NAVAL POSTGRADUATE SCHOOL

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THESIS

ASSESSING ORCHESTRATED SIMULATION THROUGH MODELING TO QUANTIFY THE BENEFITS OF UNMANNED–MANNED TEAMING IN A TACTICAL ASW SCENARIO

by

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March 2018

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    The U.S. Navy's strategy calls for maintaining dominance in the undersea domain. One way to add undersea warfare capability is to team the P-8 Poseidon with the Medium Displacement Unmanned Surface Vessel (MDUSV). A tool to study the potential benefit of integrating the two platforms is Orchestration Simulation Through Modeling (OSM), which allows the modeler to use a map of the world to define a combat zone, build agents with pre-defined behaviors and states, and run hundreds of thousands of simulated missions built with the Littoral Combat Ship Integrated Toolkit for Mission Engineering Using Simulations (LITMUS). To assess LITMUS's ability to quantify the benefit of integrating these two platforms, 95,700 tactical antisubmarine warfare (ASW) engagements are simulated using the program with the P-8 alone, MDUSV alone, and the P-8 and MDUSV working in tandem. LITMUS statistical data analysis, while limited by software constraints, indicates a 30% improvement in the probability of a kill by a P-8 hunting a submarine versus the MDUSV alone, and a 10% decrease in conditional mean time to kill the submarine given the submarine is killed when the P-8 and MDUSV work in tandem versus the P-8 operating alone. Adding a dark submarine to act as a false contact to each of the three scenarios had a negligible effect on both the conditional mean time to kill and the probability the submarine is killed. Comparison of LITMUS's results to those obtained using a different simulation model indicates the LITMUS results are optimistic and LITMUS software modifications are required to improve LIMTUS's representation of the scenario.

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ASSESSING ORCHESTRATED SIMULATION THROUGH MODELING TO QUANTIFY THE BENEFITS OF UNMANNED–MANNED TEAMING IN A TACTICAL ASW SCENARIO

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iii

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ABSTRACT

The U.S. Navy's strategy calls for maintaining dominance in the undersea domain. One way to add undersea warfare capability is to team the P-8 Poseidon with the Medium Displacement Unmanned Surface Vessel (MDUSV). A tool to study the potential benefit of integrating the two platforms is Orchestration Simulation Through Modeling (OSM), which allows the modeler to use a map of the world to define a combat zone, build agents with pre-defined behaviors and states, and run hundreds of thousands of simulated missions built with the Littoral Combat Ship Integrated Toolkit for Mission Engineering Using Simulations (LITMUS). To assess LITMUS's ability to quantify the benefit of integrating these two platforms, 95,700 tactical antisubmarine warfare (ASW) engagements are simulated using the program with the P-8 alone, MDUSV alone, and the P-8 and MDUSV working in tandem. LITMUS statistical data analysis, while limited by software constraints, indicates a 30% improvement in the probability of a kill by a P-8 hunting a submarine versus the MDUSV alone, and a 10% decrease in conditional mean time to kill the submarine given the submarine is killed when the P-8 and MDUSV work in tandem versus the P-8 operating alone. Adding a dark submarine to act as a false contact to each of the three scenarios had a negligible effect on both the conditional mean time to kill and the probability the submarine is killed. Comparison of LITMUS's results to those obtained using a different simulation model indicates the LITMUS results are optimistic and LITMUS software modifications are required to improve LIMTUS's representation of the scenario.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

AAW	Anti-Air Warfare
ASM	Anti-Ship Missile
ASUW	Anti-Surface Warfare
ASW	Antisubmarine Warfare
AUSV	Autonomous Unmanned Surface Vehicle
BAMS	Broad Area Maritime Surveillance
C2	Command and Control
CIWS	Close in Weapon System
CTUV	Continuous Trail Unmanned Vessel
DARPA	Defense Advanced Research Projects
DICASS	Directional Command Activated Sonobuoy System
DOE	Design of Experiments
EMCON	Emissions Control
EO/IR	Electro-optical/infrared
FAC	Fast Attack Craft
FIAC	Fast Inshore Attack Craft
GUI	Graphical User Interface
HAAWC	High Altitude Anti-Submarine Warfare Weapons Capability
KG	Kilograms
LCDR	Lieutenant Commander
LCS	Littoral Combat Ship
LITMUS	Littoral Combat Ship Integrated Toolkit for Mission Engineering Using Simulation
LTJG	Lieutenant Junior Grade
MAD	Magnetic Anomaly Detection
MANA	Map Aware Non-uniform Automata
MDUSV	Medium Displacement Unmanned Surface Vessel
MPA	Maritime Patrol Aircraft
NM	Nautical Miles
NOLH	Nearly Orthogonal Latin Hypercube

NSWC	Naval Sea Warfare Center
OLH	Orthogonal Latin Hypercube
ONR	Office of Naval Research
OSM	Orchestrated Simulation Through Modeling
PDMS	Point Defense Missile System
RSCS	Remote Supervisory Control Station
SIMIO	Simulation Modeling Framework Based on Intelligent Objects
UAV	Unmanned Aerial Vehicle
UHF	Ultra High Frequency
USV	Unmanned Surface Vessel
USW	Undersea Warfare
VHF	Very High Frequency
VTUAV	Vertical Take-Off UAV

EXECUTIVE SUMMARY

The U.S. Navy's ability to maintain sea control is challenged in the undersea domain. Both historically and in the present day, a principal threat to the Navy's ability to project power and maintain sea lines of communication has come in the form of submarines. While the U.S. Navy is limited by budget and manning constraints, it must continue to leverage its resources to maintain its current antisubmarine warfare (ASW) dominance.

One of the most powerful tools for the U.S. Navy to conduct ASW is the P-8 Poseidon. The P-8 Poseidon can fly at speeds in excess of 490 knots, has a stay time of approximately four hours, a combat radius of 1,200 nautical miles, and can deploy up to 120 sonobuoys. The P-8 Poseidon is also capable of launching a high altitude ASW weapon from up to 30,000 feet. The P-8 possesses a powerful communications suite that is capable of communicating with multiple unmanned aerial vehicles simultaneously.

Another new powerful asset for the U.S. Navy to conduct ASW is the Medium Displacement Unmanned Surface Vehicle (MDUSV). The MDUSV has the ability to conduct multiple waypoint missions without any human assistance, and will soon possess the ability to conduct reconnaissance, offensive-antisubmarine payloads, and intelligence-gathering operations. The MDUSV is unmanned and consequently is able to operate in sea states that are normally prohibitive for manned crews. Because the MDUSV is unmanned, it can also operate at a fraction of the cost of a normal ASW ship, such as a destroyer or cruiser.

Combining the MDUSV and the P-8 has certain apparent advantages when conducting ASW. The P-8's advanced communications suite already has the ability to communicate with unmanned aerial vehicles, therefore logic suggests it should be able to be modified to communicate with the MDUSV. The MDUSV is unmanned, therefore if an enemy submarine were to shoot at it and sink it, it would give away its positional information to the P-8 and the U.S. Navy would not incur any personnel casualties.

Because it is prohibitively expensive to conduct several thousand tests between the P-8 and MDUSV in a tactical ASW scenario with a submarine, simulation is a powerful and necessary tool to quantify the benefits of this integration. Previous research on this topic has been conducted utilizing Map Aware Non-uniform Automata (MANA). Since then, new more powerful software has been developed, such as Littoral Combat Ship Integrated Toolkit for Mission Engineering Using Simulation (LITMUS). Orchestrated Simulation Through Modeling (OSM) allows the modeler to use a map of the world to define a combat zone, build agents with pre-defined behaviors and states, and run hundreds of thousands of simulated missions built with LITMUS.

This research assesses LITMUS's ability to empirically estimate the mean time to kill and the mean number of kills for the MDUSV alone (Case A), P-8 Alone (Case B), and MDUSV with P-8 (Case C). Furthermore, this research explores what influence, if any, adding a false contact in the form of a dark submarine adds to the conditional mean time to kill the submarine given the submarine is killed and the probability the submarine is killed for each scenario. Results are compared to a previous study using a similar design of experiments but different simulation software.

The baseline scenario for exploring the MDUSV's value in ASW missions is as follows: a red submarine passes through an area 110nm wide by 50nm long at a speed of 6–10 knots and must be detected and killed. Nearly orthogonal Latin hypercube (NOLH) design of experiments is used to provide efficient sampling of the variable space and to reduce the total number of design points required for the research. This allows for more replications at each design point, which consequently produces valuable statistical data.

Analysis of the results shows that in the scenario with only the MDUSV, the MDUSV was able to kill the red submarine approximately 70% of the time, while the P-8 and P-8 with MDUSV had nearly identical probabilities of kill at 99.99%. There was a 10% improvement in the conditional mean time to kill the red submarine given it is killed when the P-8 and the MDUSV worked in tandem as opposed to the P-8 operating alone. Furthermore, adding the dark submarine had negligible effect on any of the cases.

When comparing these results with previous results conducted with MANA (Solem, 2016), it is apparent LITMUS current software limitations are the primary reason the simulation results indicate that the P-8 is so enormously successful in killing the red submarine. Specifically, LITMUS is currently unable to model a localization phase after the P-8's initial detection, which results in a sonobuoy detection by the P-8 immediately translating to a submarine kill. In reality, the P-8 requires additional time and sonobuoys to locate, track, and target a submarine. This shortcoming has been communicated to Naval Surface Warfare Dahlgren LITMUS programmers and corrective code is being developed. Because the simulated P-8 is so successful in killing the red submarine, it is difficult to glean insight from the difference between the P-8 case and the P-8 with MDUSV case. Nevertheless, even with this artificially high kill rate, it was still shown that the two platforms working in tandem were able to more quickly kill the red submarine then when they worked apart.

Further analysis of the results shows which variables are most influential in each specific case. For the MDUSV alone, the red submarine's concealment rate is the single most important factor for determining the probability of killing the red submarine. Concealment rate represents the effect of the MDUSV's acoustic sensor effectiveness against a particular submarine in a particular acoustic environment. For the P-8 alone and the P-8 with MDUSV case, the P-8's sonobuoy performance is most important in determining both the probability of killing the red submarine and conditional mean time to kill the red submarine given it is killed.

The results of this research suggests that the U.S. Navy will benefit most from continuing to improve its sonobuoy performance in a tactical ASW scenario involving a P-8. With further improvements in LITMUS, more accurate modeling can be conducted to better quantify the precise amount of improvement attained when teaming the P-8 with the unmanned MDUSV.

References

Solem, K. (2016*). Quantifying the potential benefits of antisubmarine warfare (ASW) continuous trail unmanned vessels (ACTUV) in a tactical ASW Scenario* (Master's thesis). Naval Postgraduate School, Monterey, CA.

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I.   INTRODUCTION

The U.S. Navy continues to pursue a strategy of forward presence, which is contingent upon maintaining undersea warfare dominance. Ray Mabus, the previous Secretary of the Navy, states that "Forward naval presence is essential to strengthening alliances and partnerships, providing the secure environment necessary for an open economic system based on the free flow of goods, protecting U.S. natural resources, promoting stability, deterring conflict, and responding to aggression." Both historically and in the present day, a principal threat to the Navy's ability to project power and maintain sea lines of communication has come in the form of submarines. Accordingly, the U.S. Navy continuously perfects its antisubmarine warfare (ASW) capabilities.

During the Cold War, the U.S. Navy pursued a strategy of maintaining a large number of assets that collectively tracked and monitored all Soviet submarine assets. With the rampant proliferation of inexpensive diesel submarines, the United States is no longer able to match the quantity of boats that potential adversaries such as China and Russia can put out to sea. Additionally, the U.S. Navy deploys across the globe and is dispersed accordingly, while these potential adversaries are able to concentrate their fleet in particular regions of interest.

Much time and research has been dedicated to solving this looming capacity mismatch. This includes the possibility of the Navy combining manned and unmanned systems to enhance area ASW performance. To aid decision makers on the empirical benefits of such an integration, we use simulation to demonstrate the performance difference of manned ASW systems compared to unmanned ASW systems, and then comparing each to pairing manned with unmanned ASW systems. Simulation provides an inexpensive means for decision makers to assess the type of assets to develop, how many of those assets to purchase and how they should be employed.

A.   BACKGROUND

Recognizing the growing capacity mismatch, the U.S. Navy is developing unmanned systems that operate at a fraction of the cost of manned vessels. One unmanned

system being developed is *Sea Hunter*, a vessel developed by the Defense Advanced Research Projects Agency (DARPA) to assist in ASW. Figure 1 depicts the *Sea Hunter* with its distinct trimaran hull getting underway from the Willamette River following its christening in 2016. *Sea Hunter* is an autonomous unmanned surface vessel (USV) that the Office of Naval Research (ONR) has designated a Class III Medium Displacement Unmanned Surface Vehicle (MDUSV). ONR is conducting additional testing of *Sea Hunter* in San Diego, and has demonstrated that *Sea Hunter* is able to complete multi-waypoint missions without any human assistance. By FY2018, the ONR reports that new capabilities installed in *Sea Hunter* will include the ability to conduct reconnaissance, offensive-antisubmarine payloads, and intelligence gathering (Owens, 2017).

  Sea Hunter is a trimaran vessel that improves stability without having to increase the weighted keel and therefore better withstand waves. It is 40 meters long, weighs 135 tons, and has a range of up to 10,000 nautical miles (NM). *Sea Hunter* has been installed with electro-optical/infrared (EO/IR) as well as an advanced radar that utilizes a high-frequency signal to detect vessels using stealth (Owens, 2017). It is specifically designed to be unmanned, and has a built-in compatibility with the Remote Supervisory Control Station (RSCS). This station can be located either on shore or at sea. It is feasible the RSCS can also be modified to be deployed in a Maritime Patrol Aircraft (MPA) such as the P-8 Poseidon.

Figure 1. Photo of *Sea Hunter* underway on the Willamette River.
Source: Williams (2017).

Another powerful U.S. Navy ASW asset is the P-8 Poseidon. Figure 2 shows a P-8A with its bomb doors open and labels showing the different components of the aircraft. The P-8 Poseidon replaces the aging P-3 Orion and has several new and powerful ASW capabilities. The P-8 Poseidon was developed by Boeing Defense, Space & Security and first flew in April 2009 and entered service in November 2013. The U.S. Navy has acquired 51 P-8 Poseidons (Boeing, n.d.). Boeing has also developed and sold P-8 Poseidons to the Indian Navy and the Royal Australian Air Force (Boeing, n.d.).
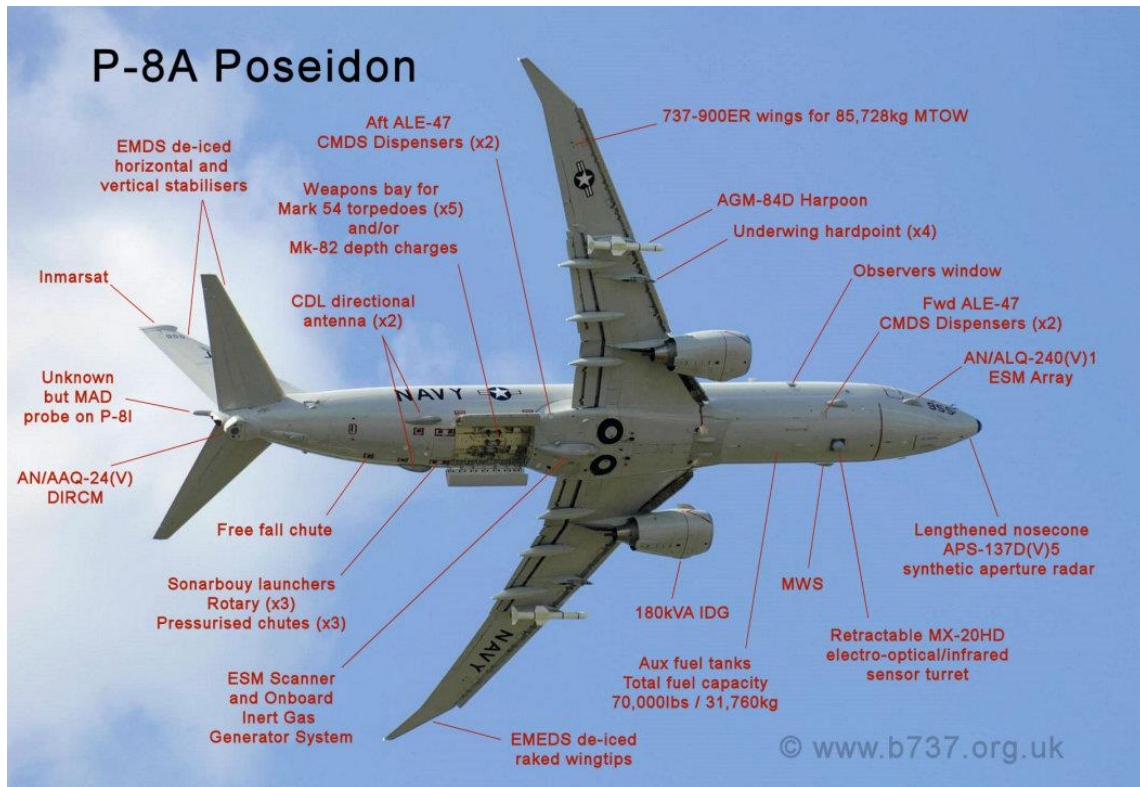
Figure 2. Photo of P-8A. Source: Dawes (2017).

The P-8 Poseidon carries and deploys up to 120 sonobuoys and has the ability to control unmanned air vehicles which allow its sensors range to be increased exponentially (Boeing, n.d.). It carries additional armaments such as the Mark 54 Torpedo, which it launches at high altitudes via its High Altitude Antisubmarine warfare Weapon Capability (HAAWC) system shown in Figure 3. The P-8's crew consists of a minimum of two pilots, with up to seven total personnel when carrying out specific missions such as extended area ASW missions. Its length is 39.47 meters, wingspan 37.64 meters, and take off payload a maximum of 85,820 kilograms (Naval Air Systems Command, 2017). Its maximum speed is 490 knots, with a typical cruising speed of 440 knots. While conducting ASW, it remains on station for approximately four hours with a combat radius of 1,200 nautical miles (NM). The most distinguishing characteristic between the P-8A Poseidon and its predecessor, the P-3 Orion is that the P-8A Poseidon is designed to operate at higher altitudes. Accordingly, the P-3's Magnetic Anomaly Detection Suite (MAD), which requires low altitude operations, is not a P-8 capability. Instead, the P-8 emphasizes HAAWC deployment to

prosecute submarines. A model HAAWC is shown in Figure 3. Furthermore, at higher altitudes the P-8 Poseidon's crew is able to fully utilize the Poseidon's sensor suite, which includes a multi-mode radar, electro-optical/infrared camera, and a multi-static active coherent acoustic system.

Figure 3. Photo of Model HAAWC. Source: Seligman (2016).

The HAAWC kit is the first enabler for the P-8A Poseidon's ASW capabilities. The HAAWC kit turns the Navy's Mark 54 lightweight torpedo into a glide weapon system that contains a miniature jet with wings, a tail, and a GPS-guided navigation system. Once it is near the water the wings and tail peel off and a parachute is deployed slowing the velocity and lowering the torpedo into the water. From there, the engine is activated and the torpedo proceeds toward its target. The HAAWC may be released from ceilings as high as 30,000 feet (Trimble, 2017).

The P-8 Poseidon uses a sonobuoy storage, deployment, and assessment system to search, find, and track submarines. The principal sonobuoy utilized in this study's simulation and deployed by the P-8 Poseidon is the AN/SSQ-62E Directional Command Activated Sonobuoy System (DICASS). Figure 4 shows DICASS being loaded onto a MH-

60R helicopter. DICASS is an expendable, command activated sonobuoy that uses active sonar transmissions in order to track submarines. It has the ability to have a variable depth set for its sensors, and uses either very high frequency (VHF) or ultra-high frequency (UHF) to transmit range, bearing, and Doppler information on active sonar contacts (Naval Air Systems Command, 1998). The DICASS receives orders from the P-8 Poseidon to vary its depth, pulse mode, and pulse duration.

Figure 4. Photo of DICASS being loaded onto an MH-60R. Source: Keller (2014).

This research uses and assesses the simulation software named the Littoral Combat Ship (LCS) Integrated Toolkit for Mission Engineering Using Simulation (LITMUS). This software runs on the Orchestrated Simulation through Modeling (OSM) Framework, which is written in Java. OSM uses a Graphical User Interface (GUI), which allows the modeler to use a map of the world to define a combat zone, build agents with pre-defined behaviors

and states, and run replications of scenarios hundreds of thousands of times to determine the average outcome and distribution of outcomes of a given scenario.[1]

LITMUS allows modelers to build agents and define their behavior. These behaviors includes platform type, available subsystems, receivers, orders, navigation, sensors, and weapons. All subsystems can have constraints placed on them, such as restricting the MDUSV's turning rate to only three degrees per second and red submarine's minimum gun range. Once all the agents have been created, an experiment may be designed and run with the number of replications for each experiment designated in LITMUS. Each replication produces a single output file which can then be parsed to gather desired metrics.

B.   RESEARCH QUESTIONS

This thesis' primary goal is to assess the LITMUS simulation's ability to provide insight into tactical employment of new technologies. We accomplish this investigation by focusing on the previously mentioned issue of employing the MDUSV with the P-8 in an area ASW tactical scenario.

All simulations runs conducted in this study utilize the same baseline scenario. The baseline scenario consists of a 110 nm by 50nm wide area. A red submarine moves at a speed of 6–10 knots from the area's southern portion to a destination point in the area's northern section while avoiding detection. The blue forces attempt to detect, localize, and engage the submarine in three different scenarios with (1) P-8 and MDUSV working in tandem, (2) MDUSV alone, and (3) P-8 alone. Each scenario then has a subcase of having a dark submarine present, and one without. Output data from the scenario runs are analyzed to compare these three scenarios to answer the following questions:

1.   What is the conditional mean time to successfully kill the submarine given the submarine is killed for each scenario?

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[1] LITMUS and OSM software are described in a non-published, unclassified office word document designed by the Naval Sea Warfare Center (NSWC) Orchestrated Simulation through Modeling (OSM) Team, based in Dahlgren, Virginia. The two word documents used by the OSM team are titled the Conceptual Model, and LITMUS Users Guide. Both of these word documents were built and used only within the OSM Team and were emailed to the author to assist with completion of the thesis.

2.   What is the improvement in conditional mean time to kill the submarine given it is killed in scenario (1) versus (2) and (3)?

3.   What influence, if any, does the presence of a dark submarine cause to the conditional mean time to kill the red submarine given it is killed for each scenario?

C.   LITERATURE REVIEW

The Naval Postgraduate School Operations Research department has a long history of using simulation to assess tactical employment of new naval technologies. LT Berner used modeling and agent-based simulation with MANA to explore the effective use of multiple unmanned aerial vehicles (UAV) (Berner, 2004). His thesis work investigated the ideal combination of Broad Area Maritime Surveillance (BAMS) UAVs and Vertical Take-Off UAVs (VTUAV). He ran 20,000 iterations of two different scenarios in MANA to demonstrate that the ideal combination of UAVs is one BAMS and two or three VTUAVs. His model also shows that the tactical employment of BAMS is not as important as the mere presence of BAMS itself.

Lieutenant Junior Grade (LTJG) Serif Kaya of the Turkish Navy also used modeling and agent-based simulation with MANA to evaluate the effectiveness of a frigate in an anti-air warfare (AAW) environment (Kaya, 2016). Using MANA, he built a scenario with a lone frigate defending itself against five aircraft armed with anti-ship missiles (ASM) and three land-based ASMs, as depicted in Figure 5. By running 25,700 simulated engagements of this scenario, LTJG Kaya used regression analysis and partition trees to analyze the results and concluded that the most important design factor for the frigate's successful defense was the selection of using either its Close In Weapon System (CIWS) or Point Defense Missile System (PDMS). LTJG Kaya also concluded that "the use of a medium range UAV in an AAW environment does not significantly contribute to mission success."
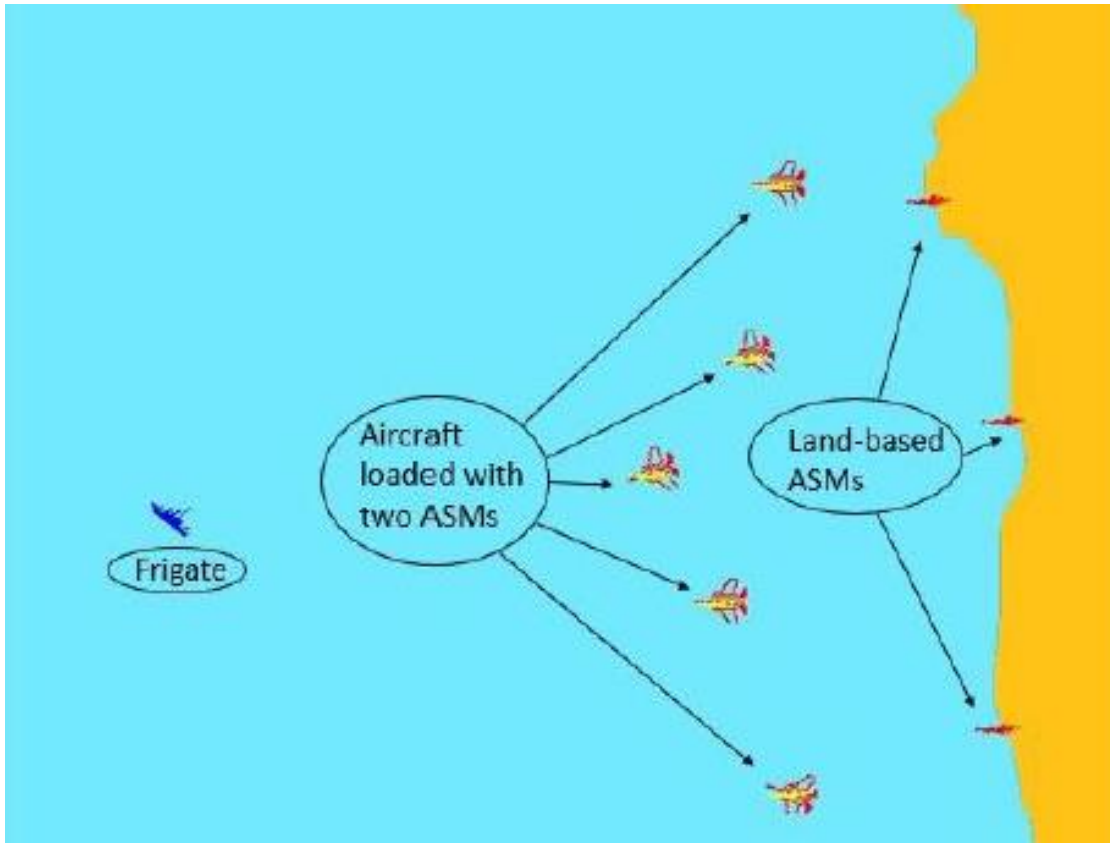
Figure 5. Screenshot of MANA scenario for LTJG Kaya's Frigate
AAW thesis. Source: Kaya (2016).

Simulation theses are also done using other software apart from MANA. One such software was the Simulation Modeling Framework Based on Intelligent Objects (SIMIO) used by Commander Anderson in his thesis to investigate the efficacious deployment of UAVs for defense against fast attack craft (FAC)/fast inshore attack craft (FIAC) (Anderson, 2016). Commander Anderson used simulation to measure the cost-effectiveness of deploying UAVs to successfully establish an anti-surface warfare (ASUW) kill chain against the FAC/FIAC threat compared to deploying manned fixed-wing aircraft. His thesis conducted over 132,000 simulation runs over 200 modeling parameters and variables and concluded that UAVs provide a viable and cost effective alternative to manned aircraft in the execution of FAC/FIAC ASUW kill chains.

Other notable Operations Research theses using simulation include a simulation to assess the Naval Integrated Fire Control-Counter Air (NIFC-CA) capability (Souba, 2017),

9

assessing high energy laser employment in ship self-defense tactics (Rockwell, 2015), and assessing the effectiveness of augmenting the P-8 with Coyote UAVs to provide low altitude MAD sensors (Williams, 2016). The first three of these used OSM.

The most recent and relevant research to this study was conducted by LCDR Solem (Solem, 2016). LCDR Solem's thesis runs a very similar scenario, albeit utilizing a software known as Map Aware Non-uniform Automata (MANA). His baseline scenario's engagement area dimensions and agents' behaviors are mimicked in this research, enabling Solem's MANA results to be compared to our LITMUS' results. By design, the principal difference between efforts is our use of the LITMUS software to assess the impact of adding a MDUSV to a P-8's area ASW operations. We assess the LITMUS software to approach this problem. In addition, a dark submarine entity is further developed in this study to act as a false alarm and/or decoy for the red submarine. The dark submarine's introduction will inherently increase the likelihood the actual red submarine is able to escape detection.

The simulation was principally written using *LITMUS User's Guide*, however, the user guide was fairly limited and many specific questions had to be answered directly by LITMUS developers at NSWC Dahlgren. All sonobuoy parameters are gathered from unclassified NAVAIR publications. All P-8 parameters are gathered from Boeing's official figures. MDUSV parameters are compiled from different sources, including ONR and various military news outlets.

D.   SCOPE AND LIMITATIONS OF THE THESIS

The purpose of this research is to assess LITMUS' ability to empirically determine the improvement gained by combining a P-8 and an MDUSV in hunting a submarine. Intelligent design of experiments is used in order to account for changes in variables which affect the possible outcome of the scenario. This research uses several thousand iterations of tactical engagements to produce the metrics we desire, namely the mean time to kill and the mean number of kills. This research also utilizes techniques from probability, statistical data analysis, and search theory and detection. All of the inputs for the parameters of the agents are gathered from open source materials in order to ensure this thesis remains

unclassified. It is important to keep in mind that for any model, it is not a perfect representation of real world events, nevertheless it can serve as a useful tool for decision makers to determine how much utility may be gained by combining a P-8 with an MDUSV in a tactical ASW scenario.

The following outline is followed for this thesis. Chapter II addresses the analytical models used, description of the agents, and the design of experiments. Chapter III addresses the results from the initial findings, and the results from each case. Chapter IV addresses the conclusions and follow on research topics.

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II.   METHODS

A sequential method is used to investigate the value of the P-8 and MDUSV in ASW missions. First, the scenario is defined and modeled in a simulation environment. Second, the design of experiments is utilized to select which design points should be investigated in the Monte Carlo simulation. Third, a simulated ASW mission is executed using the model and design points to produce data for analysis. Finally, the output data is analyzed to determine the effects of the factors on mission success.

A.   MODEL

The thesis uses the Littoral Combat Ship Integrated Toolkit for Engineering Using Simulation (LITMUS) within the Orchestrated Simulation Through Modeling (OSM) framework. LITMUS was originally developed to accommodate modeling of the Littoral Combat Ship (LCS) Surface Warfare (SUW) simulations, however, the developers wrote the software such that it can be utilized to define agents for more dynamic types of scenarios, to include ASW.

1.   Littoral Combat Ship Integrated Toolkit for Mission Engineering Using Simulation LITMUS

In LITMUS, the developer can build their own scenario using the Graphical User Interface (GUI). The developer is presented with a map of the world and can choose which part of the world they would like to have their scenario take place in. Figure 6 shows the two dimensional map the developer is able to manipulate when they initially open LITMUS.
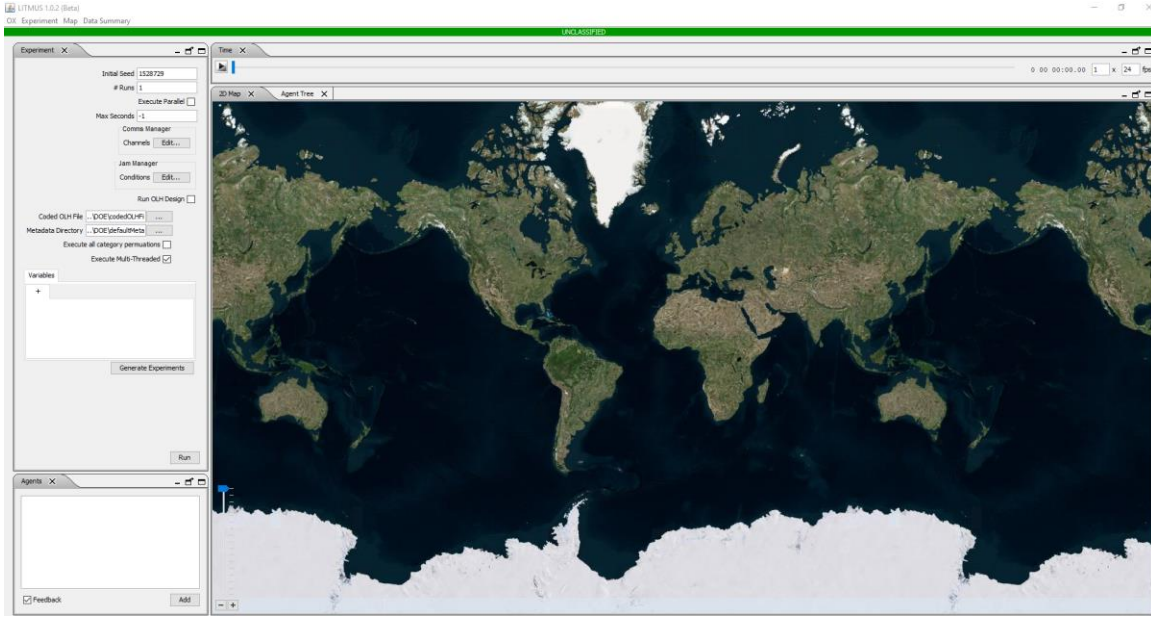
Figure 6. Screenshot of LITMUS GUI 2D map interface

2.   Experiments

The research uses LITMUS in order to create our scenario. The environment in LITMUS allows the developer to choose the number of runs to take place, the maximum amount of time each scenario can run, and the initial seed used for the experiment. By changing the initial seed, the developer can examine replications where outcomes are distinct from other replications only through random chance. When an experiment has finished running, the output file annotates the seed in the title of the output file. This is done to enable the developer to reproduce exact copies of specific outcomes. The seed is also critical because of the way pseudo-random numbers are generated within the model. An algorithm generates the seed utilizing a pseudo-random initial value, normally from the computer's internal clock. This value can then be used by the model to create pseudo-random behavior for agents. This process is a critical aspect of the simulation because it allows for the model to account for the randomness that is inherent in the real world.

The developer can also choose to have the experiment terminate when a specific condition is met, e.g., the enemy submarine is destroyed. Furthermore, the developer can also define if radars can be jammed with the jam manager and under which conditions this takes

place. The design of experiments (DOE) can also be set here. The developer can choose to load their own coded orthogonal Latin hypercube (OLH) file or they can manually add specific design points as being either category-valued or numerical-valued variables. Figure 7 shows the experiment tab and the aforementioned options that can be set.
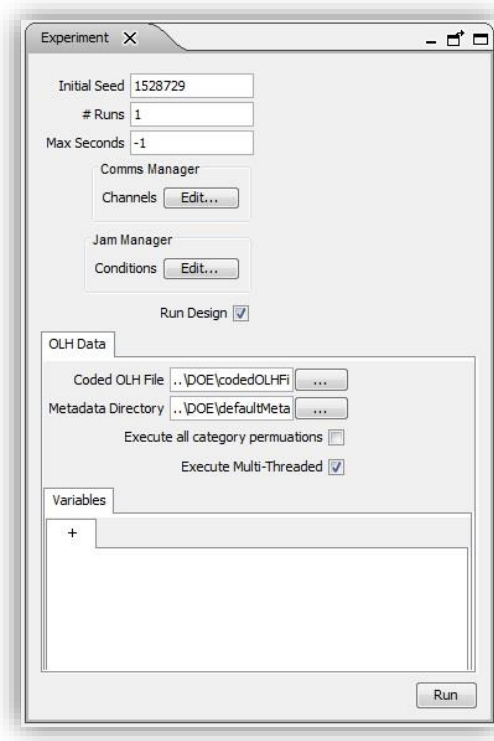
Figure 7. Screenshot of LITMUS experiment tab with options

3.   Agents

Agents are entities within the experiment that can have their characteristics and behavior defined by the developer. Agents are defined in terms of their seven modifiable characteristics. The first is platform, which allows the developer to set type (e.g., submarine), as well as the initial location. The second is subsystems, which allows the developer to add a jammer, gun, laser, sensor, wake, or missile launcher. The third is receiver, which allows the developer to add a command and control (C2) or distress signal emitting capability to the agent. The fourth characteristic is the C2 Order Manager, which

enables the agent to transmit orders to other agents. The fifth characteristic is weapon management, which allows the developer to set in firing doctrine. The sixth characteristic is navigation, which defines upper and lower bounds for the angle of turn of the agent, speed, and travel distance. The seventh and final characteristic is track management, which allows the developer to define how frequently their sensors sweep the area surrounding the agent, and their corresponding Emissions Control (EMCON) state. Figure 8 shows a screenshot of LITMUS' new agent tab and the aforementioned characteristics.

Figure 8. Screenshot of LITMUS agent tab

4. Agent Descriptions

The baseline scenario requires the model to be restricted to a finite geographic region and the agents to behave as desired within that region. The agents required are the red submarine, the blue P-8 Poseidon, the blue MDUSV, the dark submarine (acting as a false contact or decoy), and the blue sonobuoys.

a. Red Submarine

The red submarine is an agent which is hunted in the simulation. The red submarine is pseudo randomly created within a five nautical mile (NM) by 100 nm nautical mile box located directly north of the combat area, as depicted in Figure 8. Its longitude is fixed to the center of the red box, and its latitude is pseudo randomly chosen within the generation box utilizing the initial seed. A destination for the red submarine is also generated in the red submarine destination box. This location is also pseudo randomly chosen using the initial seed from the experiment. The red submarine will go directly from its generation position to its destination. It will move at a pseudo-random speed generated by the initial seed at 6 to 10 knots. While moving toward its destination, for this research, it will not conduct any evasive maneuvers if detected. Rather, it will continue toward its destination ignoring all outside agents' behaviors.

b. Blue P-8 Poseidon

The blue P-8 Poseidon agent is generated within a 10 nm by 50 nm box, colored yellow, as depicted in Figure 9. The P-8's initial position within this box is vertically fixed, and its horizontal position is pseudo randomly chosen within the box using the initial seed. Once it has been generated, the P-8 will move at a speed of 300 knots toward the east end of the patrol box until it reaches the border, then switch toward the west. It will continue to fly back and forth until either the red submarine or the dark submarine is detected.

Figure 9. Screenshot of LITMUS red submarine generation box and destination box

When either the red submarine or dark submarine is detected, the P-8 will immediately fly toward the target and destroy it via its HAAWC. The HAAWC in this simulation has a range of 10,000 meters and is 100% effective. Effective within the context of this model implies that the red submarine has been detected, classified, and localized within weapons release range, i.e., attack criteria has been established. The current version of LITMUS equates detection and P-8 movement to weapons range for this entire kill chain, which is a limitation and, as we will see, gives optimistic results. Once the target is destroyed the P-8 will return to its box then resume its patrol. The P-8 cannot discern between the red submarine and the dark submarine; ergo in some replications the P-8 will pursue the dark submarine while the red submarine escapes. Figure 10 utilizes a flowchart to depict a representation of the P-8's behavior. In Figure 10, the yellow boxes depict states, the blue ovals depict variables, and the green ovals depict Boolean conditions to the corresponding variables.
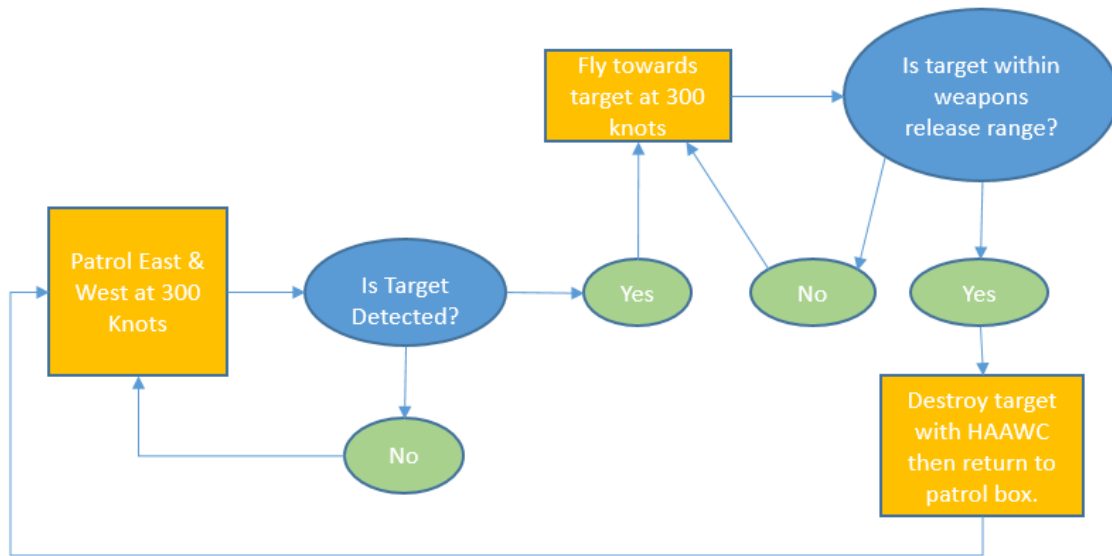
Figure 10.   Flow chart of P-8 Poseidon agent's behavior

The P-8 is able to receive positional information on its target from the sonobuoys or the MDUSV. It is worth emphasizing that the P-8 does not have any inherent ability to detect the red submarine, rather it depends on receiving positional information from either the MDUSV or the sonobuoys.

c.   Blue MDUSV

The blue MDUSV is generated 10 nautical miles south of the southeast corner of the P-8 yellow patrol box, as depicted in Figure 11. Upon being generated, the MDUSV will move at a pseudo-random speed of between 15 to 20 knots toward the latitude that bisects the green box. Once it reaches this position, it then begins patrolling east and west at its pseudo-random speed. It will continue patrolling from the eastern border of the green engagement area to the western border of the engagement area until a detection occurs, either from the sonobuoys or the MDUSV's organic sensors. Once a detection occurs, the MDUSV will move toward the position of detection and once within its weapon's release range it will fire upon the target. For this research, the MDUSV ASW weapon has a range of 10,000 meters and is 100% effective. After firing on the target it will return to a latitude that bisects the green box, then resume patrolling. Similar to the P-8, the MDUSV is unable

to discern between the dark submarine and the red submarine, so in some replications the MDUSV will chase the dark submarine while the red submarine escapes.

Figure 11.   Screenshot of LITMUS showing blue MDUSV generation position

The behavior of the blue MDUSV agent is similar to the P-8 Poseidon, with the exception that originally it moves from its generation position toward a pseudo-random location that bisects the green combat box then begins its patrol. Figure 12 utilizes a flow chart to summarize the behavior.
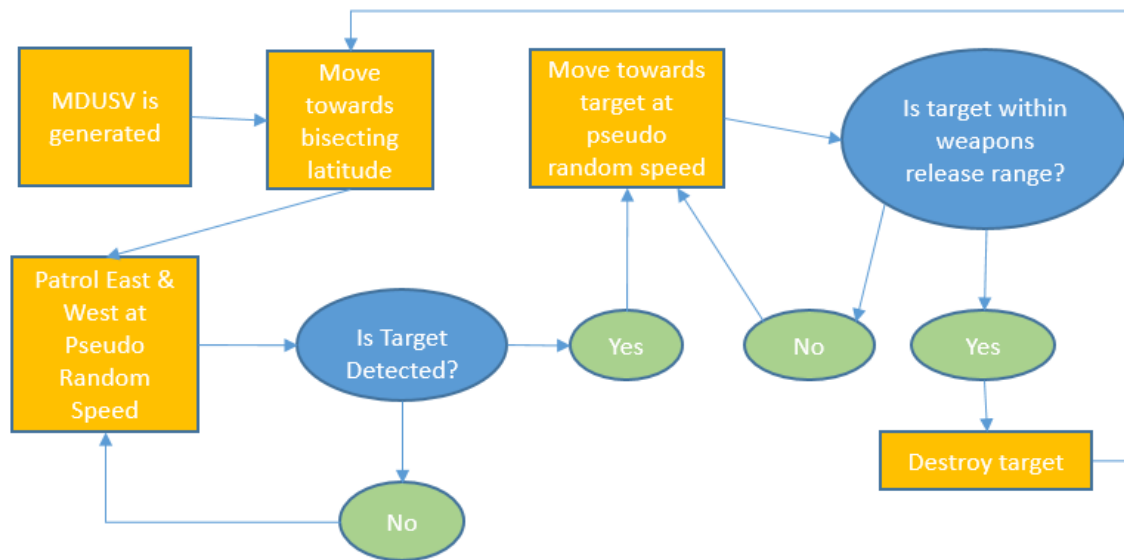
Figure 12. Flowchart depicting blue MDUSV agent behavior

The MDUSV can receive positional information on the target from its own sensors and from the P-8. Figure 13 depicts the communication paths between the blue agents.
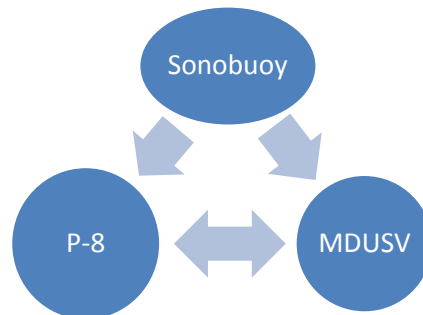
Figure 13. Flowchart depicting communications between blue agents

The MDUSV sensor performance is also pseudo-random. The MDUSV sensor range has a baseline performance that is pseudo randomly generated for each specific experiment. This value ranges from 0.1 to 2.0, depicting a degradation down to 10% effective up to highly

favorable conditions boosting detection by 200%. The MDUSV sensor performance is then multiplied by the probability of detection for preset distances, emulating a convergence zone. Table 1 shows a few different permutations of the probability of detecting a contact within a given range based on the MDUSV sensor performance. These ranges and probability of detection were derived from the convergence zone distribution field modeled by Williams (2016).

Table 1.   MDUSV sensor performance

MDUSV baseline sensor performance	MDUSV P(detect) at 5000m	MDUSV P(detect) at 9160m	MDUSV P(detect) at 18320m	MDUSV P(detect) at 27780m	MDUSV P(detect) at 37040m	MDUSV P(detect) at 46300m
0.2	0.01	0.01	0.0002	0.0002	0.01	0.0002
1	0.05	0.05	0.001	0.001	0.05	0.001
1.5	0.075	0.075	0.0015	0.0015	0.075	0.0015
2	0.1	0.1	0.002	0.002	0.1	0.002

d.   Dark Submarine

The dark submarine is an agent in the experiment that is designed with the intention of confusing, delaying, or preventing the detection of the red submarine. This adds fidelity to the model because in real life while conducting ASW operations it is common to be fooled by marine life or distant echoes of sounds from other maritime traffic. By adding the dark submarine, a means is introduced to have the model more accurately depict the unpredictability faced in real life.

The dark submarine is generated several hundred nautical miles west of the green combat area. After being generated, the dark submarine waits a pseudo random amount of time and then proceeds at a speed of 2000 knots toward a pseudo random location within the green combat area. This behavior was intentionally designed so that the dark submarine moving toward its destination is for all practical purposes instantaneous. By having the dark submarine wait a pseudo random amount of time before moving, we prevent the scenario

from occurring where the dark submarine is instantly detected and destroyed. Figure 14 shows the return to station state of the dark submarine.
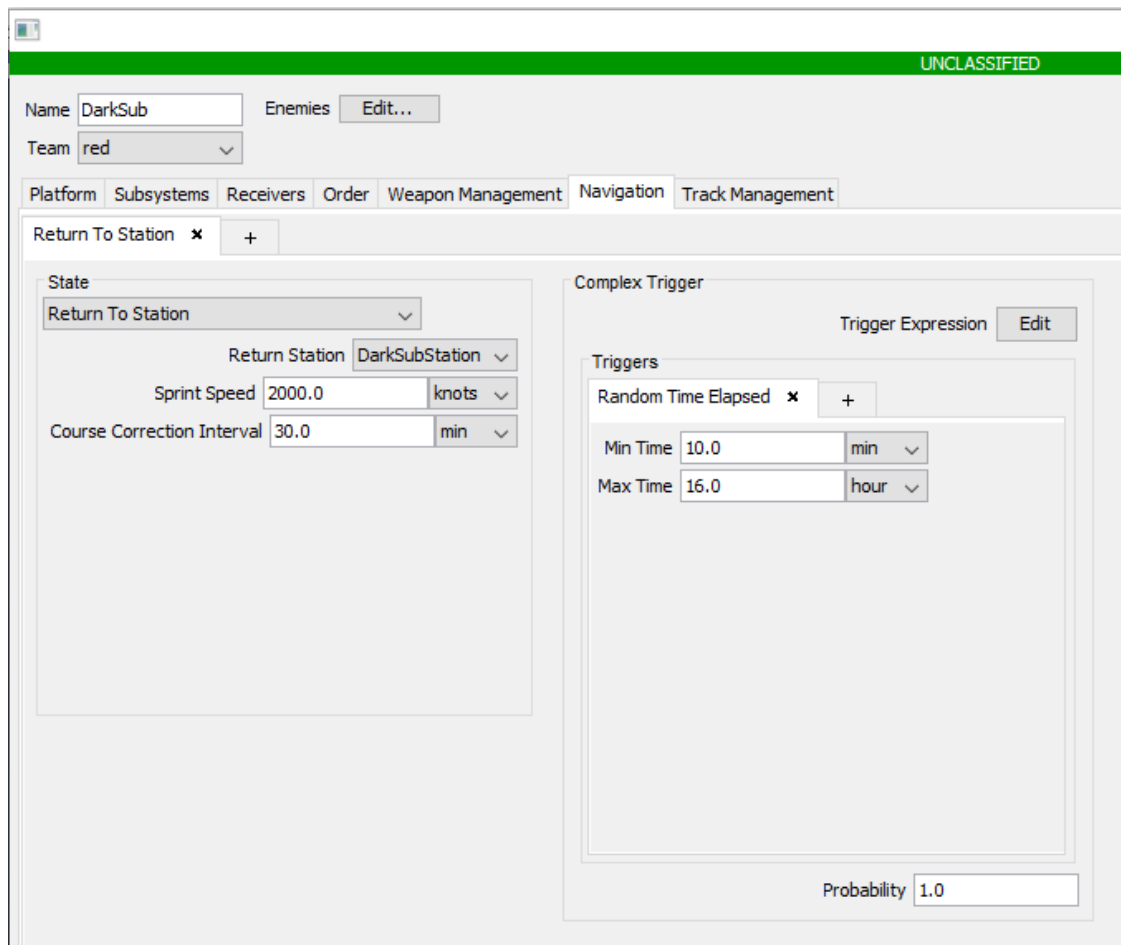
Figure 14.   Screenshot of LITMUS dark submarine return to station state

e.   *Blue Sonobuoys*

This model assumes that the blue sonobuoys have already been deployed prior to the simulation commencing. The sonobuoys positional location is deterministic (i.e., completely non-random). The sonobuoys are placed in four rows, with each row consisting of eight sonobuoys, for a total of 32 sonobuoys. Each sonobuoy is spaced 15 nautical miles apart from every buoy east and west, as well as north and south, creating a geometric grid. Every buoy is stationary, and has one way communication with the MDUSV and the P-8. The

sonobuoys use active sonar to search for the red submarine. The most northwest sonobuoy pings first, and then moving down the row easterly, each subsequent sonobuoy pings after waiting 120 seconds. Since there are eight sonobuoys per row and four rows in total, each sonobuoy pings every 3840 seconds. Figure 15 shows the sonobuoy agent's subsystem sensor which ensures that it pings every 3840 seconds, which is performed in the Scan Rate per second field. This method is introduced to replicate the effects of a multi-static sensor field employed by the P-8.
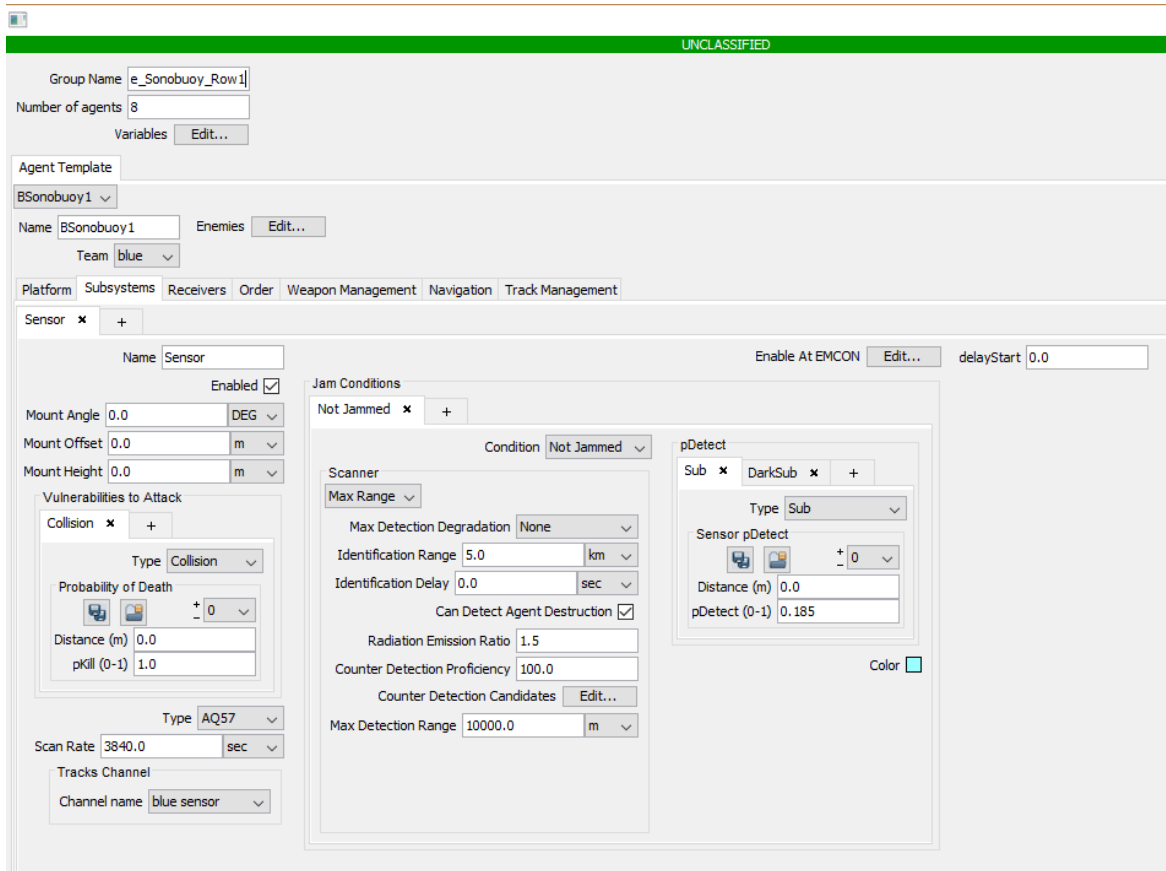
Figure 15.   Screenshot of LITMUS sonobuoy sensor configuration

Sonobuoy performance is also designed to accurately depict the effects of a convergence zone. Similar to the MDUSV sensor performance, the sonobuoy performance is also pseudo-random. The sonobuoy sensor performance range has a baseline value of 0.185 that is then multiplied by one minus the red submarine concealment rate divided by

100. By using the red submarine concealment as the numerator in the fraction and then subtracting one from the quotient, a greater red submarine concealment rate will impose a larger penalty on the sonobuoy performance.

$$sonobuoy\ performance = 0.185 * \left(1 - \frac{redSubConcealmentRate}{100}\right)$$

Table 2 shows a few different permutations of the probability of detecting a contact within a given range based on the sonobuoy sensor performance. Note that the ranges for the sonobuoy performance are not identical to the MDUSV sensor range, this is due to the difference in hardware between the MDUSV sensor and the sonobuoy. These ranges and probability of detection were derived from the convergence zone distribution field modeled by Williams (2016).

Table 2.   Sonobuoy performance table (probability of detecting submarine)

red submarine concealment	sonobuoy performance	Range 0 meters	Range 5000 meters	Range 5001 meters	Range 51855 meters	Range 51856 meters	Range 71380 meters
35	0.1205	0.12025	0.12025	0	0	0.12025	0.12025
30	0.148	0.1295	0.1295	0	0	0.1295	0.1295
24	0.1406	0.1406	0.1406	0	0	0.1406	0.1406
28	0.1332	0.1332	0.1332	0	0	0.1332	0.1332
34	0.1221	0.1221	0.1221	0	0	0.1221	0.1221
21	0.14615	0.14615	0.14615	0	0	0.14615	0.14615

B.   DESIGN OF EXPERIMENTS

The following design of experiments is utilized to investigate the model. The first step is to identify the variables to be explored or studied within the model. Then, we select the design points (unique combinations of factor levels) at which the model will be run.

1.   Variables

This model contains both categorical and numerical variables. Categorical variables are used to distinguish between the three cases tested against the red submarine: P-8 with

sonobuoys, MDUSV alone, or P-8 with sonobuoys and the MDUSV. Each of these three cases includes a scenario with and without the dark submarine, which creates a total of six categorical combinations.

The four continuous variables used are the red submarine speed, red submarine concealment rate, MDUSV speed, and MDUSV sensor performance. Mean time to kill and probability of classification are highly correlated for the sensor and consequently they are not varied independently for this experiment. Moreover, direct path and convergence zone distances used by the MDUSV sensor and the sonobuoy sensor are not varied. Recall that the sonobuoy performance and MDUSV sensor performance are actually functions of the red submarine concealment rate. Table 3 shows the continuous variables and their ranges tested in the model.

Table 3.   Continuous variables tested

Variable (units)	Minimum	Maximum
Red Submarine Speed (knots)	6	10
Red Submarine Concealment (%)	15	35
MDUSV Speed (knots)	15	30
MDUSV sensor performance-scaling factor (decimal)	0.1	2.0

2.   Design of Experiments Comparison

Recall there are three cases for this research, each with two subcases. Case A is the MDUSV and red submarine, Case B is the P-8 and red submarine, and Case C is the P-8, MDUSV, and red submarine. Each of the subcases modifies whether there is a dark submarine or not. With six unique scenarios, i.e., categorical variable combinations, and four continuous variables, the following categorical variable combinations and quantitative variable levels are used in the experiment:

- six categorical variable combinations,

- five levels for the red submarine speed (in knots, only integers),

- 21 levels for the red submarine concealment percentage, and

26

- 16 levels for MDUSV speed (in knots, integers only).

a.   *Full Factorial Design*

A full factorial design incorporating every single combination will have 201,600 design points. With 30 replications of each design point, this is a total of 6,048,000 simulated ASW missions. Running each simulation has an average execution time on a personal computer of approximately five seconds. If performed serially on one machine, these simulations would take over 11 months to complete!

b.   *Nearly Orthogonal Latin Hypercube*

A far superior implementation to the full factorial design is the nearly orthogonal Latin hypercube (NOLH) design (Cioppa & Lucas, 2007). A NOLH provides for a selection of efficient and space-filling design points while minimizing the number of design points needed (MacCalman et al., 2017). Using a special Excel file (Sanchez, 2011), a 2nd order NOLH with up to 15 factors and 1000 design points is used in this research to minimize the correlations between all second order terms. In doing so, the manual process of "rotating and stacking" is avoided while still successfully creating the design points that are efficient space-filling for the model. Figure 16 shows the pairwise scatter plot of the design points for experiments illustrating the input relationships between the factors.
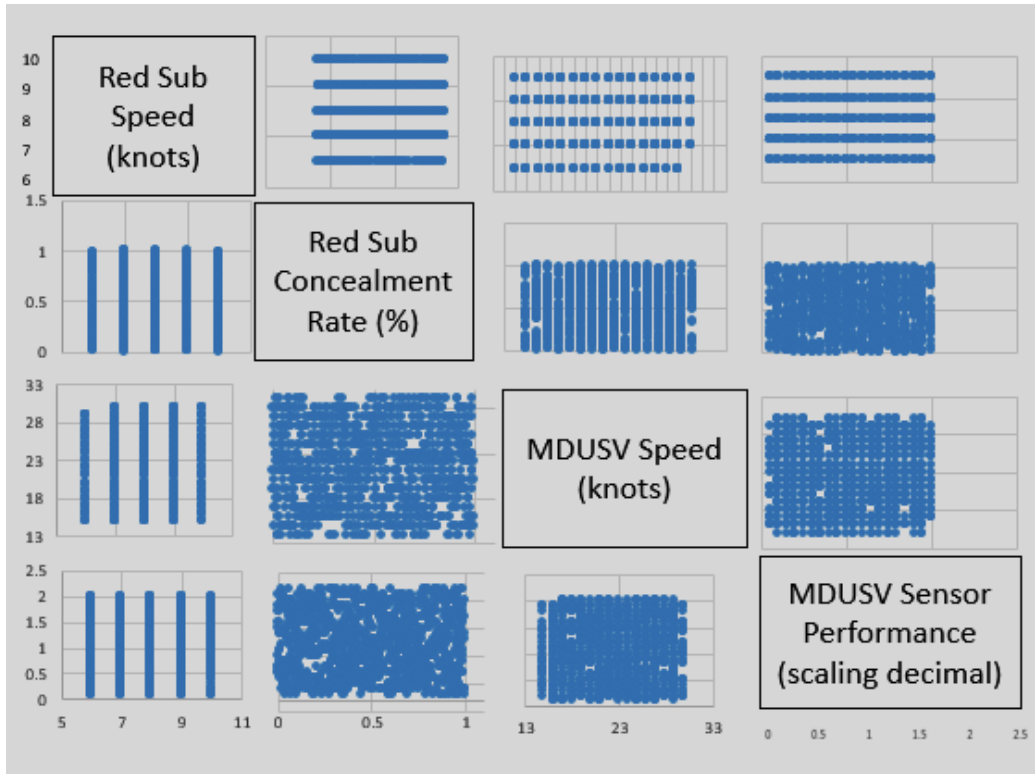
Figure 16.   Pairwise scatterplot of design points for experiments

Case A and Case C both have 1,000 design points, 30 replications, and two subcases where there is a dark submarine present and absent. Case B has 95 design points, 30 replications, and the same two subcases of a dark submarine and no dark submarine present. This creates a total of 125,700 simulated ASW missions when using the second order NOLH, and compares favorably with the over six million in the full factorial design.

3.   Advantages of Cluster Computing

Running the simulation on the NPS super computer HAMMING was imperative for the successful execution of the simulation. HAMMING has 81 computer nodes with 4,270 processors. Because of the multiple processors that can be run in parallel, running the simulation can be represented as either the total compute run time, which is the summation of all of the processors working, or as the wall clock time, which represents the actual passage of time. Running all three cases took a total of approximately 21 wall clock hours, and approximately 3,934 computational hours.

III. RESULTS

Using all of the design points and running the data on HAMMING provides data on the probability of the red submarine being killed for each of the scenarios, as indicated in Figure 17. Since there is only one red submarine, the mean number killed is the estimate of the probability the red submarine is killed.

Source Table	N Rows	Mean(SubKilled?)
Case_A-wDarkSub-AllDetects2_SubKilledByRep	30000	0.687966667
Case_B-AllDetects2_SubKilledByRep	2850	0.997894737
Case_B-woDarkSub-AllDetects2_SubKilledByRep	2850	0.997192983
Case_C-rerun-AllDetects2_SubKilledByRep	30000	0.999766667
Case_C-woDarkSub-AllDetects2_SubKilledByRep	30000	0.999766667

Figure 17.   Mean number of kills for each case. Source: M. McDonald (email to author, February 5, 2018).

A.   INITIAL FINDINGS

After running the first case with the MDUSV, dark submarine, and red submarine, the data shows there is no need to run a case with the MDUSV, no dark submarine, and red submarine. This is because for the first case, the dark submarine was never killed. Recall that the dark submarine is idle once on station, therefore it is extraordinarily unlikely that the MDUSV would have been distracted by the dark submarine and failed to kill it while the red submarine escaped. Therefore, removing it would produce similar results. Accordingly, the cases were reduced to five categorical variables.

1.   Case B and Case C Initial Findings

The two remaining main scenarios of a P-8 versus red submarine and MDUSV with P-8 versus red submarine produced nearly identical probability of kill of the red submarine. This is due to the very optimistic performance of the simulated P-8 caused by the current software limitations on LITMUS. LITMUS is currently unable to model the effects of

localization, which will add uncertainty in targeting and a time delay in attack. This means that once a sonobuoy has a positive return on the red submarine, the P-8 is essentially guaranteed a kill on the red submarine as the aircraft's superior speed over the red submarine will ensure intercept. Adding fidelity to the model by introducing uncertainty associated with the P-8 localizing the submarine with its own sensors or additional sonobuoys is necessary to properly replicate the challenges of the engagement sequence. Additionally, LITMUS needs additional programing so that if the P-8 fails in localization, it will then return to patrolling east and west. Unfortunately, there is no way currently for the agent to "forget" the location, so the P-8 will continue going to the red submarine's last known position even if its weapons have a less than 100% chance of destroying the submarine.

2.   Analyzing Cases by Mean Time to Kill Red Submarine

Because of the similarity in the probability the submarine is killed which is close to one for Case B and Case C, the mean time to kill was used as a further point of analysis to break down the difference between the two cases, i.e., quantify the benefit of the MDUSV. In a practical sense, a mean time to kill can be interpreted to indicate a more advantageous target prosecution. Figure 18 shows the distribution of the mean time to kill in seconds of the cases for the MDUSV only, MDUSV & P-8, and P-8 alone with their mean time to kill, upper and lower confidence intervals, standard deviation, and number of samples in the Summary Statistics data. This distribution excludes the times that the red submarine is not killed. From these summary statistics data, we can see that when the P-8 is working with the MDUSV, it kills the red submarine on the average 10% faster, on average by approximately 485 seconds.
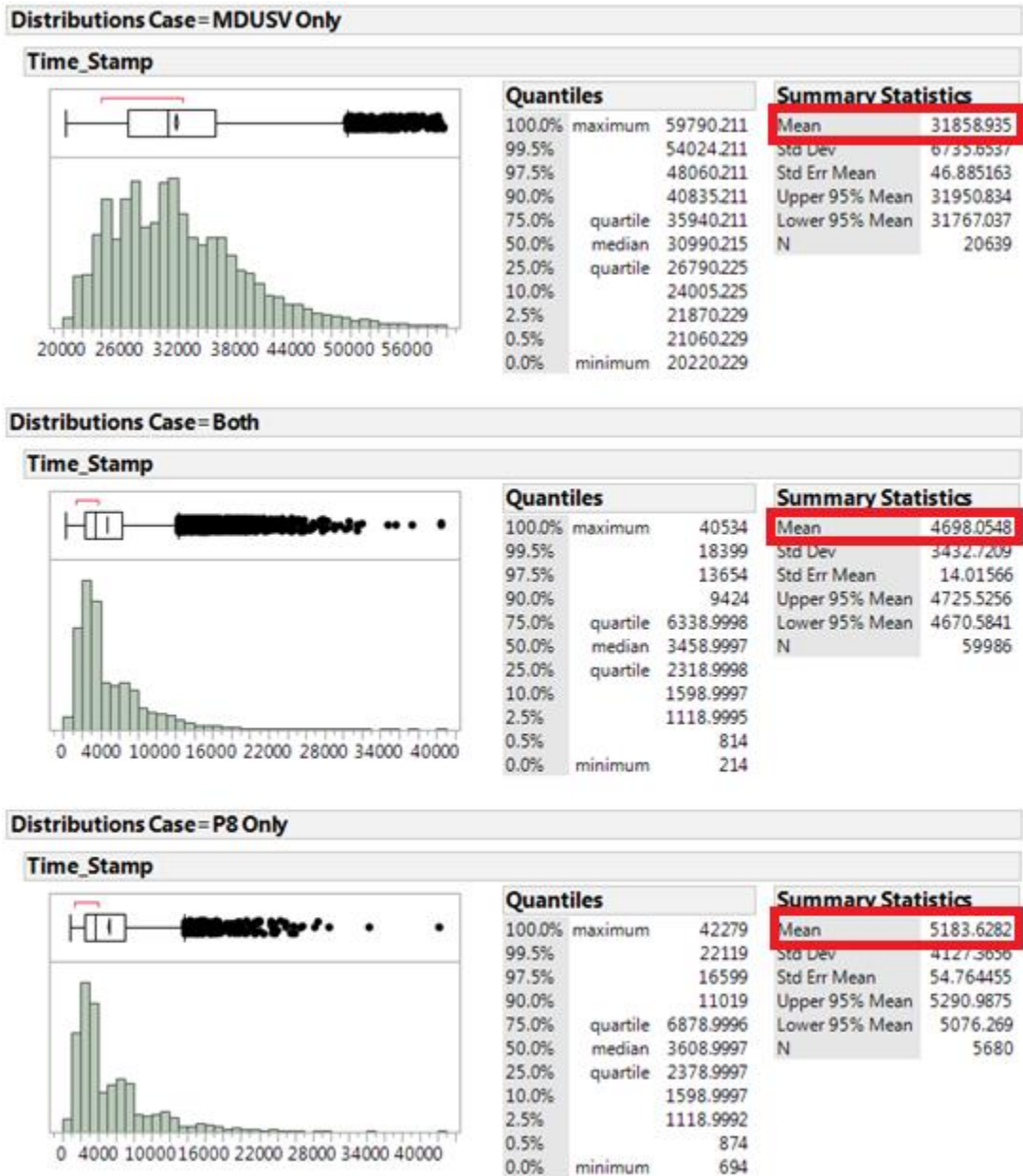
Figure 18. Distribution of mean time to kill red submarine in seconds for all cases. Source: M. McDonald (email to author, February 5, 2018).

Figure 19 shows the ordered differences report between each of the cases. This provides a visual of the statistical significance between each case with respect to the probability to kill the red submarine. From this, we can see that there is a statistically significant difference between Cases A and C, Cases A and B, but not Cases B and C.

While there is not statistical signifiance between Cases B and C with the data, there is a practical statistical difference between the mean time to kill in Case B and C, as mentioned before. Note how Figure 18 shows that using the mean time to kill the red submarine has a clearer difference than the probability to kill the red submarine, as shown in Figure 19.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value	
Both	MDUSV Only	0.3118000	0.0029207	0.304952	0.3186484	<.0001*	
P8 Only	MDUSV Only	0.3095772	0.0059680	0.295583	0.3235711	<.0001*	
Both	P8 Only	0.0022228	0.0057249	-0.011201	0.0156465	0.9203	

Figure 19.   Ordered differences report for probability to kill. Source: (M. McDonald, email to author, February 5, 2018).

B.   CASE A: MDUSV WITH DARK SUBMARINE AND RED SUBMARINE

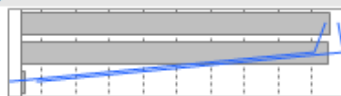For Case A, the MDUSV is able to successfully kill the red submarine approximately 69% of the time regardless of the presence of the dark submarine. In order to gather further insight into what causes a successful kill for this case, further analysis was performed using JMP.

1.   Partition for the Mean Number of Kills

Using the statistical software JMP,[2] a partition tree for the probability of kills was created, as shown in Figure 20. A partition tree is advantageous to use because it provides an excellent illustration of the relative effect of certain factors with respect to other factors under specific conditions. The first partition in Figure 20 is a pivot on the level of the red submarine concealment rate (labeled in Figure 20 with a red box). Upon branching right, you can see that for the 945 design points where the red sub concealment rate is less than 0.94609, (labeled in Figure 20 with a green arrow) the red submarine was killed with probability 0.7 (labeled in Figure 20 with the blue box). This provides a reasonable idea of the threshold for the red submarine concealment rate at which the red submarine begins to escape more often than being killed. For the 945 cases where the red sub concealment rate is less than 0.94609,

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[2] JMP is a statistical software that can be accessed at https://www.jmp.com/en_us/home.html.

the next branch in the partition tree is dependent on the MDUSV speed being greater/equal to or less than 20 knots. The next branch in the tree and the third level of the tree partitions on the red submarine speed. The fourth and final branch is dependent on the sensor performance. The level of each of these factors is commensurate with the value of this factor being a predictor for the red submarine being killed. Ergo, with respect to the factors for the case of the red sub concealment rate being less than 0.94609, we can conclude that from most accurate to least accurate predictors you have the red sub concealment rate, MDUSV speed, red sub speed, and finally the MDUSV sensor performance.

Figure 20.   Right branch for the partition of the mean number of kills for Case A.
Source: M. McDonald (email to author, February 5, 2018).

Figure 21 is used to show what happens when we instead branch left, which occurs when the red submarine concealment rate is greater or equal to 0.94609 (labeled in Figure 21 with a red box). The next level that is inspected is whether the red sub concealment is greater than or equal to or less than 0.99142. The fact that we are using the same factor for multiple levels of the tree emphasizes the enormous weight this factor has as serving as a predictor for determining whether or not the red submarine is killed. Conversely, the red submarine speed isn't a factor until you reach the third level (labeled in Figure 21 with a

green arrow), and the fourth level (labeled in Figure 21 with a purple arrow). The worst case scenario is labeled in Figure 21 with an orange box, which shows only 7.8% of the time when the red submarine is travelling faster than 9 knots and its concealment rate is greater than or equal to 0.99142 the red submarine is killed.
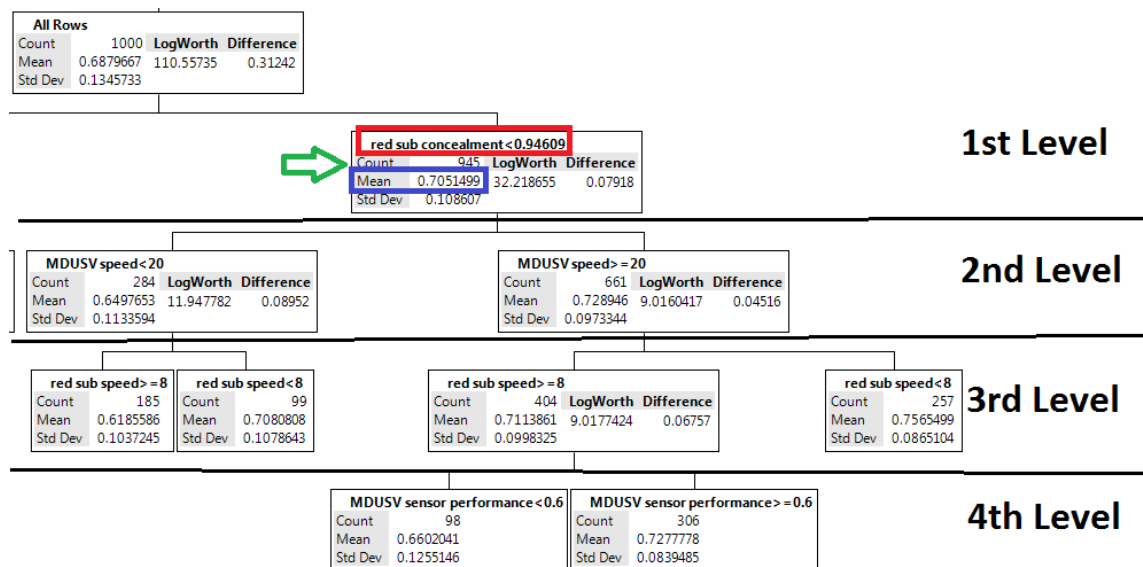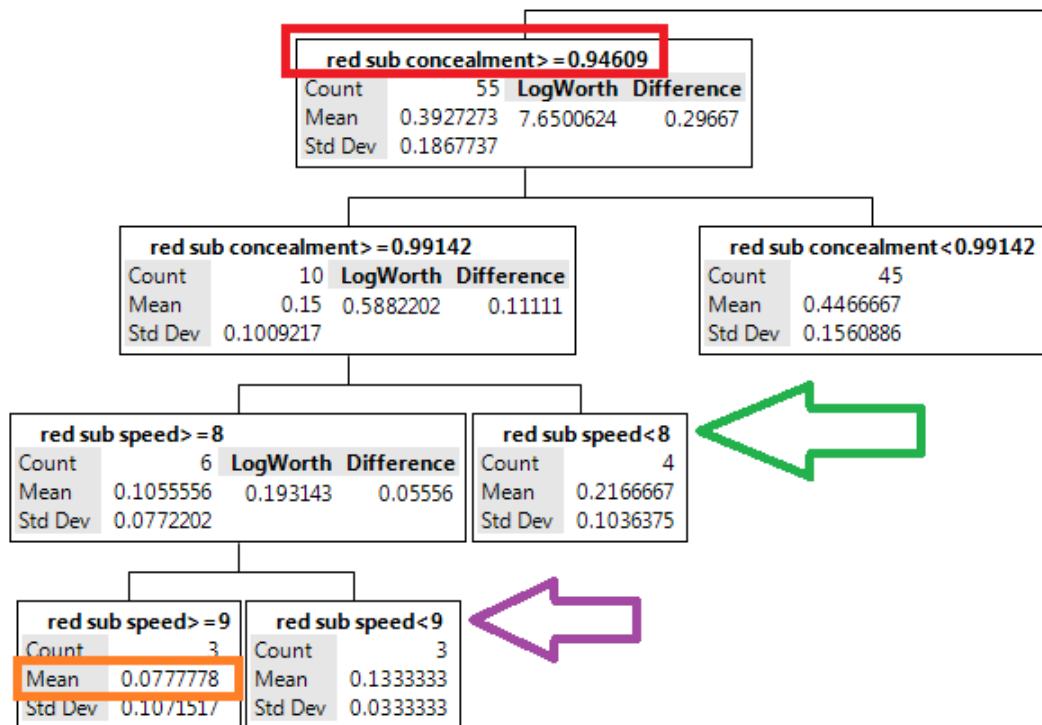

Figure 21.   Partition for the mean number of kills for Case A. Source: M. McDonald (email to author, February 5, 2018).

There are two salient conclusions that can be derived from Figure 21. First, increasing the MDUSV speed increases the likelihood to kill the red submarine more when the red submarine is travelling slower. Secondly, increasing the MDUSV sensor performance has more of an impact when the red submarine concealment is not near its maximum.

2.   Sorted Parameter Estimates

JMP also provides the ability to create a list of the sorted parameter estimates from a regression model, as shown in Figure 22. This list shows each of the factors followed by their estimate, standard error, and the *t-ratio*. The *t-ratio* is defined as the estimate divided

by the standard error. By convention, a *p-value* less than .05 suggests that the coefficient is statistically significant from 0 at the 95% confidence level. In Figure 20 and Figure 21, the *p-values* all meet this requirement; ergo they can all be used as statistically significant predictors for determining whether or not the red submarine will be killed.

The list shows the single most influential factor is the red submarine concealment rate, followed by the red submarine speed. Using the *t-ratios* listed, the red submarine concealment is the single variable with the most significance in being able to predict a kill. Because the *t-ratio* is negative, the greater the red submarine concealment rate, the less likely it is the red submarine is killed. The sorted parameter estimates list also indicates that both red submarine concealment and red submarine speed are better predictors of a kill then the MDUSV speed or the MDUSV sensor performance. As expected, a faster MDUSV and better sensor performance increase the probability that the red submarine is killed.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio		Prob>|t|
red sub concealment	-0.148205	0.012035	-12.31		<.0001*
red sub speed	-0.029951	0.002847	-10.52		<.0001*
MDUSV speed	0.0079735	0.000799	9.98		<.0001*
(red sub concealment-0.5005)*(MDUSV sensor performance-1.051)	0.1649385	0.021685	7.61		<.0001*
MDUSV sensor performance	0.0443081	0.006318	7.01		<.0001*
(MDUSV sensor performance-1.051)*(MDUSV sensor performance-1.051)	-0.056017	0.01277	-4.39		<.0001*
(red sub speed-8.003)*(MDUSV speed-22.507)	0.0021906	0.000658	3.33		0.0009*
(MDUSV speed-22.507)*(MDUSV speed-22.507)	-0.000669	0.000204	-3.29		0.0010*

Figure 22.   Sorted parameter estimates for Case A.
Source: M. McDonald (email to author, February 5, 2018).

C.   CASE B: P-8 AND RED SUBMARINE WITH AND WITHOUT DARK SUBMARINE

For Case B, the P-8 hunts the red submarine without the aid of the MDUSV. The sonobuoys are already deployed and begin pinging as soon as the simulation begins. Because there is no MDUSV, this scenario has fewer design points. The principal factors analyzed are the red submarine concealment rate, red submarine speed, and sonobuoy performance. For Case B, regardless of the presence of the dark submarine, the P-8 kills the red submarine approximately 99.7% of the time. As previously mentioned, due to

software limitations and the speed difference between the P-8 and the red submarine, a single positive return from a sonobuoy is essentially sufficient to kill the red submarine.

Because the mean number of kills is so high for Case B, it is more beneficial to analyze the mean time to kill to gather insight regarding the design points.

1.   Partition for Mean Time to Kill

JMP was used to create a partition for mean time to kill the red submarine, as shown in Figure 23. The first divide in the partition tree is from the sonobuoy performance. When the sonobuoy performance has less than a 16% probability to detect the red submarine per ping, the mean time to kill increases by 2237 seconds. This is identified as the difference between the figures in the blue box and orange box in Figure 23. At the second and third levels of the partition tree, the primary factor used to divide the tree is still sonobuoy performance. This indicates that the sonobuoy performance is the dominant factor. The green box in Figure 23 shows the best case scenario with a mean time to kill of 4000 seconds, which occurs when the sonobuoy performance is equal to or greater than 0.24. Conversely, the red box indicates the worst case scenario, i.e., slowest time to kill, of a mean 7609 seconds. This occurs when the sonobuoy performance is less than .14 and the red submarine is moving at 10 knots (its maximum speed in our design). Recall that this partition tree only shows cases where the red submarine is killed, therefore within the context of this partition tree worst case refers to slowest time to kill, not whether or not the red submarine escaped.
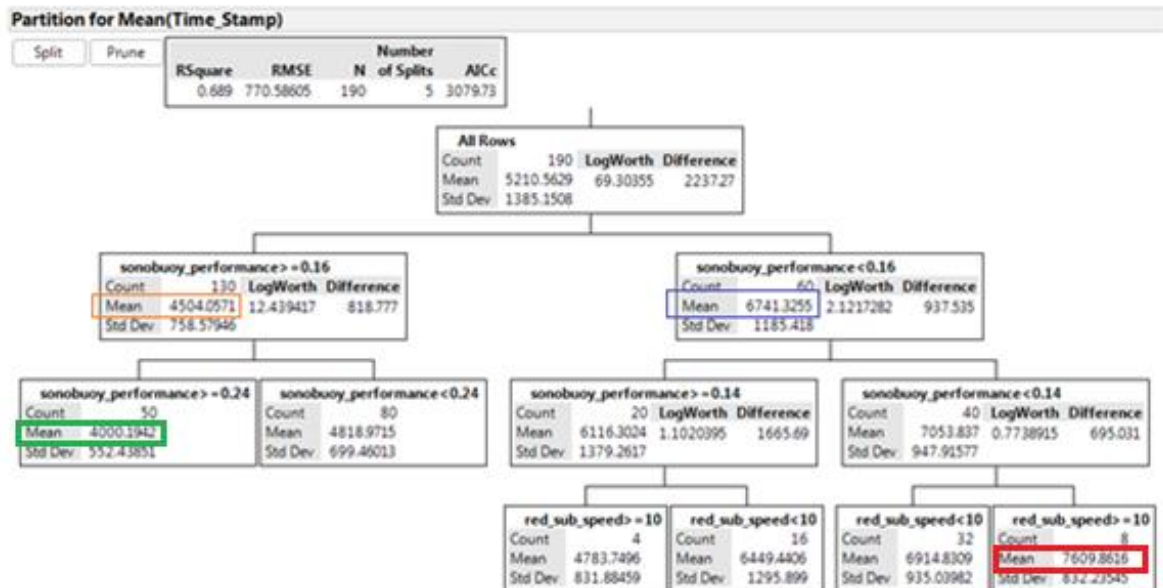
Figure 23.   Partition for mean time to kill for Case B. Source: M. McDonald
(email to author, February 5, 2018).

2.   Sorted Parameter Estimates

Another means to quantify the influence of the sonobuoy performance is to use the sorted parameter estimates generated by JMP using a regression fit. As shown in Figure 24, the sonobuoy performance is overwhelmingly the most important factor to estimate the mean time to kill the red submarine. Figure 24 shows that the sonobuoy performance has a *t-ratio* nearly 17 times more influential than the red submarine speed. This means that the sonobuoy performance is significantly better than the red submarine speed in being a predictor of the mean time that the red submarine will be killed, given that it is killed.

Figure 24.   Sorted parameter estimates.
Source: M. McDonald (email to author, February 5, 2018).

37

D. CASE C: P-8, MDUSV AND RED SUBMARINE WITH AND WITHOUT DARK SUBMARINE

Similar to Case B, the presence of the dark submarine has little influence on whether or not the red submarine is killed. In each sub case, the red submarine is killed approximately 99.76% of the time. Accordingly, it is again more insightful to examine the design points with respect to the mean time to kill.

1. Partition for Mean Time to Kill Red Submarine

Figure 25 shows a partition tree for the mean time to kill the red submarine. The partition tree initially branches on the red submarine concealment rate, as shown in the blue boxes. Specifically, when the red submarine concealment rate is greater than 0.75546, the mean time to kill is increased from 4221.5 seconds to 6160.5 seconds, an increase of approximately 1939 seconds, as indicated in the green box highlighting the difference between branching on that design point. The red box shows that the MDUSV speed is only a significant factor in the fourth and last level of the partition tree, which is a clear indication that it does not have as much of an ability to act as a predictor for whether or not the red submarine is killed.
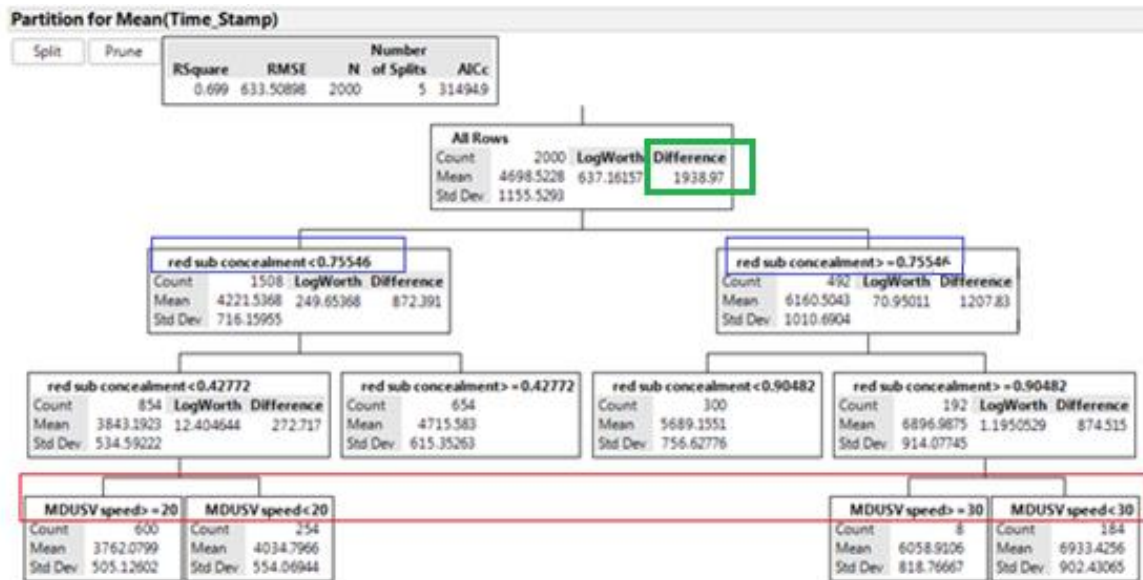
Figure 25.   Partition for mean time to kill red submarine for Case C. Source: M. McDonald (email to author, February 5, 2018).

2.   Sorted Parameters List

The sorted parameters list as shown in Figure 26 confirms the observations provided by the partition tree for the mean time to kill the red submarine. The first row of the list indicates that the factor with the greatest influence is overwhelmingly the red submarine concealment, which has almost 10 times more weight than the next single factor, the MDUSV speed.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio		Prob>|t|
red sub concealment	3251.602	46.58928	69.79		<.0001*
(red sub concealment-0.5005)*(red sub concealment-0.5005)	3529.8798	180.4625	19.56		<.0001*
red sub speed	-84.11318	10.99866	-7.65		<.0001*
MDUSV speed	-21.1451	3.090644	-6.84		<.0001*
(red sub speed-8.003)*(red sub concealment-0.5005)	-111.2978	37.60094	-2.96		0.0031*
(red sub speed-8.003)*(MDUSV speed-22.507)	2.0967466	2.539962	0.83		0.4092

Figure 26.   Sorted parameters list for Case C. Source: M. McDonald (email to author, February 5, 2018).

E.   ANOVA COMPARISON

Recall the design of this experiment is to closely imitate previous research conducted by LCDR Solem using MANA, and in doing so ascertain the functionality of the new software LITMUS. Accordingly, valuable insight can be gathered by comparing the one-way analysis of variance (ANOVA) to compare the means of the simulation outputs. Figure 27 shows a side-by-side comparison of MANA's ANOVA testing vis-à-vis LITMUS' ANOVA testing.
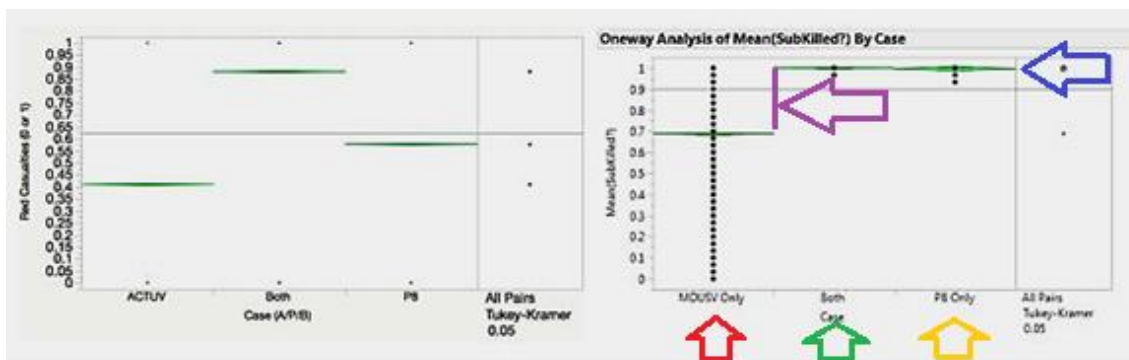

Figure 27.   MANA ANOVA vis-à-vis LITMUS ANOVA results.
Adapted from M. McDonald (email to author, February 5, 2018) and
Solem, (2017).

It is clear upon comparing the two results that the LITMUS testing is producing much higher rates of killing the red submarine for each case. For the MDUSV only case, as indicated by the red arrow, the red submarine is being killed approximately 30% more often. For the MDUSV & P-8 case, as indicated by the green arrow, the red submarine is killed 8% more often. For the P-8 only case, as indicated by the yellow arrow, the red submarine is being killed 32% more often. The purple arrow and purple line highlight the 38% improvement in the submarine being killed when the P-8 and MDUSV work together, compared to when the MDUSV operates alone. Upon closer inspection, what appears to be horizontal green lines on Figure 27 are actually showing the confidence interval within each case. There is notably more variance in the P-8 case in the LITMUS version, which has a slightly diamond like shape, as indicated by the blue arrow, than the MANA version

which visually appears more like a horizontal line. The diamonds show the 95% confidence interval on the mean. They are so flat because our sample sizes are so large, hence the standard error on the mean is very small.

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IV.   DISCUSSION

The goal of this research is to assess LITMUS' ability to quantify the potential mission benefits of integrating a P-8 with an MDUSV in a tactical ASW scenario. The validity of the results from this research would be confirmed by comparing the output to previous research conducted on an identical scenario with MANA. Recall from Chapter 1, the MDUSV offers several tactical advantages in an ASW scenario that complement a P-8. One advantage is the MDUSV is unmanned; therefore if the red submarine were to engage the MDUSV, it would result in no casualties and give away its position to the P-8. Another advantage is the MDUSV has the potential to be outfitted with weaponry such as the Mark 54 Lightweight Torpedo, and its weapons release authority could be retained by the P-8 to remove any moral or legal difficulties in having an unmanned system carry weapons. Finally, an additional advantage is that the P-8 already has a complex communications suite capable of speaking to multiple unmanned aerial vehicles, ergo the logic that follows is that it is feasible to modify these systems to accommodate two directional communications with the MDUSV.

LITMUS offered several advantages while conducting this research. The graphical user interface was fairly straightforward and the animations were very helpful in debugging while building the scenario. NPS research associates were instrumental in assisting with the development of the scenario in LITMUS and the statistical data analysis of the output.

The disadvantage of modeling this scenario in LITMUS is principally the newness of the software and the amount of debugging that occurred while conducting research. Because the software is relatively new, research such as the one conducted for this thesis is the principal medium to identify bugs and challenges for researchers. This created an iterative process where the researchers frequently had to contact the LITMUS developers with inquires on what would normally be routine issues. Not all of these issues were resolved in time for the completion of this effort. Principal among these issues was the inability for an agent to "forget" about a track it held in its memory and add uncertainty in localization to targeting criteria. This factor was ultimately responsible for the extremely high kill rates for Case B and Case C in the simulation.

A. CONCLUSIONS

The first and second question are answered by examining the statistical results produced by JMP for each case (i.e., MDUSV alone, P-8 alone, MDUSV and P-8 together, each with and without the dark submarine). The mean time to kill the red submarine decreased nearly six-fold when the P-8 was added to the MDUSV, and there was a 10% improvement in the conditional mean time to kill given the submarine is killed for the P-8 and MDUSV compared to the P-8 alone.

The third question can be divided into two implied questions, namely what was the influence of the dark submarine (false targets) on the mean time to kill as well as the probability the submarine is killed. For both questions, the answer is a negligible effect. For Case A, the effect was unexpected in that the MDUSV did not destroy the dark submarine a single time. For Cases B and Case C, the dark submarine was frequently destroyed by the P-8 although this only added a marginal amount of time until the red submarine was killed.

B. FOLLOW-ON WORK

There are ample questions that can be further explored for this scenario using LITMUS. The most pressing issue is re-running the model once the P-8's behavior can be modified to introduce variability in successfully engaging the red submarine after detection, and if unsuccessful, returning to a patrol state. Once the model adequately represents the P-8's detect to engage sequence, re-running the experiment with classified data for sensor and platform performance will be necessary. Future improvements to LITMUS may also include enhancing the red submarine's behaviors to allow evasion and intelligent maneuver to avoid active sensors. Finally, providing the red submarine agent with an anti-ship missile (ASM) capability to conduct a pre-emptive attack on the MDUSV will be necessary to explore MDUSV vulnerability.

Further sensitivity analysis may include adding more dark submarines to create the effect of increasing false alarm rates and determine when the red submarine has a notable decrease in the probability the submarine is killed due to this factor.

Further physical testing of the environment will need to done to understand its effect on the MDUSV's sensor ability to capitalize on the convergence zone. This will more accurately reflect specific weather conditions through the use a detailed physics-based model for critical areas of interest.

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