is simulated by a kinetic weapon that fires at the target detected by a sensor with a probability of kill based on the previously described Weapon Pk.

i. Enemy UUV Speed

The model treats each threat UUV as a MDUUV similar to the ones previously used by the Blue forces in NB Model 1. The first factor varied was their speed, which is the same for the Lone Wolf UUV as well as for those deployed by Deceptor Cargo Ships. This ranged from 4–20 kph.

j. Number of Lone Wolf UUV

The next factor was the number of Lone Wolf UUV, ranging from 1 to 30. Each threat UUV carries 3 small torpedoes and is capable of detonating itself against a target, meaning that each threat UUV is capable of killing four targets with a 100% probability of success per attack.

k. Number of Deceptor Cargo Ships

The number of Deceptor Cargo Ships secretly carrying threat UUVs ranged from 0 to 5. For the purposes of this model, there is no forewarning of their arrival and so they cannot be intercepted by Blue Surface Craft. This represents the fact that they are able to unload their UUV without suspiciously departing from the traffic lanes, as is described in Model 1. The key difference from Model 1 is that they do so after having already sailed past the sensor barrier.

l. Number of UUV Per Deceptor Cargo Ship

The number of threat UUVs secretly carried onboard each Deceptor Cargo Ship is varied from 0 to 5. Obviously this parameter is only relevant if there are a positive number of cargo ships. The total number of threat Deceptor UUVs across all cargo ships varies between 1 and 25. These UUVs have the same design specifications as the Lone Wolf UUV.

m. Number of Bomber Ships

The number of Bomber ships utilized varies from 1 to 5 Bomber Ships. In this scenario, they differ from the Deceptor Cargo Ships because Bomber Ships can be detected and boarded by Blue surface ships at any time. This is done to simulate the fact that certain flagged vessels may be designated as Contacts of Interest that must be boarded and inspected prior to passing within a certain distance of key infrastructure points, and others may be flagged as suspicious when they depart from commercial shipping lanes. Another key difference is that the Bomber Ships must sail directly over the infrastructure they are targeting, whereas the Deceptor Cargo Ships can deploy the UUVs from a less suspicious distance.

n. Speed of Bomber Ships

The speed of the Bomber Ships in the model ranges from 10 to 37 kph.

o. Additional Assumptions: Bomber Ship Weapon

The amount of ammunition carried onboard the Bomber Ships is unlimited, allowing the Bomber Ship to proceed from target to target indefinitely until stopped by a defending surface ship. This is done to highlight the fact that even crude attacks such as an anchor drop can be extremely effective if not physically prevented by defending forces, as well as to illustrate the fact that oftentimes critical infrastructure is closely spaced and a single or small group of attackers could do inordinate amounts of damage to those clusters of targets.

p. Additional Assumptions: UUV Fuel/Battery Life

In order to model UUV Fuel/Battery Life, the model is based on a stop time condition of approximately 24 hours. This stop time condition ensures that even if enemy UUV have evaded defending units, if they take too long to reach their intended targets they will still be counted as unsuccessful attacks. This stop condition holds true for both Lone Wolf UUV and UUV deployed from the Deceptor Cargo Ships.

3. Model

Data collected from this model came from two major model variations, the first of which was an initial look at how the model performed and the second of which was a refined version that was built with assistance from Ms. Mary McDonald of the Simulation Experiment and Efficient Designs (SEED) Center at the Naval Postgraduate School.

The initial iteration considered the defense of 50 infrastructure nodes, and was restricted by a limitation of MANA that did not allow any factor to be set to 0. This caused an issue for factors 10 and 11 in Table 22, as one of the desired outcomes was the exploration of how the defense responds to individual threats as well as to multiple threats. This was important as the Deceptor Cargo Ship was designed to bypass the barrier defenses entirely and so it was desirable to be able to analyze the model with and without its inclusion.

This desire notwithstanding, factor 10 and 11 were limited to a minimum of one in the first iteration of data collection, limiting analysis to model variations that included all three threat types. The design with the updated factors was determined using JMP's space filling Latin Hypercube function applied to the parameters listed in Table 22. This gave us 33 design points which were then fed into MANA. Each design point was played out 30 times for a total of 990 iterations in MANA. In order to examine the impact of point defense systems on the model, the first set of data was based on area and barrier defense and not point defense and therefore did not include factor 8. The second set of data included point defense and incorporated all 14 factors. This too was run 990 times.

In the second iteration, the model was adjusted to incorporate the minimums of factors 10 and 11 to the originally desired level of 0. Because of these changes, the number of design points was drastically increased, jumping from 33 to 128. We once again examined two different scenarios: one included point defense and one did not. The new design points were once again run 30 times apiece bringing the total to 3,840 iterations for both the point defense and non-point defense versions of the model. In all the second iteration of the model included 7,680 individual runs worth of data for follow on analysis.

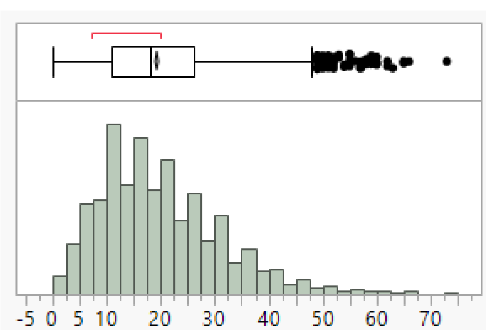
In the analysis section to follow, the two data sets will be either described as MANA data, meaning 990 runs were conducted per model variation, or SEED data, meaning 3840 runs were conducted per model variation.

D. ANALYSIS

The two measures of effectiveness considered in the analysis is the number of pipeline node casualties and the number of enemies killed. The goals of this analysis were to step through and attempt to answer several questions that might be useful to a defense planner. This was accomplished via statistical analysis with Excel tables and with the JMP statistical package.

Due to the major emphasis that Gulf Model 1 placed on exploring the decision space surrounding the employment of UUV barrier defenses, the first question that Gulf Model 2 looked to answer was whether barrier defenses and area patrol assets alone would be sufficient to stop or substantially reduce the damage done by attacking UUVs.

To determine this, we compared the performance of the Barrier/Area Defense version of the model to the Point/Barrier/Area Defense version using the SEED data. The histograms in Figure 71 and Figure 72 were compiled using the SEED data in JMP and illustrate the substantial differences in performance between the two defense systems. In total, the 3,840 runs of the Barrier/Area Defense version suffered an average of 19 casualties per run. In contrast, the Point/Barrier/Area defense version of the model suffered an average of 5 casualties per run. Figure 75 and Figure 76 also serve to show that the node casualty distributions are not normally distributed around the mean, but rather have long trails towards the higher end, underlining the rareness of circumstances in which very large number of node casualties are possible. Moreover, they illustrate that over 25% of the Point/Barrier/Area Defense design points succeed in achieving two or fewer node casualties. The MANA data set produced similar results.



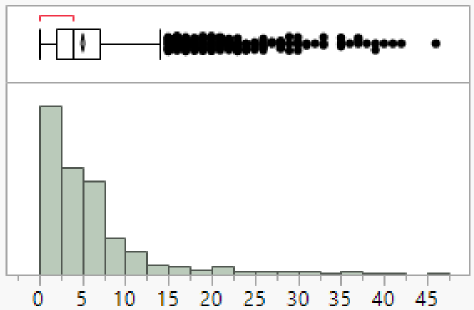
Quantiles

100.0%	maximum	73
99.5%		56.795
97.5%		45
90.0%		34
75.0%	quartile	26
50.0%	median	18
25.0%	quartile	11
10.0%		7
2.5%		3
0.5%		2
0.0%	minimum	0

Summary Statistics

Mean	19.401042
Std Dev	10.838803
Std Err Mean	0.1749104
Upper 95% Mean	19.743968
Lower 95% Mean	19.058115
N	3840

Figure 75 Barrier/Area Casualties



Quantiles

100.0%	maximum	46
99.5%		33
97.5%		21
90.0%		11
75.0%	quartile	7
50.0%	median	4
25.0%	quartile	2
10.0%		0
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics

Mean	5.0627604
Std Dev	5.4551112
Std Err Mean	0.0880315
Upper 95% Mean	5.2353534
Lower 95% Mean	4.8901675
N	3840

Figure 76 Point/Barrier/Area Casualties

Another useful insight for a defense planner would be to categorize a level of risk each threat category represents. The enemy asset performance is shown in Table 23, utilizing the MANA data set with the Barrier/Area Defense version of the model. Table 23 shows that the most lethal threat by far is the Deceptor Cargo Ship and its UUV weapons. This explains the previous analysis as the barrier defense versions of the model are unable to stop Deceptor Cargo Ship from passing the barrier and dropping off their weapons near the defenseless infrastructure nodes.

Table 23 Enemy Performance Against Barrier Defense

Enemy Performance	**Average # of nodes destroyed per run (out of 50 nodes)**
Bombers	2.0
Lone Wolf UUVs	1.2
Deceptor Ship UUVs	7.9
Total	11.1

Table 24 presents similar results using MANA data for the Point/Barrier/Area Defense version. When point defense is included, the Bomber Ships now inflict the most damage. The number of successful UUV attacks (either Deceptor or Lone Wolf) drops substantially. This is logical, as the point defense weapons will be successful in negating much of the effect of the Deceptor UUVs and Lone Wolf UUVs but should have no effect on the number of successful Bomber Ship attacks.

Table 24 Enemy Performance against Point/Barrier/Area Defense

Enemy Performance	Average # of nodes destroyed per run (out of 50 nodes)
Bombers	2.2
Lone Wolf UUV	0.2
Deceptor Cargo Ship UUVs	1.5
Total	3.9

In assessing the effectiveness of the enemy attacks in the version without point defense (Table 25), an average of 3 Bomber Ship destroyed 2.0 nodes, an average of 15.5 Lone Wolf UUVs destroyed an average of 1.2 nodes, and an average of 9 Cargo Deceptor UUVs destroyed an average of 7.9 nodes. Recall that each UUV can destroy up to 4 nodes, so Lone Wolf UUVs can destroy up to an average of 62 nodes and Deceptor UUVs can destroy up to an average of 36 nodes. The Deceptor UUVs have a higher success rate than Lone Wolf UUVs as with no point defense, the only way a Deceptor UUV can be killed is via Surface or Air. The success rate drops substantially for both Lone Wolf and Deceptor UUVs once point defenses are utilized (Table 24). However, the Deceptor UUV success rate is still much higher than the Lone Wolf rate because the Lone Wolf UUVs have to successfully navigate through the barrier, unlike the Deceptor UUVs. This further illustrates how point defenses have the potential to substantially drive up the cost for the attacking forces.

Another area of interest for a potential decision maker is the analysis of the effectiveness of each of the individual units at their disposal with regards to how they might be best deployed. Table 25 shows how surface ships are almost equally as effective as aircraft at UUV interception while also serving as the sole platform capable of boarding and stopping enemy surface ships. While much of this may possibly be attributed to the particular design of the aircraft used in the model, it is an important indicator as to the vital role that surface ships can perform in a theater wide defense. Note the number of Lone Wolf UUVs killed by Surface, Air, and Barrier is identical between the Barrier/Area variant and the Point/Barrier/Area variant.

Table 25 Average Effectiveness of Blue Assets against Attacker Assets by Class type

	Blue **Asset**	**Bombers Killed (out of the average 3 per run)**	**Lone Wolf Killed (out of the average 15.5 per run)**	**Cargo Deceptor UUV Killed (out of the average 9 per run)**
Barrier/Area	Surface	2.9	2.2	1.7
	Air	0	2.5	1.3
	Barrier	0	3.7	0
Point/ Barrier/Area	Surface	2.9	2.2	0.4
	Air	0	2.5	0.5
	Barrier	0	3.7	0
	Pipeline	0	1	6.2

Another important observation from Table 25 is that adding point defense did not substantially increase the average number of Lone Wolf UUVs killed in each engagement, increasing it only from 8.4 to 9.4. Even so, as Table 23 and Table 24 show, adding point defense substantially reduces the number of nodes that enemy Lone Wolf UUVs kill on average. This underscores the fact that, while potentially a useful tool in deciding Blue asset usefulness, kill count is not the most important measure of effectiveness for a successful defense.

Note the total number of UUVs killed in each column of Table 25 is much less than the average number of UUVs deployed (displayed at the top of each column). These remaining UUVs are still active at the end of the 24-hour time period of the simulation; at this point all UUV endurance is assumed to be depleted. Some of these UUVs still active are "failures" in that they destroy zero nodes and run out of fuel because their targeting ability was either too imprecise or, more often, their travel speed too low to get to a target node before running out of fuel. However, some of the active UUVs have destroyed nodes and are hunting to destroy more when they run out of fuel. For example on average 3 Deceptor UUVs are killed in the Barrier/Area variant, leaving on average 6 active at the end of the 24 hour period. These 6 have the potential to destroy 24 nodes, but only 7.9 on average are destroyed (Table 23). This implies the Attacker has the potential to inflict far greater damage than a superficial examination of Table 23 and Table 24 might reveal. If the Attacker has better UUV technology, either in the form of improved endurance, speed, or targeting capabilities, the Blue forces would suffer more than losses than presented in Table 23 and Table 24. Fortunately, with point defenses there are far fewer active Deceptor UUVs at the end of the 24 hour period (1.9), and so less potential for unrealized node losses.

Examination of Table 24 and Table 25 reveals the importance of surface ships to defense. Point defense provides an effective subsurface defense against UUVs. However, the only way to stop Bomber Ships is via ships. As ships are such an expensive and important asset, the decision maker will likely want to know the number of ships required in theater in order to effectively accomplish the mission. One way this can be determined is by examining the SEED data with the decision tree functionality in JMP. Figure 77 presents a decision tree splitting on number of Deceptor UUVs deployed by Deceptor Cargo ships and number of Blue Ships. The figure is created from the SEED data for the point defense version of the model. The tree illustrates how changing the number of ships in theater can drastically affect the number of critical nodes lost. The left branch shows that when there are less than 12 Deceptor UUVs deployed and when there are four or more surface ships in the model, the mean number of node casualties is 3.28, whereas when there are less than four surface ships the mean number of node casualties jumps up to 11.12. The right branch highlights the importance of surface ships. When 12 or more Deceptor UUVs are deployed, on average 8.5 fewer nodes are destroyed in scenarios with 5 or more surface ships compared to less than 5 surface ships. This data is validated by the similarly performing runs from the SEED data for Barrier/Area defense without point defense assets.

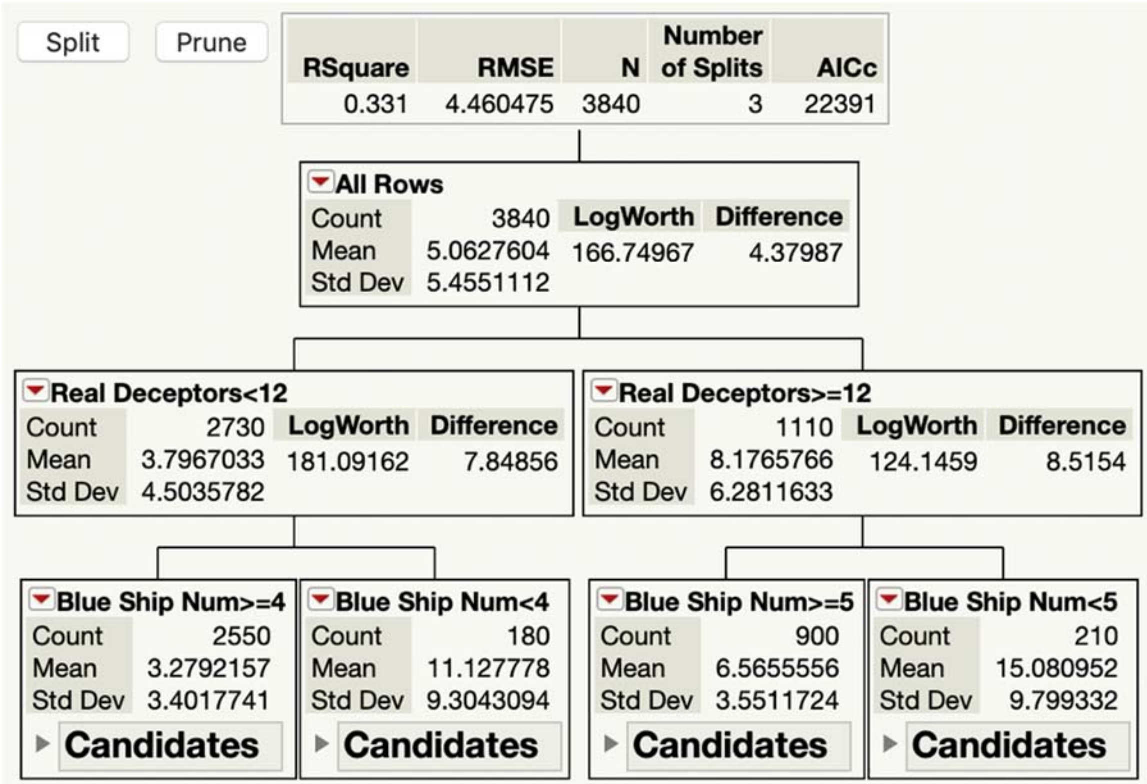


Figure 77 Point/Barrier/Area Defense Decision Tree showing Surface Ship Effects

Another important question for a decision maker concerned with surface ships is the relative speed difference between threat ships and Blue ships. As seen in Figure 78, utilizing the SEED data tree diagrams helps explore this decision space by illustrating the substantial impact that the speed of the threat has on the ability of the threat Bomber Ship to successfully conduct an engagement. When the Blue ship, which in the model travels at 40 kmh, has less than a 5 kmh speed advantage over the enemy ship, the mean number of nodes lost is 10.22, as opposed to the mean of 4.62 nodes lost when the speed difference is greater than 5 kmh. This is logical as the greater the speed difference, the more likely a blue force will be able to engage an attacker, particularly if the geometry of the engagement is unfavorable and a chase is involved. This conclusion is further validated by examining the next row down, where a speed difference of greater than 24.3kmh results in a mean number of nodes lost of 2.67, as opposed to the mean of 5.21 when the speed difference is less than 24.3. In practice, helicopters launched from surface ships may improve the speed advantage of surface ships and further increase their importance. It is worth reiterating here that the surface ships in the model are looking for ships which they have been notified in advance as being potential threats that must be boarded for investigation. If this assumption does not hold true, then defense against Bomber Ships will be limited, and surface ships will have less of an impact. However, surface ships still play a valuable role in their interdiction of subsurface UUV threats even if interdiction of Bomber Ships is not possible (see Table 25). In general, a substantial of the enemy threat lies in surface vessels that are capable of either destroying infrastructure nodes themselves or delivering UUVs, and the functions served by surface ships in this model are absolutely critical to the defense as a whole.

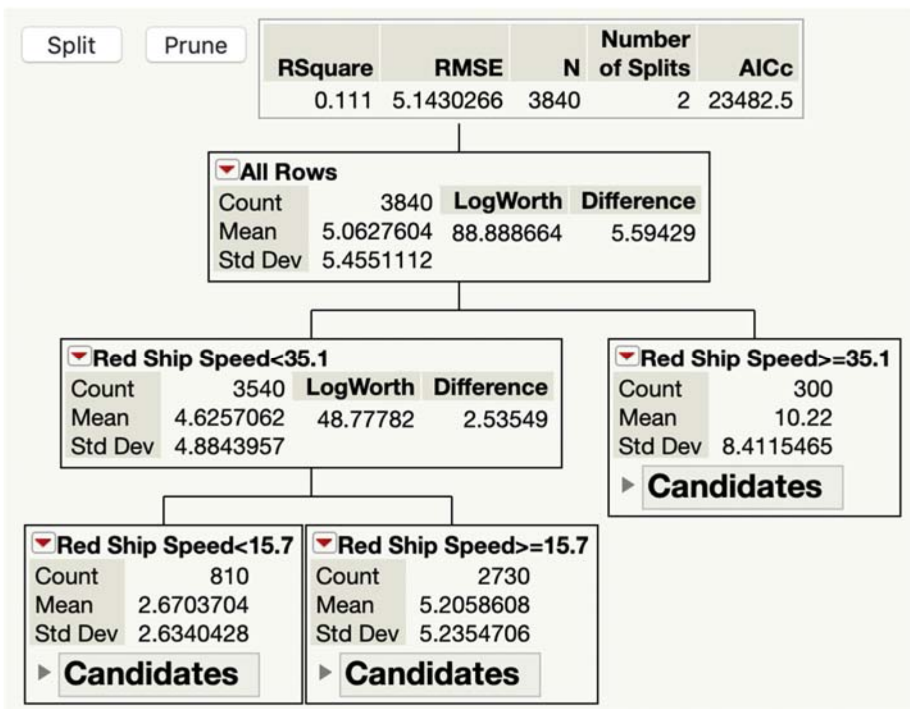


Figure 78 Point/Barrier/Area Defense Decision Tree Showing Speed Effects

One of the primary goals of this study was to explore the decision space so as to be able to perform a cost analysis that would help decision makers perform trade-offs when determining where to spend their money when it comes to acquiring assets and improving capabilities required for the defense of underwater infrastructure.

Based on the above analysis, the primary recommendation is that the point defense approach be implemented if at all possible. Secondly, there needs to be at least 4 surface ships with boarding teams on patrol at all times. Barrier sensor range of 1500m or more should be developed if possible, as larger sensor ranges will allow response assets more time to reach their targets before they are lost again. Finally, if point defense is utilized, the more Blue UUV per point defense position the better. Table 26 shows these minimum level force recommendations based on this model. The UUV requirement in Table 26 is based on point defense having seven UUV's each, ships having 15 each, p-8's having 6 each, and the barrier UUV stations having 4 each.

Table 26 Force Structure Recommendations

asset type	number of assets needed
Sensor Field	1
UUV	850
Surface Ships	4
Patrol Aircraft	3

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VI. COST ESTIMATION

A. INTRODUCTION

In this chapter we perform cost analysis on the four defense scenarios described in Chapters 4 and 5. The four scenarios implement different systems and equipment for defense of their respective pipelines. The systems and weapons that were investigated for the cost analysis were: a sensor field, a SDUUV, a MDUUV, a LDUUX or XLDUUV, UUV docking stations, the cost to bury pipes, maritime air patrols, and maritime ship patrols. All cost estimates are adjusted to the year 2035 for consistent comparison, refer to Table 27. To do this we first convert the data from the year in the original source to FY35 using the raw index from the navy's weapons procurement inflation table by using the following equation:

System Cost (FY35) = Raw Data Cost * (FY35 Index / Raw Data Index)

This analysis also accounted for potential technological advancements that could take place in the next 15 years with regards to UUV sensors, speed, and battery life. Table 27 summarizes the cost estimates for the inputs, and the supporting details appear in the following eight sections of this chapter. The Deepwater horizon oil spill serves as an upper bound in Table 27 which is the maximum amount a defender would be willing to pay for a defense system based on an estimate of the cost to recover from an undefended attack. Starting in Section B, we present the specific analysis for each of four scenarios.

Table 27 Cost Normalization Process

	Raw Data			Divide by index to convert to FY35$		
System	**System Cost ($M)**	**Year**	**Index**	**Year**	**Index**	**System Cost ($M)**
Burying Pipeline (per Kilometer)	$1.60	FY15	0.9707	FY35	1.4254	$2.35
XLDUUV	$10.75	FY19	1.0384	FY35	1.4254	$14.76
MDUUV (MK 48)	$3.80	FY05	0.8091	FY35	1.4254	$6.69
SDUUV (MK 54)	$0.84	FY14	0.9601	FY35	1.4254	$1.25
Patrol Aircraft (Boeing P-8 Poseidon)	$295.00	FY15	0.9707	FY35	1.4254	$433.18
Surface Ship (DDG-51)	$2,234.40	FY10	0.8975	FY35	1.4254	$3,548.62
Sensor Field	$154.00	FY06	0.8091	FY35	1.4254	$271.30
Deepwater Horizon (Upper Bound)	$62,000	FY10	0.8975	FY35	1.4254	$98,466.80

B. UUVS

We associate each UUV technology with a similar current technology based on size and speed. This allows us to make reasonable cost estimates based on known quantities. For example, UUVs that deploy from a docking station in this report are considered MDUUVs, UUVs that carry smaller UUVs are XLDUUV, and the smaller UUVs carried by the XLDUUVs are considered small sized UUVs.

The MK 54 torpedo represents an estimate of a SDUUV. A MK 54 torpedo is 2.87 meters in length, has a 0.324 meter diameter, and has a top speed of 83 km/h (Jane's Naval Forces 2001). The MK 48 torpedo represents an estimate for a MDUUV. A MK 48 torpedo is 6.1 meters, has a 0.533 meter diameter, and has a top speed of 101 km/h (Jane's Naval Forces 2001). The Boeing Orca UUV represents an estimate of an XLDUUV. The Boeing Orca UUV has a length of 15.5 meters, has a 2.1 meter diameter, and a top speed of 14.5 km/h (Trevithick n.d.). This data is summarized in Table 28

For each scenario the number of Blue UUVs is multiplied by the estimated cost of its associated UUV to derive the total cost. Lastly because the UUVs will have a more advanced sensor package than what a torpedo has, a ten percent increase in the cost was added to the UUVs compared to the torpedoes as shown in Table 28.

Table 28 Key Parameters for UUVs

	Types of UUVs		
	SDUUV (MK 54 Torpedo)	MDUUV (MK 48 Torpedo)	XLDUUV (Boeing Orca)
Length (m)	2.87	6.1	15.5
Diameter (m)	0.324	0.533	2.1
Speed (km/h)	83	101	14.5
Weight(lbs)	608	3965	200,000
Volume (ft^3)	9.465	33.25	433.5
Cost ($M)	$0.84 (FY14)	$3.8 (FY05)	$10.75 (FY19)
Cost ($M, FY35)	$1.25	$6.69	$14.76
UUV w/ Sensor Pkg ($M)	$1.37	$7.63	$16.23

For the cost of UUVs there is a clear relationship between size and the cost of the UUV. The relationship does not appear to be linear but is instead concave, as shown in Figure 79 and Figure 80. This may be useful information in future studies to estimate the cost of a UUV that is not captured in the three types of categories.

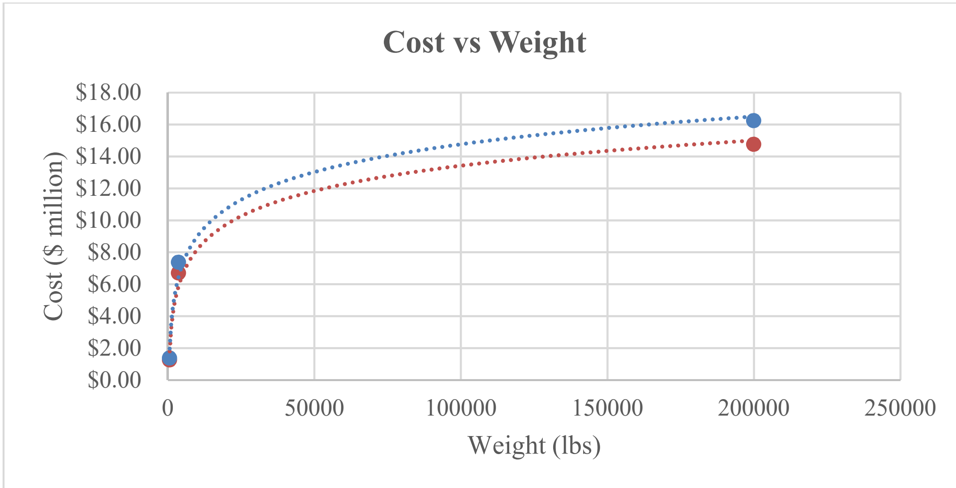

Figure 79 UUV Cost vs Weight for

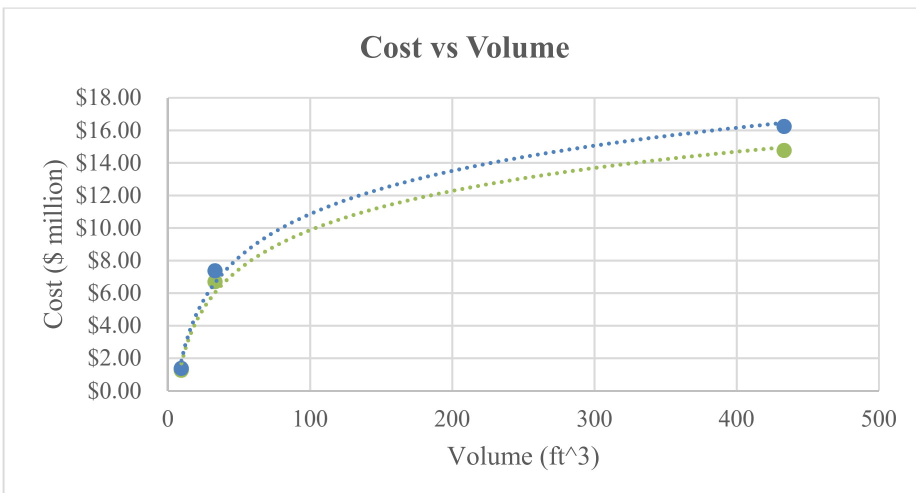

Figure 80 UUV Cost vs Volume

C. SENSOR FIELD

For the sensor field a different approach is necessary. To estimate sensor field requirements in the regions of interest to detect submarines or UUVs broaches the classification constraints of this report. Instead, the cost of the sound surveillance system (SOSUS) provides an adequate estimate at the unclassified level. The SOSUS in the Atlantic would be different from the sensor network employed in the Gulf of Mexico or Natuna Besar. The sound profiles of each region differ from each other and will likely require different numbers and types of hydrophones. However, SOSUS provides a "ballpark estimate" of how much each sensor network will cost and keeps the capstone project unclassified. The "ballpark estimate" of the sensor network in 1999 year dollars is around $150 million (Pike 1999).

D. POSEIDON P-8

One scenario used the Boeing P-8 Poseidon in the defense system. The P-8 will still be in use in 2035, therefore we use the current cost of a P-8 then normalize it to the year 2035. In 2035 P-8's will cost approximately $295 million in 2015 (Department of Defense 2014). The normalized values are listed in Table 27.

E. ARLEIGH BURKE DDG

Arleigh Burke DDGs are used as the estimates for the surface control vessels. Arleigh Burke DDGs will cost approximately $3,549 million in 2035 (O'Rourke 2011). DDGs are used in the capstone project because they have undersea warfighting capabilities. DDGs are incorporating the AN/SQQ-89A(V)15 which will increase their ability to track, detect, and find underwater contacts (Keller 2019). There are possible cheaper alternatives, such as, Coast Guard National Security Cutters (NSC) or Littoral Combat Ship (LCS). They would have to be retrofitted for undersea warfare and would be less capable than DDGs, but they would still likely cost substantially less than a DDG. NSC's cost on average around 670 million per ship (O'Rourke 2019).

Cost estimation for a DDG is difficult since this project doesn't anticipate building any new DDGs for the Gulf of Mexico or Natuna Besar. However, there will be a cost in the loss of a DDG operationally to other parts of the world. At a minimum the operation and maintenance costs need to be accounted for if a DDG is used in either theater in addition. The estimate for the cost of a DDG is included in Table 27 or consideration but is not added to the final total for the group that used it.

F. BURIED PIPELINE

Carpet bombing is a plausible attack scenario. The best way to combat this would be to bury as much pipe as possible. A buried pipe might also effectively thwart several other of the attack scenarios considered in this report. It costs roughly $1.6 million per kilometer in 2015 to bury pipe (MarEx 2015).

G. UNDERWATER DOCKING STATION

Currently there are not any operational employed underwater docking stations for UUVs. Fortunately, the navy contracted Aerojet Rocketdyne to develop an underwater docking station (Aerojet Rocketdyne 2017). Since this is a prototype, an 80% learning curve was used out to 20 units and then averaged to get an estimate of the cost of a docking station as shown in Figure 81(Nussbaum 2018). The final values are not normalized as they are future estimates. A learning curve was applied because it is expected that the price per unit of the underwater docking station would decrease as familiarity with the manufacturing and installation process increased (Wong 2013).

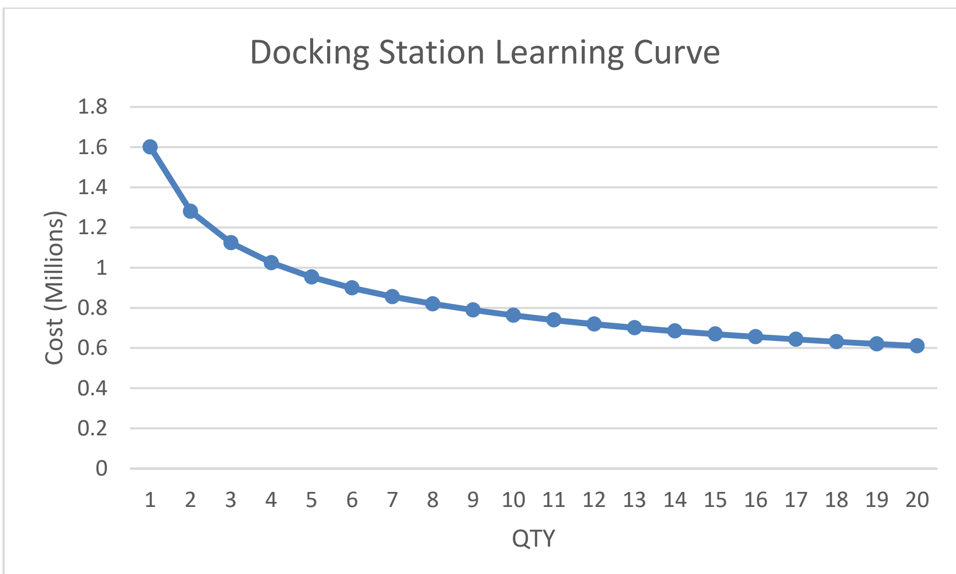

Figure 81 Docking Station Learning Curve

H. OPERATION AND MAINTENANCE

To avoid classification constraints, the operation and maintenance data is not included in estimating the cost of the undersea defense system. It should be noted that this estimate will then be less than the actual total cost of the undersea defense system.

I. COST OF SUCCESSFUL ATTACK

When is the cost of the defense system too high? The cost of a defense system should be less than the cost incurred from an attack on an undefended system. How damaging would a successful attack be? A successful attack may look like the Deepwater Horizon spill and could potentially cost as much as $62 billion in 2010 (Bomey 2016). A successful attack would likely cost at least this much and could be worse if multiple parts of the infrastructure are damaged. If the defense system would cost more than the Deepwater Horizon spill, it may be more cost effective to simply repair the oil pipelines, than to try to defend them.

J. COST ANALYSIS FOR GULF OF MEXICO

The cost estimation was conducted by identifying the systems required for each defense scenario. The estimated cost for each system that has been discussed in Chapter 5 are summarized into Table 29 and Table 30, it shows the total cost estimate to construct the defense systems for Gulf of Mexico One and Gulf of Mexico Two.

Table 29 contains an estimate for a point defense system used by Gulf of Mexico One, estimated in 2035 year dollars. The total cost minus the sensor field of defense infrastructure is $33.01 million, which covers 20 km of the area of operation. The Gulf of Mexico One simulated an area of operation is much smaller as compare to Gulf of Mexico Two.

To adequately compare them, we scale the values in Table 30 The simulated area of operation for Gulf of Mexico One covers 20 km instead of the proposed 1000 km defense layout. Thus, the values from Table 29 will be multiplied by 50 times and the total defense infrastructure cost with sensor field will be $1,540.30 million to defend the entire Gulf of Mexico.

Table 29 Gulf of Mexico One, Cost Estimation

System	Number of Systems Needed	Estimated Cost per System (Including Operating Cost) ($M)	Total Cost ($M)
Barrier Defense (3 Ports) (AO: 20 km)			
MDUUV w/ Sensor	3	$7.63	$30.52
Docking Station	3	$0.83	$2.49
		Total Cost:	$33.01
Barrier Defense (Scaled to Entire Gulf of Mexico) (AO: 1000 km)			
Sensor Field	1	$271.00	$271.30
MDUUV w/ Sensor	150	$7.63	$1,144.50
Docking Station	150	$0.83	$124.50
		Total Cost:	$1,540.30

Table 30 presents the cost estimate of a point defense and barrier system. The point defense system includes UUVs and docking stations. The barrier system incorporates surface ships, aircraft, and a sensor field with affiliated docking stations and UUVs to respond, The total cost of the system defense for the Gulf of Mexico Two sum up to $6,854.74 million.

The cost of using surface ships was not included in the total cost because it isn't anticipated that DDGs will be built specifically for the purpose of defending the Gulf. However, losing operational DDGs in other regions of the world is an operational cost that needs to be considered by the commander. We also do include the O&M cost for surface ships or aircraft in this table, so the final value needs to be inflated by an estimate of those costs.

Table 30 Gulf of Mexico Two, Cost Estimation

System	Number of Systems Needed	Estimated Cost per System, Including Operating Cost ($M)	Total Cost ($M)
Point Defense (50 Nodes) and Barrier Defense (1265 km)			
Sensor Field	1	$271.00	$271.30
MDUUV w/ Sensor	850	$7.63	$6,485.50
Docking Station	118	0.83	$97.94
Surface Ship	4	O&M cost undisclosed	-
Patrol Aircraft	3	O&M cost undisclosed	-
		Total Cost:	$6,854.74

Based on the above estimations, it will cost $1.5 billion and $6.8 billion to implement the defensive systems proposed by Gulf One and Gulf Two respectively. The implementation is more cost effective than not defending them and tending to the cleanup and repair requirements after an attack which will cost approximately $98.5 billion in year 2035.

K. COST ANALYSIS FOR NATUNA BESAR

Table 31 and Table 32 present the cost estimates for Natuna Besar One and Natuna Besar Two, respectively.

From Table 31 presents the total cost for a point defense on a single platform for Natuna Besar One. The total defense infrastructure cost will be $66.18 million which consists of 3 x XLDUUV with sensor, 12 x SDUUV and 3 x docking station.

Table 31 Natuna Besar One, Cost Estimation

System	Number of Systems Needed	Estimated Cost per System (Including Operating Cost) ($M)	Total Cost ($M)
Point Defense for 1 Platform			
SDUUV	12	$1.25	$15.00
XLDUUV w/Sensor	3	$16.23	$48.69
Docking Staion	3	$0.83	$2.49
		Total Cost:	$66.18

From Table 32, the total cost of the system defense for the Gulf Blue sum up to $2.2 million which covers 3.2 km of the area of operation. The total cost minus the sensor field of defense infrastructure is $8.46 million which cover 3.2 km of the area of operation. As the simulated area of operation for Natuna Besar Two covers 3.2 km instead of the proposed 640 km defense layout. Thus, the values from Table 32 are multiplied by 200 times and the total defense infrastructure cost with the sensor field will be $1,963.3 million to defense the entire Natuna Besar region pipeline.

Table 32 Natuna Besar Two, Cost Estimation

System	Number of Systems Needed	Estimated Cost per System (Including Operating Cost) ($M)	Total Cost ($M)
Barrier Defense (AO: 3.2km)			
MDUUV w/ Sensor	1	$7.63	$7.63
Docking Station	1	$0.83	$0.83
		Total Cost:	$8.46
Barrier Defense (Scaled) (AO: 640km)			
Sensor Field	1	$271.00	$271.30
MDUUV w/ Sensor	200	$7.63	$1,526.00
Docking Station	200	$0.83	$166.00
		Total Cost:	$1,963.30

Based on above estimations, it will cost $13.5 billion for Natuna Besar One to implement a point defense system to safeguard 152 oil and gas platforms within the region. As for Natuna Besar Two, it will cost $2 billion to install a barrier defense system to cover the 640 km of pipeline. Similarly, the implementation is more cost effective then not defending and performing cleanup and repair after an attack.

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VII. CONCLUSIONS AND RECOMMENDATIONS

The project team recognized that in order to design a manned and unmanned system capable of providing seabed infrastructure defense against a multitude of threats, future designers will first require insights into various aspects of the problem. These insights will need to explore the problem space ranging from individual engagements at the tactical level to macro level trends which will help guide theater level defense.

Through a tailored research approach the team focused on identifying desirable systems and operational tactics to support undersea infrastructure defense. This suggested the development of multiple simulation models for Natuna Besar and the Gulf of Mexico. The models simulate both small scale and integrated full-scale wide area operations. Despite the differences in design there are a couple of key insights that hold true across the four different models that should inform the CONOPS and system design used to defend undersea infrastructure. The proposed designs are cost effective when compared to the economic impact from a successful attack.

A. MAJOR INSIGHTS

1. CONOP Design

A simple point defense of critical assets is more effective than any barrier defense implementations on their own, a finding which was consistent across each of the modeling efforts. This is because none of the barrier defenses examined proved to be impregnable to the full range of underwater threat capabilities. Whether a barrier is added or not, the defensive system should be made up of a networked acoustic sensor array communicating with interceptor UUVs launching from fixed docking stations. Roving patrols do not provide any benefit as long as the sensor network is able to adequately cover the region. The sensor array should be built two or preferably three rows deep in order to provide the defending UUVs the most time to engage the threat. Additionally, this system is not intended to replace all traditional maritime and coastal defenses. The defense of undersea infrastructure has the highest success rate when existing surface and air assets are able to receive information from the sensor array and provide additional firepower to the defending UUVs.

2. System Design

The most important factor in system design is minimizing the time required to engage and effectively neutralize the threat. Speed of the intercepting UUVs is important, but time to engage can also be reduced by having more docking stations and reducing the distance between them. Continuous targeting updates to the UUVs from a fixed sensor array as well as sufficient firepower to disable the threat with one weapon ensures that timely engagements result in mission success.

B. DETAILED INSIGHTS

1. Natuna Besar Model One (NB1)

NB1 focused on the best way to employ defensive UUVs in a point defense against offensive UUVs. It investigates a CONOP in which the enemy utilizes a diversion tactic with some of its forces to draw away the defenders and leave the infrastructure vulnerable to an attack by the main enemy force. This tactic allows the enemy to have the highest probability of destroying the oil platform with the least number of attacking UUVs.

For defender UUV employment, two different defensive configurations are examined. One of these configurations is a true point defense, in which the defenders are concentrated within close proximity of the defended assets. The other configuration employs the defensive UUV in a patrol around the defended target. In both simulation models, the only defense assets deployed are UUVs, equipped with the capability to conduct defensive sensing and mitigation of incoming threats.

The simulation results conclude that the point defense CONOPS is more effective than conducting a perimeter patrol. The patrolling model would need to defend a larger area, and even though that area is relatively small, the defense forces were spread too thin. As a result, a concentrated enemy attack of even moderate size will easily overwhelm the few defenders close enough to respond in time.

Detailed analysis of the model focused on identification of desirable system characteristics. This analysis concluded that firepower is the most decisive factor for the defenders to achieve victory in the model, wherein firepower is a quantifiable metric calculated by assessing the numbers and quality of the attacking and defending forces (see page 79). When partitioning design points into high and low scenarios, the high firepower scenarios generate a success probability of 0.88, while the low firepower scenarios have a success probability of only 0.19. The importance of firepower on mission success suggests initial investment for development of a point defense system should focus on creating highly accurate weapons that can consistently neutralize the threat every time the UUV is employed.

2. Natuna Besar Model Two (NB2)

NB2 was composed of three distinct simulations which provided insights for the composition of a defense system along the Natuna gas pipeline. The first scenario modeled the use of underwater docking stations that were fixed to certain points on a defensive barrier and that released their defending UUV when attackers were detected by supplemental detection sensors. The second scenario modeled the use of patrolling defensive UUVs, which have organic targeting systems onboard and do not need inputs from the sensor fields. The third scenario modeled the use of both types of defenders.

Based on the overall results from the three simulations, it is not recommended to deploy a combination of fixed shooters and patrolling shooters in immediate vicinity of the pipeline. If the fixed shooters are capable of neutralizing attacking UUV, then the fixed shooters alone are sufficient to defend against enemy attacks; adding patrolling shooters provides little benefit at increased cost. Also, if the fixed shooters are not capable of destroying the attacking units, the few available patrolling units are insufficient to make up for this deficiency and the enemy attack will succeed. As such, it would be more cost effective to just deploy fixed interceptor UUVs.

The best way to employ the two defending UUV types together would be to deploy them as two entirely separate layers of defense. The patrolling UUV could deploy beyond the wired-guided fixed shooter defense range, so that the patrollers perform a separate role of early elimination of threats. The fixed shooter can only engage targets close to the pods near the pipe due to its guide wire length limitation.

Analysis of the first simulation showed that the probability of success is largely dependent on the speed difference between the defending UUV from the docking station and the adversary UUV. Depending on the speed difference, the distance between each docking station can be determined based on the insights from the simulation results. This suggests that investments into increasing the speed of the defending UUV decreases the required number of docking stations.

3. Gulf of Mexico Model One (GM1)

GM1 examined the use of sensor fields to localize a threat UUV and to guide the defending UUV through to a successful interception. The primary insight gleaned by this model is that the ability to track is more important than having a sophisticated sensor with a high probability of detection. That is, as long as a threat UUV remains in the sensor field, a less sophisticated sensor with a low probability of detection will still detect, track, and maneuver the friendly UUV to interdict the threat UUV. Given the technical challenges associated with delaying a threat UUV to ensure that it spends additional time in a sensor field, this suggests that any system will necessarily employ multiple layers (or rows) of sensors to increase the opportunities to track threat UUVs. However, adding more than three rows of sensors provided diminishing returns in comparison to having more defending UUV positioned closer together and capable of achieving higher speeds.

Another important insight generated by this model is that a larger density of defender UUVs over a given area is important because it helps decrease the interdiction time. Having one friendly UUV cover a large area is not feasible in trying to achieve a high probability of kill as even a fast defending UUV may not be able to achieve an interception before the enemy UUV has left the sensor field. Any system design must consider the expected speed of enemy UUVs in order to determine the required interdiction time and employ defending UUV of high enough speed and enough number to meet that time.

4. Gulf of Mexico Two

The single most important observation from the GM2 model is derived from the analysis done in forming the assumptions upon which the model was built; without actionable intelligence to identify critical contacts of interest, and the legal authority to stop and board those shipping vessels, it is nearly impossible to stop those vessels from destroying undersea infrastructure. Either directly through the use of their anchors or onboard weapons, or indirectly by releasing target-seeking UUV within close proximity of their targets, they will be able to accomplish their mission.

Allowing for the assumption that those criteria have been met, the GM2 model underlines the issue that a barrier defense of undersea sensors and UUV alone, or even in conjunction with area defense patrols, is insufficient. Not only did adding point defense weaponry and sensors at critical nodes more than halve the average number of enemy successes, it also limited enemy successes to fewer than 2 on 25% of the runs modeled, as opposed to the mere .5% of the time where that was achieved without point defense. This suggests that if at all possible, point defense must be allocated to critical infrastructure. Additionally, the model showed that increasing ammunition available for point defense units was more important than increasing it for any other unit class. This is because the aircraft and ships only rarely conducted enough interdictions to utilize even the lower level ammunition allotments modeled.

Besides point defense, the next most important observations from GM2 have to do with the functions served by defending surface ships in the model. Since enemy ships and ship-borne UUVs pose the greatest threat, fielding defensive assets capable of stopping them is of the highest priority. One way the model shows this can be done is by ensuring that the defending assets have the speed necessary to rapidly close and board with the threat. In the model, this is shown by examining the speed difference between defender and enemy ships. In practice, this could be greatly amplified by ensuring that defending ships have helicopter based boarding teams that could respond even faster. Moreover, giving those helicopters the ability to carry counter UUV weapons would further enable ships near underwater sensor fields the ability to kill high speed attacking UUVs.

Maritime patrol aircraft were of limited utility in the model due to fact they don't have persistent organic subsurface sensors and they lacked the speed and numbers to reliably get on sight and make interdictions when targets were communicated to them by other sensing platforms. This is in large part also due to the relatively small size of the sensor fields compared to the Gulf of Mexico at large; sensors with more depth or layered in wider arrays would give response aircraft more time to threats before they passed the sensor coverage area. Aircraft tactics and operations are also important in this regard, as aircraft patrols assigned solely to patrolling the barrier should put them in a better position to respond to threats while within range of the barrier sensors.

5. Cost Analysis

The cost analysis team calculated a minimum total cost estimate for each defense group. Operation and maintenance costs could not be included due to data sensitivity in some areas and a lack of available data in others, but it is worth observing that major acquisitions projects can often face operations and maintenance costs between 80% and 95% of total life cycle cost (Josiah, 2002). The following values are expressed in 2035 year dollars. The cost of the barrier defense simulated by Gulf of Mexico Model One scaled to the required size for the Gulf of Mexico would cost $1.5 billion. The combination of a point defense and a more capable barrier defense utilized in Gulf of Mexico Model Two would cost at least $6.8 billion, excluding the cost for the surface ships and patrol aircrafts. On the high end, assuming that operations and maintenance cost form roughly 95% of the total life cycle cost of this system, the implementation of these defensive systems can be estimated to cost approximately $27.4 billion and $130.2 billion respectively. In contrast, a single successful attack on the Gulf of Mexico oil pipelines could mirror the nearly $100 billion recovery cost of an attack which causes a Deepwater Horizon type spill. The cost effectiveness of implementing a defense system in the Gulf of Mexico is dependent on these estimations and the likelihood and expected frequency of an attack. Since underwater infrastructure attacks are a newly emerging threat class, they fit the "Black Swan Event" category of possible events of incalculable probability of occurrence. Even so, at slightly higher than half the cost of a single attack with Deepwater Horizon level consequences, this investment is potentially viable depending on how seriously decision makers take the threat.

The barrier defense simulated by Natuna Besar Two scaled to a 640 km which is the total pipeline length for Natuna Besar, and this would cost $1.9 billion. The point defense simulated by Natuna Besar Gold to defend a single platform was $66 million. However, there are approximately 152 oil platforms in the Natuna Besar region, so the scaled total cost will be $10 billion. Once again assuming a 95% operations and maintenance cost, these defensive schemes quickly balloon to $36 billion and $190 billion respectively. At an 80% operating and maintenance costs, these numbers reach a more tangible but still enormous $7.6 billion and $40 billion respectively. Both of the estimated costs for the Natuna Besar region are below the estimated cost of a successful attack in the context of recovering from a Deepwater Horizon level environmental disaster, but it is unclear whether regional governments will weigh that risk in the same way that U.S. decision makers might, particularly considering the substantially smaller defense budgets at their disposal.

C. RECOMMENDATIONS

Implementing a defensive system responsible for protecting underwater infrastructure defense of the Natuna Besar or Gulf of Mexico regions is a proposition of breathtaking proportions. It would require significant amounts of capital for both the initial design of and deployment of the defensive systems in the short term and for the administration, maintenance, and eventual replacement of those systems over the ensuing decades. Before pushing ahead with any such projects in a piecemeal fashion, high level decision makers should take several factors into consideration.

First, while there is substantial appeal in investing in active defenses such as those investigated in this paper, due to the optimism generally associated with new technologies and the potential applications they may have towards unforeseen uses, equal attention should be paid towards passive defensive measures, resilient and redundant systems, and repair and recovery capabilities. As the saying goes, with high value targets the defender needs to be successful every time, but the attacker only needs to be lucky once. Ultimately, efforts to discourage attacks, mitigate the damage from attacks when they happen, and recover from them as quickly as possible may be more valuable in the long run than any active defense.

Second, if active defenses are developed and deployed, it is critical that a thorough systems engineering process guides that effort. The decades' long nature of such an enterprise, the enormous number of shareholders, the enormity of the technical challenges, the evolving nature of the threat, and the massive amounts of capital required to tackle every major aspect of the problem demand it. Without thorough systems engineering efforts to gain insights into potential issues faced by the enterprise developers and head them off before they raise their heads, enterprise level defense of underwater infrastructure is bound to be railed by cost overruns, incompatible systems, and substandard performance.

D. FUTURE WORK

In the event that decision makers decide to invest in an active defense system to protect underwater infrastructure, the following observations from each respective model provide some direction into further research that should be done prior to commencing such a project.

1. Diversionary Tactics

One important finding for this project had to do with the general effectiveness of diversionary tactics for the attacking UUV. Further research should be done into making autonomous systems intelligent enough to avoid being drawn away by a diversion tactic.

2. Underwater Communication

The proposed communication systems rely on current technologies such as fiber or copper wire for UUV guidance systems. Increased accuracy for the intercepting UUV could be attained with future research into underwater communication systems. An analysis of alternatives should be performed to determine the best way of networking the UUVs.

3. Detect to Engage

The models for barrier defense focused on two functions—detecting and intercepting underwater vehicles coming through the barrier. It did so by investigating a single alternative for each function; sensors for detection and underwater docking stations which launched defender UUV for the interception. For future work, alternative designs should be investigated for performing the detection and interception functions. For detection, permanent or semi-permanent underwater sensors should be investigated for their ability to sense enemy UUVs attempting to pass the barrier. For interception, airborne drones capable of maintaining station over a yet-to-be-determined portion of the barrier and dropping interceptors directly above enemy UUV would be an ideal candidate to decrease intercept time. Each alternative should be evaluated for technical feasibility and performance against a wide range of threats.

4. Vulnerability Assessment

In order to accomplish point defense of critical and critically vulnerable infrastructure, it is imperative that research is done on identifying which infrastructure nodes meet that definition. This is a tricky proposition for several reasons. First, it requires expert knowledge on infrastructure systems, particularly with respect to their vulnerabilities and the roles they play within their respective enterprises. With respect to their vulnerabilities and the roles they play within their respective enterprises. Second, conducting that research, amassing that data, and acting on it by implementing point defense solutions is problematic in and of itself in that in the wrong hands that information could help an enemy plan their attack far more effectively than they would have otherwise been able.

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APPENDIX A – UUV SPECIFICATIONS

A. REMUS 100

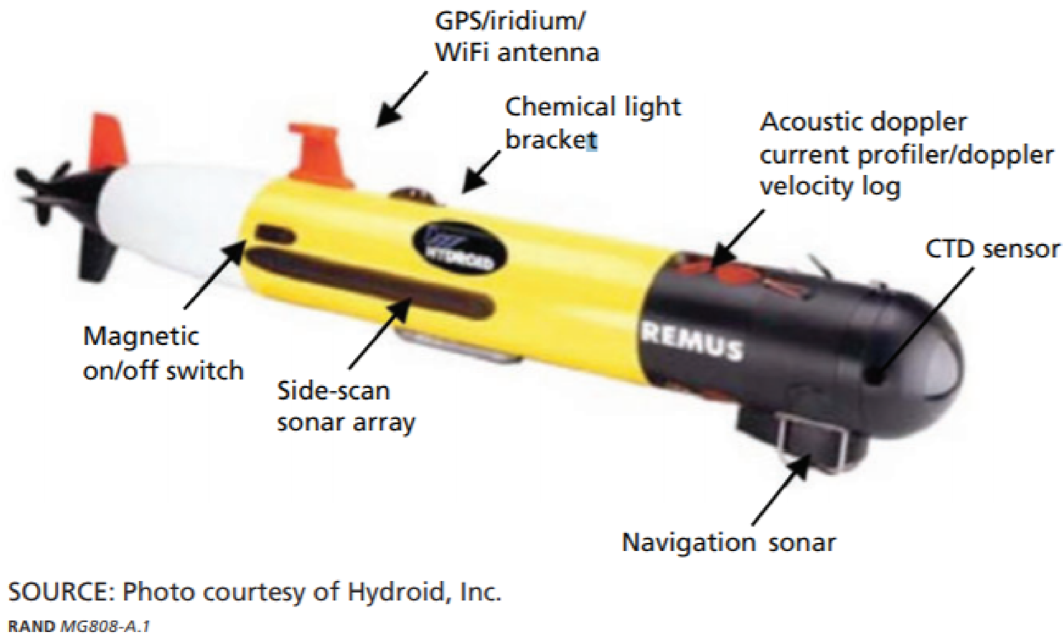

Figure 82 "Remus 100" UUV. Source: Buton (2009)

Table 33 Remus 100 Specifications

Weight	37 Kg
Range	-
Endurance	8-22 hours
Speed	1-10 kph
Propulsion	Electrical engine
Payload weight	-
Depth	100m
Sensors	RD1 1.2 MHz up/down-looking Doppler Current Profiler/ Doppler Velocity Log; Marine Sonics Technology 600-, 900-, or 1,200-kHz side-scan sonar;

B. BLUEFIN 9

Table 34 Bluefin 9 Specifications

Weight	50 Kg
Range	-
Endurance	12 hours
Speed	3.6-10 kph
Propulsion	Electrical engine
Payload weight	-
Depth	100 m
Sensors	

C. BLUEFIN 12—LATER MODEL OF BLUEFIN 9

Figure 83 Bluefin 12S, Courtesy of General Dynamics

Table 35 Bluefin 12 Specifications

Weight	50 Kg
Range	-
Endurance	10-23 hours
Speed	3.6-10 kph
Propulsion	Electrical engine
Payload weight	-
Depth	200 m
Sensors	900 kHz side-scan sonar

D. BLUEFIN 21

Table 36 Bluefin 21 Specifications

Weight	750 Kg
Range	-
Endurance	25 hours
Speed	8 kph
Propulsion	Electrical engine
Payload weight	-
Depth	4500 m
Sensors	455-kHz side-scan sonar

1. Remus-600—equipped with SSAM sonar that enable Remus-600 to detect mines on the seabed or partially buried and in service in the Royal Navy (Kongsverg 2019).

Table 37 Remus-600 Spec

Weight	240 Kg
Range	-
Endurance	70 hours
Speed	10 kph
Propulsion	Electrical engine
Payload weight	-
Depth	600 m
Sensors	Acoustic Doppler Current Profiler; side-scan sonar; CTD. Dual-frequency side-scan sonar

2. Remus-3000 (Kongsverg 2019).

Table 38 Remus-3000 Spec

Weight	345 Kg
Range	-
Endurance	77 hours
Speed	7 kph
Propulsion	Electrical engine
Payload weight	-
Depth	3000 m
Sensors	Acoustic Doppler Current Profiler; side-scan sonar; CTD. Dual-frequency side-scan sonar

3. Hugin—a family of UUV developed in Norway by Kongsberg

Figure 84 HUGIN UUV. Source: Kongsverg (2019)

Table 39 HUGIN Spec

Weight	100-1500 Kg
Range	-
Endurance	24-74 hours
Speed	4-11 kph
Propulsion	Electrical engine
Payload weight	-
Depth	3000-6000 m
Sensors	Low-frequency broadband sonar; SAS

4. AQUA EXPLORER 2—UUV used for underwater cable inspection (Proceedings, 2000).

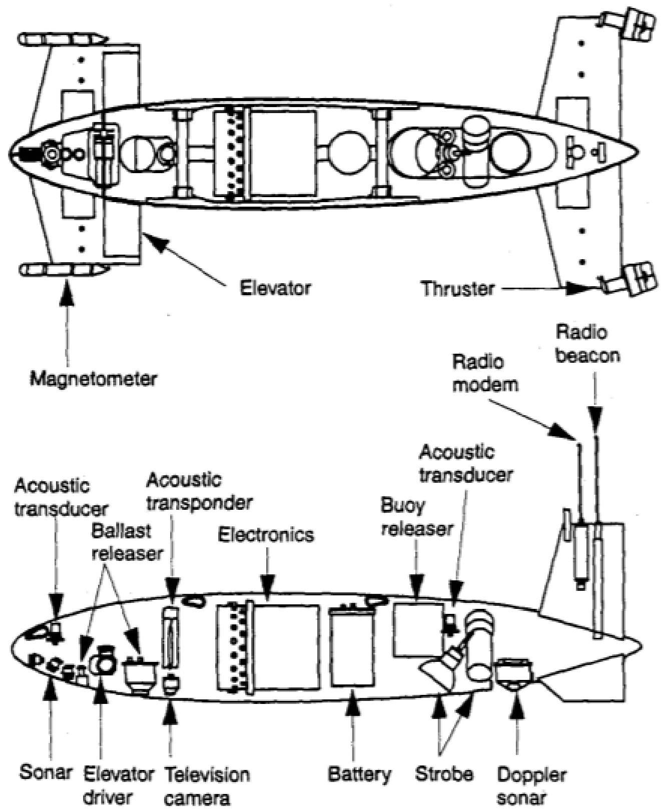

Figure 85 AE2. Source: Proceedings (2000)

Table 40 AQUA EXPLORER 2 Spec

Weight	300 Kg
Range	-
Endurance	24-74 hours
Speed	5-10 kph
Propulsion	Electrical engine
Payload weight	-
Depth	2000 m
Sensors	Two magnetometers; still camera; video camera

5. Theseus—Canadian UAV used for laying underwater cables

Figure 86 Theseus UUV. Source: ISE (2019)

Table 41 Theseus Spec

Weight	8600 Kg
Range	>1600
Endurance	168 hours
Speed	7.5 kph
Propulsion	Electrical engine
Payload weight	1910 Kg
Depth	2000 m
Sensors	-

6. “Spray Glider”—Gliding UUV

SOURCE: Photo courtesy of Bluefin Robotics Corporation.
RAND *MG808-A.13*

Figure 87 Spray Glider UUV. Source: Davis, Eriksen, Jones, and Clayton (2002)

Table 42 Spray Glider Spec

Weight	51 Kg
Range	7000 km
Endurance	8000 hours
Speed	1kph
Propulsion	Electrical engine
Payload weight	3.5 Kg
Depth	-
Sensors	-

7. “Seaglider”—glider UUV developed by University of Washington, was used to monitor data in the Gulf of Mexico during 2010 Deepwater Horizon oil spill incident.

Figure 88 Seaglider UUV, Courtesy of University of Washington

Table 43 Seaglider Spec

Weight	52 Kg
Range	4600km
Endurance	-
Speed	1 kph
Propulsion	Electrical engine
Payload weight	25 Kg
Depth	1000 m
Sensors	-

8. “Deepglider”—developed from “seaglider”

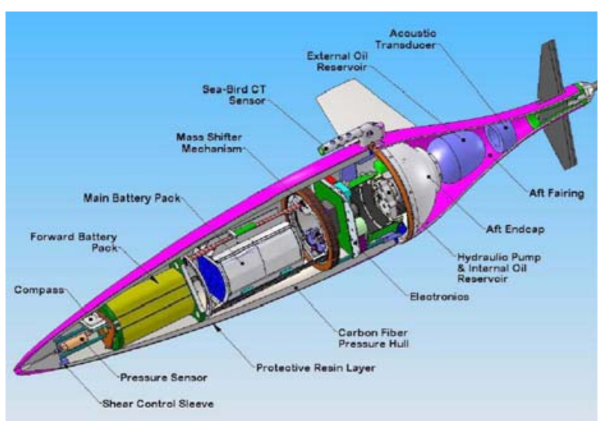

Figure 89 “Deepglider” UUV. Source: Osse and Eriksen (2007)

Table 44 Deepglider Spec

Weight	62 Kg
Range	8500 km
Endurance	-
Speed	1 kph
Propulsion	Electrical engine
Payload weight	25 Kg
Depth	6000 m
Sensors	-

9. “Panther XT”—developed by SAAB, ROV used for seabed work such as pipeline survey

Figure 90 “Panther XT” ROV. Source: SaabSeaeye (2019)

Table 45 Panther-XT Spec

Weight	500 Kg
Range	-
Endurance	-
Speed	5.5 kph
Propulsion	-
Payload weight	110 Kg
Depth	1500 m
Sensors	-

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APPENDIX B – TORPEDO SPECIFICATIONS

A. MK-48: AMERICAN HEAVYWEIGHT TORPEDO, IN SERVICE FROM 1972. (PETTY, 2019)

Table 46 MK-48 Spec

Weight	1500 Kg
Range	>8 km
Endurance	-
Speed	>51.2 kph
Propulsion	Piston engine
Warhead weight	-
Depth	-

B. SHKVAL – RUSSIAN TORPEDO (RUSSIA, 1995), (TYLER, 2000)

Figure 91 Shkval Torpedo

Table 47 Shkval Spec

Weight	2700 Kg
Range	~10 km
Endurance	-
Speed	>370 kph
Propulsion	Piston engine
Warhead weight	-
Depth	-

1. SAAB future torpedo—Turped 47: SAAB corporation is a manufacture of torpedoes such as Turped 45 and are currently developing the next generation and published the general specifications of the future Torpedo (Saab, 2017).

Table 48 Turped 47 Spec

Weight	340 Kg
Range	10 km
Endurance	-
Speed	74 kph
Propulsion	-
Warhead weight	-
Depth	300 m

2. “Spearfish” is a heavyweight torpedo, in service for the royal navy since 1992 (Spearfish, 2017).

Table 49 Spearfish Spec

Weight	1850 Kg
Range	50 km
Endurance	-
Speed	150 kph
Propulsion	Gas turbine
Warhead weight	300 Kg
Depth	-

3. “F21” French heavyweight torpedo (DCNS, 2019).

Table 50 F21 Spec

Weight	1500 Kg
Range	50 km
Endurance	-
Speed	92 kph
Propulsion	Electric engine
Warhead weight	250 Kg
Depth	500m

4. “MK54”—lightweight torpedo developed by “Raytheon” and in use by the U.S. Navy (Petty, 2019).

Table 51 MK54 Spec

Weight	276 Kg
Range	-
Endurance	-
Speed	-
Propulsion	liquid propellant
Warhead weight	44 Kg
Depth	500 m

5. “MU90”—lightweight torpedo, In service with France, Italy, Germany, Denmark Poland (MU90, 2019).

Table 52 M90 Spec

Weight	304 Kg
Range	>10 Km
Endurance	-
Speed	>92 kph
Propulsion	liquid propellant
Warhead weight	-
Depth	>1000 m

C. SAAB FUTURE TORPEDO

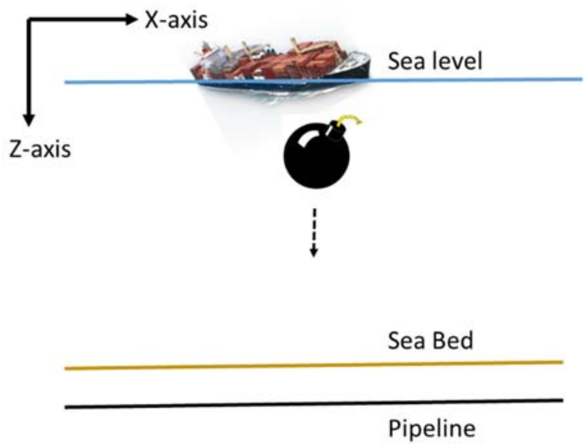
Turped 47: SAAB corporation is a manufacture of torpedoes such as Turped 45 and are currently developing the next generation and published the general specifications of the future Torpedo (Saab, 2017).

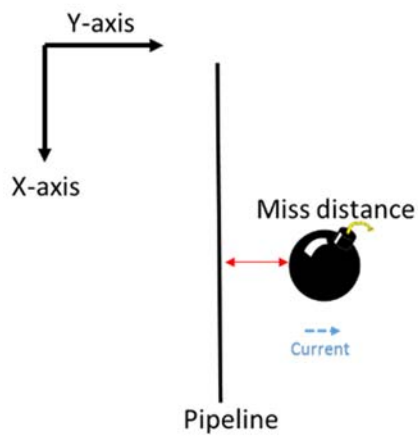
Table 53 Turped 47 Spec

Weight	340 Kg
Range	10 km
Endurance	-
Speed	74 kph
Propulsion	-
Warhead weight	-
Depth	300 m

APPENDIX C – “UNDERWATER CARPET BOMBING” SCENARIO – HIT PROBABILITY CALCULATION

1. Enemy vessel (disguised as commercial vessel) sailing along a pipeline and dropping munition :





X-axis : pipeline direction
Y-axis : perpendicular to X , on seabed plane
Z-axis : Depth

2. Assumptions :
   a. Depth : 50–1500 m (Gulf Coast, 2019)
   b. Error in ship in Y-axis (error from being directly above pipeline) < 5m (simple commercial GPS accuracy, probably can be much better)
   $$\Delta y_0 = 5m$$
   c. Current average speed : 0.1-0.2 m/sec
   $$V_y = 0.2\ m/sec$$
   d. Munition Weight : 500Kg
   e. Munition content : TNT
   f. Munition Volume : using TNT density of 1650 kg/m^3 :
   $$V = \frac{mass}{density} = \frac{500}{1650} = 0.3m^3$$
   g. Munition radii (assuming sphere shape)

$$V = \frac{4\pi}{3}R^3 \rightarrow R = \sqrt[3]{\frac{3V}{4\pi}} \cong 0.4m$$

h. Kill distance—most tricky to estimate., obviously depend on how deep the pipe is burried, anc no model for sea-bed penetration found. Using [33] we can see that a 500kg TNT bomb can have significant Impact up to 90 charge radii or in our case 36m. creating more than 25m of high-pressure gas bubble. The report has only data up to 100ft but we can see that the impact increases with depth so usually in our scenario the impact will increase.

i. From Sulfredge 2019 we can get the data of the impact to different underwater structures but not to pipes or buried pipes. We can maybe use the tables showing the impulse generated in different depths and distances to estimate the distance that will cause damage to pipes.

3. Calculations :
   a. Time to bottom = t
   b. Acceleration using newton's 2nd law:

$$a = \left(1 - \frac{m_w}{m_o}\right) g$$

   Where m_o is munition mass and m_w is the water mass being pushed by munition

   c. m_w is the water mas of the munition volume :

$$m_w = density * Volume = 1000 * 0.3 = 300kg$$

   (using water density 1000 kg/m^3)

   d. From b and c :

$$a = \left(1 - \frac{300}{500}\right) 10 = 4\frac{m}{sec^2}$$

   e. From d we can calculate the time to seabed :

$$D = \frac{1}{2}at^2$$

$$using\ worst\ case\ of\ D = 1500\ m:$$

$$t = \sqrt{\frac{2D}{a}} = \sqrt{\frac{2 * 1500}{4}} = 27.3\ sec$$

   f. Now we can calculate the drift cause by the currents , assuming the current speed is constant:

$$\Delta y = V_y t = 0.2 * 27.3 \cong 5.5m$$

   g. If we consider the ship navigation error in the worst case, we get to a total miss distance of 10m.
   h. Since miss distance is much smaller than the estimated kill distance

LIST OF REFERENCES

"A Torpedo for Tomorrow's Needs." (2017). Saab Corporate. Accessed 11 April 2019. https://saabgroup.com/media/stories/stories-listing/2017-06/a-torpedo-for-tomorrows-needs/.

Acker, Timothy W., and Meecham, Andy. (2016, October). "Underwater Threat Detection and Tracking Using Multiple Sensors and Advanced Processing." *Journal of the Acoustical Society of America* 140, no. 4: 3349–3349.

Aerojet Rocketdyne. (2017). "Aerojet Rocketdyne Awarded U.S. Navy Contract to Mature Power and Energy Management Systems for Underwater Unmanned Vehicles | Aerojet Rocketdyne." March 24, 2017. https://www.rocket.com/article/aerojet-rocketdyne-awarded-us-navy-contract-mature-power-and-energy-management-systems.

Ahmad Mazlan, and Ahmad Naddi. (2015). "A Fully Actuated Tail Propulsion System for a Biomimetic Autonomous Underwater Vehicle." PhD thesis, University of Glasgow. http://theses.gla.ac.uk/6343/1/2015ahmadmazlanphd.pdf.

Alderson, David L., Brown, Gerald G., Carlyle, W. Matthew, and Wood, R. Kevin. (2011). "Solving Defender-Attacker-Defender Models for Infrastructure Defense," *12th INFORMS Computing Society Conference*.

"Anti-Submarine Warfare: Concept of Operations for the 21st Century, by Task Force ASW. (2004). http://www.navy.mil/navydata/policy/asw/asw-conops.pdf. Accessed 26 April, 2019.

"Autonomous Underwater Vehicle, HUGIN." Autonomous Underwater Vehicle, HUGIN – KONGSBERG MARITIME. Accessed 11 April 2019. https://www.kongsberg.com/maritime/products/marine-robotics/autonomous-underwater-vehicles/AUV-hugin/.

AUVAC. (2019). "BioSwimmer Spec." Accessed May 01, 2019. https://auvac.org/configurations/view/266.

Barber, F. M. (1874). "Lecture on the Whitehead Torpedo. U.S. Torpedo Station, 1874." http://hdl.handle.net/2027/nyp.33433006791994 and https://babel.hathitrust.org/cgi/pt?id=nyp.33433006791994;view=1up;seq=9.

Barker, P. (2018, March 15). "Undersea Cables and the Challenges of Protecting Seabed Lines of Communication." Retrieved from CIMSEC: http://cimsec.org/undersea-cables-challenges-protecting-seabed-lines-communication/35889.

Bjorno, L. “Developments in Sonar Technologies and Their Applications.” (2013). In *2013 IEEE International Underwater Technology Symposium* (UT), 1–8.

BOEM. “BOEM Gulf of Mexico OCS Region Blocks and Active Leases by Planning Area April 1, 2019.” (2019, April 1). Retrieved April 29, 2019, from https://www.boem.gov/Gulf-of-Mexico-Region-Lease-Map/.

Bomey, Nathan. (2016, July 14). “BP’s Deepwater Horizon Costs Total $62B.”. https://www.usatoday.com/story/money/2016/07/14/bp-deepwater-horizon-costs/87087056/.

Bousso, R. (2018, January 15). “BP Deepwater Horizon Costs Balloon to $65 Billion.” Retrieved from Reuters: https://www.reuters.com/article/us-bp-deepwaterhorizon/bp-deepwater-horizon-costs-balloon-to-65-billion-idUSKBN1F50NL.

Broadmeadow, James, Dziekan, Francis, Frantz, Francis, Gudz, Rodney, Kelley, Patrick, Kennedy, Shawn, Moreira, Christine et al. “Improved Anti-Submarine Warfare (ASW) Effectiveness MSSE.” Capstone Project, Monterey, California, Naval Postgraduate School, 2008.

Brown, Gerald, Carlyle, Matt, Salmeron, Javier and Wood, Kevin. (2005). *Analyzing the Vulnerability of Critical Infrastructure to Attack and Planning Defenses*. 10.1287/educ.1053.0018.

Brown, Carlyle, and Wood. “Optimizing Department of Homeland Security Defense investments: Applying defender-attacker (-defender) optimization to terror risk assessment and mitigation.” Appendix E of *Department of Homeland Security Bioterrorism Risk Assessment—A Call for Change*, National Research Council, Washington, DC, 90–102, 2008.

Brown, G. G. and Cox, Jr., L. A. (2011), “Making Terrorism Risk Analysis Less Harmful and More Useful: Another Try.” *Risk Analysis*, 31: 193–195. doi:10.1111/j.1539-6924.2010.01563.x.

Brown, Carlyle, Salmeron, and Wood. “Defending critical infrastructure.” *Interfaces* 36:530–544, 2006.

BSEE. (n.d.). Gulf of Mexico. Retrieved April 28, 2019, from https://www.bsee.gov/stats-facts/ocs-regions/gulf-of-mexico.

Button, Robert W. *A Survey of Missions for Unmanned Undersea Vehicles*. Santa Monica, CA: RAND, 2009. https://www.rand.org/content/dam/rand/pubs/monographs/2009/RAND_MG808.pdf.

Chu, Peter C. "Unmanned Undersea Vehicle (UUV) for Navy's Science/technology and Operations, 2010." https://calhoun.nps.edu/bitstream/handle/10945/42440/Chu_Unmanned_undersea_vehicle_%28UUV%29_for_Navy%E2%80%98s_wof_2010_chu.pdf?sequence=1&isAllowed=y.

Cranswick, D. (2001). "Brief Overview of Gulf of Mexico OCS Oil and Gas Pipelines: Installation, Potential Impacts, and Mitigation Measures." Washington, DC: BOEM.

Davis, Russ & C. Eriksen, Charles & P. Jones, Clayton, *Autonomous Buoyancy-Driven Underwater Gliders*. 10.1201/9780203522301.ch3, 2002 http://www.ifremer.fr/lpo/gliders/donnees_tt/references/techno/4Gliders.pdf.

DCNS Naval-Group, F21 Brochure. (2019). Accessed 11 April 2019. https://www.naval-group.com/wp-content/uploads/2017/01/f21-the-french-navys-new-heavyweight-torpedo.pdf.

Dean, J. (2017). *Threats to Undersea Cable Communications*. Washington, DC: Office of the Director of National Intelligence.

Department of Defense. 2014. "Program Acquisition Cost by Weapon System," March, 1–15. Washington, DC: Department of Defense.

Edelstein, K. (2017, March 8). Oil and Gas Development in Gulf of Mexico. Retrieved April 28, 2019, from https://www.arcgis.com/home/item.html?id=7aa4535ca4364efe86da66e0cbc376ab.

Gas Exports Presentation. Premier Oil, London, England, June 23, 2010.

Gaskill, M. (2018, June 14). Submarine Spying – Operation Ivy Bells in the Cold War. Retrieved from War History Online: https://www.warhistoryonline.com/cold-war/submarine-spying-operation-ivy-bells.html

Gassier, David, Rebollo, Jerome, and Dumonteil, Romain. "Implementing a Low-Cost Long-Range Unmanned Underwater Vehicle: The SeaDiver Glider." Monterey, California. Naval Postgraduate School, 2007. https://calhoun.nps.edu/bitstream/handle/10945/819/NPS-MV-07-001.pdf?sequence=1&isAllowed=y.

Glenney, B. (2019, February 4). "The Deep Ocean: Seabed Warfare and the Defense of Undersea Infrastructure." Retrieved from CIMSEC: http://cimsec.org/the-deep-ocean-seabed-warfare-and-the-defense-of-undersea-infrastructure-pt-1/39593.

Gulf of Mexico Fact Sheet. (n.d.). U.S. Energy Information Administration. Retrieved April 10, 2019, from https://www.eia.gov/special/gulf_of_mexico/.

Jane's Naval Forces. 2001. "Background Information: Mk 48 ADCAP - Underwater Warfare Systems." February 2, 2001. https://web.archive.org/web/20010401035621/http://www.janes.com/defence/naval_forces/news/juws/juws010202_1_n.shtml.

Kaiser, M. J. (2018, September 1). "Review of Gulf of Mexico well activity highlights decline." *Offshore*, https://www.offshore-mag.com/drilling-completion/article/16762013/review-of-gulf-of-mexico-well-activity-highlights-decline.

Kashubsky, M. (2011). "A Chronology of Attacks on and Unlawful Interferences with, Offshore Oil and Gas Installations, 1975–2010." *Perspectives on Terrorism*, 139–167.

Keller, John. "Navy Bulks-up Anti-submarine Warfare (ASW) Capability for Destroyer and Cruiser Surface Warships." Military & Aerospace Electronics - Military Technology, Weapons, Equipment & Systems for the Military Industrial Complex. January 18, 2019. Accessed April 29, 2019. https://www.militaryaerospace.com/articles/2019/01/anti-submarine-warfare-asw-surface-warships.html.

Kuzoian, Alex. "Animated Map Reveals the 550,000 Miles of Cable Hidden under the Ocean That Power the Internet." *Business Insider*. September 01, 2015. Accessed November 17, 2018. https://www.businessinsider.com/animated-map-global-fiber-optic-internet-cables-2015-9.

Liraz, Shay Paz. (2018). *Ships' Trajectories Prediction Using Recurrent Neural Networks Based On AIS Data*. Monterey, CA; Naval Postgraduate School.

Love, Matthew S. A. B. (2013). *The Gulf of Mexico Ecosystem: A Coastal & Maritime Atlas*. New Orleans: Ocean Conservancy.

MacCalman, Alex D., Beery, Paul T. and Paulo, Eugene P. (2016). "A Systems Design Exploration Approach that Illuminates Tradespaces Using Statistical Experimental Designs." *Systems Engineering*, 19(5), pp.409-421. http://hdl.handle.net/10945/58169.

Main, D. (2015, April 2). "Undersea Cables Transport 99 Percent of International Data." Retrieved from *Newsweek*: https://www.newsweek.com/undersea-cables-transport-99-percent-international-communications-319072.

Manning, M. (2016, October 28). "Offshore Oil Production in Deepwater and Ultra-deepwater is Increasing." Retrieved from eia.gov: https://www.eia.gov/todayinenergy/detail.php?id=28552.

MarEx. (2015). “Offshore Pipe Burial Could Be Cheaper.” *The Maritime Executive*. January 28, 2015. https://www.maritime-executive.com/article/offshore-pipe-burial-could-be-cheaper.

MarEx. (2019). “Indonesia Deploys Anti-Air System in S. China Sea” Accessed 2 March 2019. https://www.maritime-executive.com/article/indonesia-deploys-anti-air-system-in-s-china-sea.

María Adela, Monreal-Gomez, D., and A.-d.-L.-M. (2004). *Environmental Analysis of the Gulf of Mexico*. Mexico: Harthe Research Institute for Gulf Of Mexico Studies.

Morel, Michel, George, Jean-Pierre, Littaye, Anne, Jangal, Florent, Napoli, Aldo, Giraud, Marie-Annick, and Lebrevelec, Jacques. (2008). “ScanMaris c Automatic Detection of Abnormal Vessel Behaviours.” In *Comptes-Rendus Du Colloque International 3AF* : “L’Europe et La Transformation de Ses Forces.”

MPA. (2019). “Maritime and Port Authority of Singapore” Accessed 1 May 2019. https://www.mpa.gov.sg/web/portal/home/maritime-singapore/introduction-to-maritime-singapore/facts-and-trivia.

“Natuna Gas Field – Greater Sarawak Basin.” (2017). Offshore Technology | Oil and Gas News and Market Analysis. Accessed November 17, 2018. https://www.offshore-technology.com/projects/natuna/.

NOAA Gulf of Mexico Data Atlas. (n.d.). Retrieved April 28, 2019, from https://www.ncddc.noaa.gov/website/DataAtlas/atlas.htm?plate=Offshore%20Structures.

Nussbaum, Daniel. (2018). “Learning Curve.” Class Lecture, Naval Postgraduate School.

Office of the Chief of Naval Operations Washington, DC. *The Navy Unmanned Undersea Vehicle (UUV) Master Plan*, 2004. http://handle.dtic.mil/100.2/ADA511748.

Offshore Technology. (2010, May 6). Deepwater Horizon: A Timeline of Events. Retrieved from Offshore Technology: https://www.offshore-technology.com/features/feature84446/.

“Operations Manual Ver 1.5 06/17/2004,” Webb Research 2004, Accessed 11 April 2019. http://www.ifremer.fr/lpo/gliders/donnees_tt/tech/slocum/SLOCUM_M.PDF.

O’Rourke, Ronald. (2011). *Navy DDG-51 and DDG-1000 Destroyer Programs: Background and Issues for Congress*. Report RL32109. Washington, DC: Congressional Research Service.

O'Rourke, Ronald. (2016). "Coast Guard Cutter Procurement: Background and Issues for Congress," Library of Congress. Congressional Research Service. Washington, DC.

Osse, T.J, and Eriksen, C.C. (2007). "The Deepglider: A Full Ocean Depth Glider for Oceanographic Research." In *OCEANS* 2007, 1–12. IEEE.

Petty, Dan. (2019). "Navy.mil Home Page." The U.S. Navy – Fact File: MK 48 - Heavyweight Torpedo. Accessed 11 April 2019, https://www.navy.mil/navydata/fact_display.asp?cid=2100&tid=950&ct=2.

Petty, Dan. (2019). "Navy.mil Home Page." The U.S. Navy – Fact File: MK 54 - Torpedo. Accessed 11 April 2019, https://www.navy.mil/navydata/fact_display.asp?cid=2100&tid=1100&ct=2.

Pike, John. (1999). "The Sound Surveillance System (SOSUS)." April 21, 1999. https://fas.org/irp/program/collect/sosus.htm.

Product Spec. (2019). "Bluefin-21 Unmanned Underwater Vehicle (UUV)." General Dynamics Mission Systems. Accessed 11 April 2019. https://gdmissionsystems.com/en/products/underwater-vehicles/bluefin-21-autonomous-underwater-vehicle.

Product spec. (2019). "Panther-XT." Saab Seaeye. Accessed 11 April 2019 https://www.saabseaeye.com/solutions/underwater-vehicles/panther-xt.

Product spec. (2019). "Theseus AUV." International Submarine Engineering https://ise.bc.ca/product/theseus-auv/. Accessed 11 April 2019.

Product spec. (2019). "MU90/IMPACT." Accessed 11 April 2019. https://web.archive.org/web/20150715050000/http://www.eurotorp.com/the-products/mu90-impact_25.

"Russia to Deploy High-Speed Torpedo." (1995). Armed Forces Newswire Service. http://search.proquest.com/docview/446351716/.

Sakawa, K, Kojima, J, Kato, Y, Matsumoto, S, and Kato, N. "Autonomous Underwater Vehicle AQUA EXPLORER 2 for Inspection of Underwater Cables." In *Proceedings of the 2000 International Symposium on Underwater Technology* (Cat. No.00EX418), 242–247. IEEE, 2000.

"Seaglider Specifications." (2019). Applied Physics Laboratory, University of Washington, Accessed 11 April 2019. http://www.apl.washington.edu/project/projects/seaglider/pdfs/seaglider_specifications.pdf.

Soeriaatmadja, Wahyudi. (2019). “Indonesian President Joko Widodo’s trip to South China Sea islands a message to Beijing, says minister” Accessed 2 March 2019. https://www.straitstimes.com/asia/se-asia/indonesian-president-sails-to-south-china-sea-islands-in-message-to-beijing.

“Spearfish Heavyweight Torpedo.” (2019). Defense Update: August 17, 2017. Accessed 11 April 2019. https://defense-update.com/20170816_spearfish.html.

Sulfredge, C. David, Robert H. Morris, and Robert L. Sanders. *Calculating the Effect of Surface or Underwater Explosions on Submerged Equipment and Structures*. Accessed April 29, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.129.8805&rep=rep1&type=pdf.

Sun, Peng, and Boukerche, Azzedine. “Modeling and Analysis of Coverage Degree and Target Detection for Autonomous Underwater Vehicle-Based System.” *IEEE Transactions on Vehicular Technology* 67, no. 10 (October 2018): 9959–9971.

“Surface Currents in the Caribbean Sea and Gulf of Mexico.” (2019). Accessed April 29, 2019. https://oceancurrents.rsmas.miami.edu/caribbean/spaghetti-speed.html.

Tovey Alan. (2014, December). “Already faster than a cheetah, the Navy’s two-tonne Spearfish torpedoes are getting an upgrade.” *Telegraph*, United Kingdom. Accessed 11 April 2019.

Trevithick, Joseph. (n.d.) “Boeing Is Building Big Orca Drone Subs For The Navy To Hunt And Lay Mines And More.” The Drive. Accessed May 14, 2019. https://www.thedrive.com/the-war-zone/26513/boeing-is-building-the-navy-big-orca-submarine-drones-to-hunt-and-lay-mines-and-more.

Tyler, Patrick E. (2000, Dec. 01). “Behind Spy Trial in Moscow: A Superfast Torpedo.” *New York Times*. Accessed 11 April 2019. https://www.nytimes.com/2000/12/01/world/behind-spy-trial-in-moscow-a-superfast-torpedo.html.

U.S. Department of Commerce, and National Oceanic and Atmospheric Administration. (2018). “What Is a Hydrophone?” NOAA’s National Ocean Service. Accessed April 30, 2019. https://oceanservice.noaa.gov/facts/hydrophone.html.

“View Details of Chart 11006, Gulf Coast – Key West to Mississippi River.” Nautical Charts Online. Accessed April 29, 2019. https://www.nauticalchartsonline.com/chart/zoom?chart=11006.

Whitcomb, Clifford, and Paul Beery. (2016). “Exploring the Design Space.” *Trade-off Analytics: Creating and Exploring the System Tradespace*, edited by Gregory S. Parnell, 405–436. Hoboken, NJ: John Wiley & Sons.

Wong, Lam F. (2013). “A Generalized Learning Curve Adapted for Purchasing and Cost Reduction Negotiations.” *Advances in Operations Research* 2013: 9.

Wood, Stephen. (2019). *Autonomous Underwater Gliders*. Florida Institute of Technology. Accessed 11 April 2019. http://my.fit.edu/~swood/26_Wood_first.pdf.

Wrathall, L. R. (2010). "The Vulnerability of Subsea Infrastructure to Underwater Attack: Legal Shortcomings and the Way Forward." *San Diego International Law Journal*, 223–262.

Yuan Zhuang, Yang Li, and Wei Su. (2016). "Influence of Anchoring on Burial Depth of Submarine Pipelines." PLoS ONE 11, no. 5: e0154954. https://doaj.org/article/fedc9f8a02b44c848d378e3f5ff02e05.

Zeringue, B. A. (2017). U.S. *Outer Continental Shelf Gulf of Mexico Region Oil and Gas Production Forecast: 2018–2027*. New Orleans: Bureau of Ocean Energy Management.

Zha, Bing-Ting, Yuan, Hai-Lu, and Tan, Ya-Yun. (2019, Jan. 15). "Ranging Precision for Underwater Laser Proximity Pulsed Laser Target Detection." *Optics Communications* 431: 81–87.

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