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EVALUATION OF FUTURE UNMANNED UNDERWATER VEHICLE CAPABILITIES IN AN AUTOMATED COMPUTER-AIDED WARGAME

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THESIS

EVALUATION OF FUTURE UNMANNED UNDERWATER VEHICLE CAPABILITIES IN AN AUTOMATED COMPUTER-AIDED WARGAME

by

Herman Wong

December 2018

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13. ABSTRACT (maximum 200 words)

The U.S. Navy is restructuring its fleet architecture. Assessments undertaken as part of the restructuring process revealed a lack of construction sites to support increasing fleet size. As such, the Navy is exploring the feasibility of using unmanned underwater vehicle (UUV) platforms to supplement the fleet. Current UUVs provide minimal surveillance and mine detection capabilities; one solution is adding offensive and enhanced detection capabilities to UUV platforms. This study utilized a model-based systems engineering (MBSE) approach in the Joint Theater Simulation Level Global Operations environment to explore the effects of UUVs with enhanced capabilities. The approach included the process of developing the conceptual prototype, concept of operations, measures of effectiveness, varying UUV factors (speed, composition, and sonar type), and designs of experiment. After analyzing the output of 540 simulation runs, the results provided evidence that all three factors are significant in UUV operational performance and showed that using advanced UUVs increase task forces' capabilities. Furthermore, the experimentation reveals strong correlations between UUV composition and speed for detection and engagements, and confirmed using active sonar as advantageous in combat, thereby shaping the trade-space for UUV features. This study demonstrates the utility of MBSE for conducting feasibility assessments for the future fleet.

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ABSTRACT

The U.S. Navy is restructuring its fleet architecture. Assessments undertaken as part of the restructuring process revealed a lack of construction sites to support increasing fleet size. As such, the Navy is exploring the feasibility of using unmanned underwater vehicle (UUV) platforms to supplement the fleet. Current UUVs provide minimal surveillance and mine detection capabilities; one solution is adding offensive and enhanced detection capabilities to UUV platforms. This study utilized a model-based systems engineering (MBSE) approach in the Joint Theater Simulation Level Global Operations environment to explore the effects of UUVs with enhanced capabilities. The approach included the process of developing the conceptual prototype, concept of operations, measures of effectiveness, varying UUV factors (speed, composition, and sonar type), and designs of experiment. After analyzing the output of 540 simulation runs, the results provided evidence that all three factors are significant in UUV operational performance and showed that using advanced UUVs increase task forces' capabilities. Furthermore, the experimentation reveals strong correlations between UUV composition and speed for detection and engagements, and confirmed using active sonar as advantageous in combat, thereby shaping the trade-space for UUV features. This study demonstrates the utility of MBSE for conducting feasibility assessments for the future fleet.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

APL	Applied Physics Lab
ASW	anti-submarine warfare
AUV	Autonomous Unmanned Vehicle
CAW	computer aided wargaming
CBSA	Center for Strategic and Budgetary Assessments
CCD	central composite design
CEP	combat events program
CG18	Cobra Gold 2018
CNO	Chief of Naval Operations
COCOM	combatant commander
CONOP	concept of operation
COP	common operating picture
CPX	command post exercise
DAU	Defense Acquisition University
DDG	guided missile destroyer
DoD	Department of Defense
DoN	Department of Navy
DOE	design of experiments
DOT	Department of Transportation
DP	design point
GUI	Graphical User Interface
INCOSE	International Council on Systems Engineering
ISR	intelligence, surveillance, and reconnaissance
JTLS-GO	Joint Theater Level Simulation Global Operations
LITMUS	Lightweight Interstitials Toolkit for Mission Engineering using Simulation
LS	landing ship
MBSE	model-based systems engineering
MCM	mine countermeasure
MIB	more is better

MOEs	measures of effectiveness
MOPs	measures of performance
N9	Navy Warfare Systems Directorate
NDAA	National Defense Authorization Act
NPS	Naval Postgraduate School
OOB	orders of battle
PACOM	Pacific Command
R&D	research and development
RSS	Royal Singaporean Ship
SE	systems engineering
SEED	Simulation Experiments and Efficient Designs
SSK	diesel-electric submarines
TS	target strength
TPFDD	Time-Phased Force and Deployment Data
UAS	unmanned aerial system
UAV	unmanned aerial vehicle
U.S.	United States
USS	United States Ship
UUV	unmanned underwater vehicle
WHIP	web-hosted interface program
XLUUV	extra-large unmanned underwater vehicle

EXECUTIVE SUMMARY

In fiscal year 2016, the Senate Armed Services Committee ordered the Navy to increase its fleet to 355 ships. However, the lack of construction facilities impedes this endeavor. Rear Admiral Brian Luther, deputy assistant secretary of the Navy for budgets, estimated that the objective of 355 ships will not come to fruition until the 2050s (Larter 2018). As a result, the U.S. Navy is exploring potential fleet restructuring options. There is very high interest in supplementing traditionally manned naval assets with unmanned systems. One such system is the unmanned underwater vehicle (UUV). With top-level interest in both fleet and unmanned systems, the Office of Naval Research (N9) requested a method and process to test future capabilities of UUVs and an experimentation environment or tool to conduct such investigations. Moreover, current UUVs mainly operate to support mine warfare and minor surveillance missions (Department of Defense 2007), so their impact in other roles is not understood.

The aim of this research was to use a model-based systems engineering (MBSE) approach in a computer-aided wargame, specifically the Joint Theater Level Simulation-Global Operations (JTLS-GO), to explore the effects of advanced UUV capabilities as an asset in the future U.S. naval fleet and as an alternative to the dwindling submarine force.

The MBSE approach is a multi-step process that explores the whole project from beginning to end. This approach led to the development of an advanced UUV concept and vignette or concept of operations (CONOP) from Cobra Gold 2018 (CG18), a six-nation (PACOM sponsored) command post exercise (CPX). Creation of the vignette permitted the iterative examination of CG18 to identify capability shortfalls that the UUVs could address. In this case, the vignette focused on interactions between an enemy (Sonoran) task force against an allied task force, including the USS *Benfold* (DDG-65) and RSS *Endurance* (LS-207). The results of the real exercise included casualties sustained by the aforementioned ships. These casualties were due to lack of situational awareness and lack of offensive firepower. These issues presented an opportunity and motivation for UUV injection into the simulation to augment sensors and firepower. Afterward, the process of identifying and establishing the operational requirements and the constraints of the new

capabilities ensued. The new simulated UUV design must be able to provide additional offense and reconnaissance capabilities. Measuring how well the UUVs performed and what attributes to vary led to the development of the measures of effectiveness (MOE) and measures of performance (MOP). These measures helped direct the formulation of the design of experiments (DOE), which guided the experimentation and assessment of the notional UUVs.

The MOEs included detection effectiveness and enemy attrition. The performance factors (attributes) of interest consisted of UUV speed, number of UUVs (UUV fleet composition), and sonar type (active or passive). The DOE involved the testing of these factors at three different values (levels). The combination of the factors at varying levels led to an experimentation with 18 design points.

The JTLS-GO model is an event-driven wargaming simulation designed by Rolands and Associates that serves to test multi-sided joint campaigns and operations (Rolands and Associates 2018). The program tests several layers of warfare including political, strategic, operational, and tactical levels.

Although JTLS-GO is useful for simulating engagements, its functionality, according to Cayirci and Marincic (2009), is to train headquarters staff to command and control units more efficiently. Thus, testing futuristic concepts using JTLS-GO alone is not feasible as it requires significant resources. To capitalize the human response and results from CG18, the author transformed the original JTLS-GO simulation program into an automated computer-aided wargaming (CAW) simulation with the help of the NPS Simulation Experiments and Efficient Designs (SEED) center. This transformation permitted multiple, repetitive simulations of future capabilities for statistical analysis.

This work involved 540 simulation runs, utilizing 810 hours of computer time. Using regression, trend, and partition tree analysis, the following conclusions were made:

1. By establishing a modeling and experimentation environment in an automated version of CG18 in JTLS-GO, the MBSE approach

provides a pathway to assessing operational impacts of future UUV capabilities.

CG18 in JTLS-GO provided the framework to utilize an MBSE approach to define the operational gaps, create UUV prototypes, define how and what to measure (MOEs and factors), and experiment rapidly. The methodical and meticulous effort required in MBSE demonstrated that the application of this process was beneficial in exploring UUV future capabilities and also showed how it can provide opportunities to examine a host of future fleet capabilities.

2. The presence of UUVs offers additional capabilities in providing situational awareness and offensive firepower, reducing surface vulnerabilities.

Even the addition of UUVs with the least effective factor combinations produced positive results: three Sonoran units killed and 60% of units detected. UUVs with the preferred factor values for detection resulted in RSS *Endurance* (LS-207) sinking 12 out of 30 simulations. Meanwhile, USS *Benfold* (DDG-65) sunk only two out of 30 simulations with these UUVs in the exercise. When UUVs with preferred factor values for attrition are in the environment, the RSS *Endurance* (LS-207) sunk 10 out of 30 simulations, and the USS *Benfold* (DDG-65) sunk two out of 30 simulations. As a result, the UUVs' performance led to a decrease in allied casualties in the simulation environment.

3. Active sonar improves both lethality and detection, but more is not necessarily better for speed and UUV fleet composition.

Table ES-1 presents the best and worst UUV configurations from the experiment. Based on the table, the recommendation for the preferred combination is a medium-sized UUV fleet that travels at speeds of 8 knots with active sonar. This configuration, on average, results in destroying nearly 88% of the enemy targets.

Table ES-1. UUV Design Point Results

	Best Design Points				Worst Design Points				
MOEs	UUVs	Speed (kts)	Sonar	Results	UUVs	Speed (kts)	Sonar	Results	Δ Results
Detection-MIB (%)	12	8	Active	87%	16	5	Active	65%	22%
Attrition-MIB (Kills)	16	8	Active	5.7	12	12	Passive	3.2	2.5
Recommendation:	**12-16**	**8**	**Active**						

The abbreviation MIB equates to "More Is Better."

The results from the MBSE approach with an automated JTLS-GO simulation package offer insights on advanced UUV performance without the need of heavy human and material capital. While the Navy is in the process of planning for its architectural future, it should consider assessing platforms with tools of this nature. In addition, the Navy should also consider adding advanced UUV platforms to supplement the fleet.

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I. INTRODUCTION

A. PROBLEM STATEMENT

There is a dearth of information to determine the value of including unmanned underwater vehicles in the Navy's organization and operations. Additionally, the architects of the future U.S. fleet currently lack an experimentation environment with which to explore the solution space for future unmanned underwater vehicle (UUV) capabilities to protect against hostile surface and undersea combatants.

B. PROBLEM DESCRIPTION

The termination of the Soviet Union saw a shift of U.S. naval maritime strategy from the early 1990s to present times. The emergence of near-peer adversaries including Russia and China influenced the call for the expansion of the U.S. Navy, which fundamentally affects the composition of the future fleet architecture. Studies from the Center for Strategic and Budgetary Assessments (CBSA), the independent MITRE Corporation, and the Navy Project Team have suggested different avenues in tackling the makeup of the future Navy fleet. However, expanding the Navy is much more complex than just producing a set number of ships. According to Rear Admiral Brian Luther, deputy assistant secretary of the Navy for budgets, estimated that the objective of 355 ships will not come to fruition until the 2050s (Larter 2018). This slow buildup rate is the result of limited ship building capabilities. As a result, using UUVs can fill both the production and capability gaps.

The utilization of unmanned system capabilities is not new to the United States military. For more than a decade, aerial unmanned systems have supported various mission areas including surveillance and strikes. In fact, the Department of Defense (DoD) in their report, *Unmanned Systems Roadmap (2007-2032),* stresses the importance of integrating unmanned systems in future combat to supplement mission objectives when traditional assets are unavailable. For example, according to Admiral Harry Harris in a congressional testimony on February 24, 2016, stated there was a "shortage of submarines and my requirements are not being met" (Holmes 2016). The heavy toll of maintenance and training cycles limit the availability of these assets leading to undersea warfare vulnerabilities to United States and allied naval assets. The incorporation of unmanned systems has the potential to alleviate these vulnerabilities (Holmes 2016).

Even though integration of unmanned systems in support of the Intelligence, Surveillance, and Reconnaissance (ISR) mission is common, the unmanned systems in support of anti-submarine warfare (ASW) lags. Currently, testing of unmanned surface vessels (USV) such as the Sea Hunter and extremely large unmanned underwater vehicle (XLUUV) prototypes are underway, but they are not yet operationally available (Tanalega 2018). Despite not having offensive assets in the field, the Department of Navy (DoN) created a tactical memo to establish potential tactics using unmanned vehicles in the maritime domain in the *UUV Master Plan 2004*. Discovering how different unmanned underwater vehicle capabilities can increase maritime success is one of the Navy's long-term goals. As such, the Office of Naval Research (N9) has expressed great interest in researching how unmanned systems impact the underwater domain in both fleet architecture and future capabilities.

While research focusing on simulation and exploration of current unmanned system tactics occurs frequently, these studies lack emphasis in researching future capabilities of these systems. Also, current research has focused on individual engagement of UUV systems and does not reflect their integration into a complex military campaign. This lack of foresight in UUV research has limitations that a model-based system engineering (MBSE) approach can address.

C. PURPOSE

This thesis uses the MBSE approach to discover potential effects of UUVs on the future U.S. Naval fleet architecture and to offer options to mitigate a lack of submarine assets. The results from this study may aid the Office of Naval Research in developing requirements to include UUVs in the current maritime strategy.

D. RESEARCH QUESTIONS

To inform the use of UUVs in a complex military campaign, this research proposed to answer the following inquiries:

1. How can modeling and simulation be used to assess the operational impact of future unmanned underwater vehicles' capabilities?
2. How can the addition of UUVs decrease the vulnerabilities to surface assets?
3. What are the attributes of UUVs needed to fill operational deficiencies in a theater-level campaign?

E. SCOPE AND METHODOLOGY

The specific scope of this research focuses on future UUVs' capabilities that can improve ASW and maritime reconnaissance mission areas. The study explores how adding UUVs in the future fleet architecture could enhance the operational commander's decision-making process. The intent is to explore and investigate the impact of UUVs in the aforementioned mission areas and establish requirements desired for current and future UUV employment.

The primary approach for answering the research questions was model-based systems engineering (MBSE). This type of systems engineering (SE) "is the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing through-out development and later life cycle phases" (INCOSE 2007). It is in the conceptual phase and development of system level requirements where the focus of this approach lies in this thesis. One method of creating valid requirements is through the implementation of computer-aided wargaming (CAW) to study the effects of new systems in their projected operating environment. Although various combat simulations exist, opportunity offered the Joint Level Theater Simulation-Global Operations (JTLS-GO) for this study. For the scope and needs of this thesis, JTLS-GO will be used to understand the operational impact and effectiveness of advanced UUVs.

Using the MBSE approach for this research is a multi-step process. The first step involved the development of the UUV model and vignette from the real Cobra Gold 2018

(CG18) scenario in the JTLS-GO environment. Creating the vignette permits the examination of CG18 to identify capability shortfalls that the UUVs can fulfill. This approach recognizes the second step by identifying and establishing the operational requirements and the constraints. The last step involved defining the boundaries by developing the measures of effectiveness (MOEs) and measures of performance (MOPs). These measures helped direct development of the design of experiments (DOE) that will guide how UUVs are implemented in the JTLS-GO model.

Adapting the events from CG18, a six-nation command post exercise (CPX), the JTLS-GO will simulate the deployment of UUVs in a realistic military campaign. Although JTLS-GO is useful for simulations, its functionality, according to Cayirci and Marincic (2009), is to train headquarters staff to command and control units more efficiently. This requires large human capital to run an exercise. Thus, testing future capabilities in a realistic combat environment with realistic decision-making is complex using the JTLS-GO CAW alone. As a result, this thesis, with the help of the NPS Simulation Experiments and Efficient Designs (SEED) center, uses an automated version of the JTLS-GO CAW model with an MBSE approach to answer the research questions.

F. STUDY ORGANIZATION

In Chapter II, the presentation of background information describes the current tactics and systems that motivate this research, and the tools and software necessary to support it. Chapter III illustrates the parameters and provides the methodology used in the scenario and design of experiments (DOE) for the simulation. Chapter IV shows the results from the plan described in Chapter III and provides the analysis of the simulation output. Finally, Chapter V presents the conclusions from the automated model-based simulation and serves as a starting point for further research and work in automated computer-aided wargaming.

II. LITERATURE REVIEW

This chapter initially examines the call for a redesign of the future fleet architecture and demand for UUVs. Next, the chapter provides a survey of different UUV models. Thirdly, the chapter investigates the UUV concept of operations (CONOPs). After that, the literature review examines other theoretical and naval articles. The chapter ends with the examination of JTLS-GO.

A. FUTURE FLEET ARCHITECTURE

Senator John McCain, Chairman of the Senate Armed Services Committee, spearheaded the directive in the National Defense Authorization Act (NDAA) for Fiscal Year 2016 to set up three independent inquiries on the status of the U.S. Navy and the evaluation of the fleet composition. His reasons for this addendum are in the following:

> First, 11 Navy combatant ship classes begin to retire in large numbers between 2020 and 2035. Second, other world powers are challenging our Navy's ability to conduct sea control and project power. Third, as the Columbia-class submarine program proceeds, it is projected to consume the equivalent of one-third to one-half of the historical shipbuilding budget, which is already insufficient to meet the Navy's desired force levels. (McCain 2017)

Senator McCain's intent was to find solutions in restructuring the Navy with limited resources and mandatory maintenance commitments. As a result, one aspect in continuing the projection of American sea power is to use unmanned systems. Furthermore, according to the Department of Defense's (DoD) *Unmanned Systems' Roadmap 2007–2032*, the cost of unmanned systems is a fraction of manned equivalent systems. The three analyses from the directive include those by the Center for Strategic Budgetary Assessment (CBSA), MITRE, and the Navy Project Team.

1. MITRE

In a 2016 report, the MITRE Corporation provided several recommendations to the Navy concerning future fleet architecture. MITRE's findings revealed that current fleet mix is a "scaled down version of the balanced force that exited World War II" (MITRE

2016). As a result, this old structure does not support the "current national security environment" according to the study. In fact, MITRE suggested increasing the fleet to 414 ships, especially in the number of attack submarines. However, budgetary constraints make MITRE's recommendation nearly impossible. MITRE (2016) called for "Undersea Enablers" to dominate the undersea domain including a combination of the capability to "connect submarines, autonomous unmanned vehicles, distributed sensor networks, undersea cables, and a variety of other systems." Most importantly, MITRE advocated creating enough "UUVs to augment the submarine force in sufficient numbers to matter" (MITRE 2016).

Most of the naval requirements can be fulfilled by the UUVs that are already in inventory or those that are under development by other services. The Navy is undergoing an improvement of its UUVs, aiming to come up with better sensors, endurance, and expanded portfolios of the UUVs used in the undersea warfare division. Frink (2012) identified that in the past, the UUVs are niche machines applied in the research of certain tasks. Frink (2012) further explained that the challenges in "building and operating unmanned submersibles make them less useful than their airborne and land-bound versions. With technologies evolving, UUVs are expanding into the mainstream with abilities to complete a wider variety of missions other than their research-specific predecessors."

2. Center for Strategic and Budgetary Assessment

The CSBA is "an independent, nonpartisan policy research institute" with a goal to "promote innovative thinking about national security strategy and investment options" (Clark et al. 2017). In step with MITRE, the CBSA made similar recommendations for the U.S. Navy. Although increasing the fleet is ideal, the CBSA acknowledged the impracticality of this avenue due to budget constraints. The CBSA provided detailed specifications for operating in the hostile underwater domain. Two of these concepts included offensive and defensive undersea warfare. Part of this strategy involved the employment of UUVs. As such, this organization recommended a fleet size of 382 ships including the procurement of 40 XLUUVs by 2030. Again, there is an emphasis on the use of UUVs.

3. Navy Report

The third input required by the NDAA for FY 2016 came from the U.S. Navy. Similar to the previous reports, the Navy Project Team recommended the increase of naval assets in the future architecture. The Navy Project Team recommended the "expanded use of unmanned underwater vehicles from submarines ... to provide theater commanders with options to deploy sensors and weapons into highly contested previously denied water space" (Navy Project Team 2016). Above all, this report suggested the development of a fleet of 136 unmanned ships by the year 2030 with the expectation that 30 UUVs will be operationally available at all times.

The conclusions from all the reports were similar. They endorsed two significant points in altering the fleet architecture for 2030: 1) increase the fleet size and 2) increase the production of UUVs to support fleet activities.

B. UUV BACKGROUND

Dan Gettinger, Co-Director of the Center for the Study of the Drone at Bard College, offered a brief history of the robotic submarine in his article, "Underwater Drones (Updated)." Gettinger (2016) noted the first civilian use of the platform in support of "marine exploration and research." These vehicles' purpose evolved to salvaging especially for air and naval incidents at sea: the Titanic, Korean Airlines 007, Egypt Air 990, and Air France 447. More importantly, according to Mr. Gettinger, the development of the UUV has "allowed both universities and small businesses access to new opportunities for undersea exploration in the same way that unmanned aerial vehicles have democratized access to the sky" (Gettinger 2016). Due to this revelation, the DoD and the U.S. Navy ventured in adapting this platform for defense usage.

1. UUV Categories

UUVs fall into four major categories per the DoD and the U.S. Navy (Figure 1). According to the Department of Defense (2007, 22), the four types of UUVs are "Man-portable, Lightweight, Heavyweight, and Large;" the distinguishing characteristics of these vehicles fall into two characteristics: displacement and diameter. Man-portable UUVs are vehicles that have between "25 to 100 pounds of displacement, and Lightweight UUVs have a diameter of "12.75 inches and a displacement of 500 pounds" (Department of Defense [DoD] 2007, 22). Meanwhile, the Heavyweight UUVs are slightly larger with a diameter of "21 inches and 3000 pounds of displacement" (DoD 2007, 22).

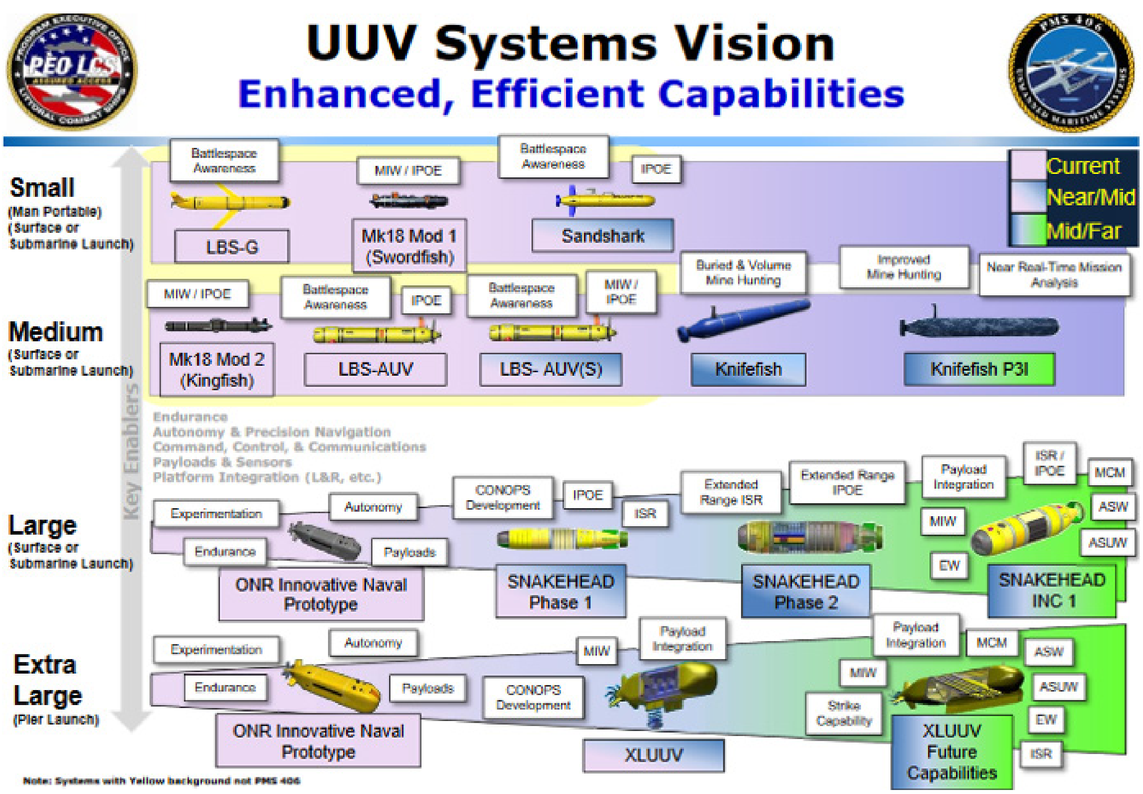

Figure 1. Screenshot of UUV Categories from Sea Air Space Symposium. Source: Berkof (2017).

Lastly, the largest UUVs have at least a "displacement of 10 long-tons" (DoD 2007, 22). The Navy, however, has different terminologies for these four UUV classes; as displayed in Figure 1. Although the size of the UUVs are similar to the descriptions from the DoD, the consideration of UUV sizes is paramount for mission support.

2. Current Fleet

In October 2016, Rear Admiral Tim Gallaudet delivered a presentation on the existing fleet inventory of UUVs at the Unmanned Systems Defense conference, as displayed in Figure 2.

Figure 2. UUV Inventory in 2016. Source: Gallaudet (2016).

Figure 2 shows a substantial stock of Remus Autonomous Unmanned Vehicles (AUVs) and Gliders for maritime reconnaissance, yet only 25 UUVs support the mine countermeasure (MCM) warfare. The current inventory heavily supports the top two priorities for UUV implementation displayed in Table 1 but lacks supporting the 15 remaining mission areas established in the *Unmanned Systems Roadmap 2007–2032*. Observing the current inventory demonstrates a need for more UUVs in support of other missions.

3. Concept of Operations (CONOP)

The Department of Defense in conjunction with the Navy's *UUV Master Plan* created a mission priority list for UUVs. These missions are ranked from most important to least important (1 to 17) and are in Table 1. These missions are different for each size of UUV. The top three mission areas, "ISR, Inspection, MCM," are the same for the four classes of UUVs; the different mission requirements lie in the later rankings (DoD 2007, 22). Generally, the smaller vehicles support surveying and information operation missions while the conditions for larger UUVs favor delivering of payloads and supporting anti-submarine warfare.

Table 1. COCOM UUV Needs Prioritized by Class. Source: Department of Defense (2007).

Mission Area	Man-portable	Light-weight	Heavy-weight	Large
ISR	1	1	1	1
Inspection/Identification	2	2	2	2
MCM	3	3	3	3
Payload Delivery	8	7	4	7
CBRNE Reconnaissance	4	5	8	12
Covert Sensor Insertion	5	4	10	11
Littoral Surface Warfare	12	9	5	5
SOF Resupply	6	10	9	6
Strike	14	8	7	8
CN3	7	6	12	13
Open Ocean ASW	13	17	6	4
Information Operations	11	11	13	10
Time Critical Strike	15	13	11	9
Digital Mapping	9	12	15	14
Oceanography	10	16	16	15
Decoy/Pathfinder	16	15	14	17
Bottom Topography	17	14	17	16

The RAND Corporation investigated the concept of operations (CONOPs) illustrated in the *UUV Master Plan,* "Hold at Risk, Maritime Shield, and Protected Passage" (DoN 2004, 12). Based on their investigation, they recommended the "transfer of some responsibilities from manned vessels to unmanned vehicles" because fewer ASW ships will be available to support these operations in the future (Button et al. 2009, 85). Figure 3 presents an illustration of these three major CONOPs that apply to UUVs.

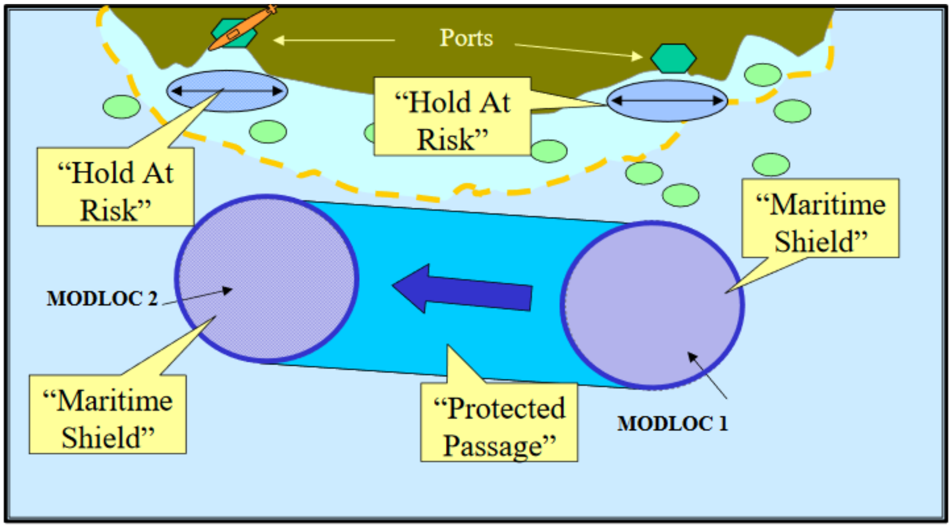

Figure 3. Screenshot of ASW Profiles for UUVs.
Source: Department of the Navy (2004).

According to the Navy (2004, 12), the "Hold at Risk" mission describes the tracking of targets of interest entering and exiting a port. "Maritime Shield" is the active process of keeping designated areas free of enemy submarines. Finally, the 2004 *UUV Master Plan* describes "Protected Passage" as the process of denying enemy submarine access in designated sea lanes (DoN 2004, 12). These concepts influenced several scenarios that we developed to examine UUVs.

C. PREVIOUS WORK

The Applied Physics Lab (APL) at John Hopkins University investigated the use of UUVs in a "Maritime Shield" scenario (DoN 2004, 12). In this scenario, the UUVs were positioned in front of a strike group. They screened for hostile underwater units to maintain an ASW superiority environment (Deutsch and Parry 2009). Their experiment focused specifically against diesel-electric submarines (SSK) due to their abilities to penetrate naval battle groups including one situation of "a PLAN Song Class SSK being within 8 kilometers of a U.S. aircraft carrier" (Deutsch and Parry 2009, 5).

Deutsch and Parry (2009) presented an in-depth computer-modeled scenario which involved: the deployment of multiple UUVs to a common location; the operation of "active sonar at depth during an outward radial sweep," (Figure 4); the employment of "active sonar at depth during barrier screening" operations; and the retrieval, refueling, and relocation of UUVs to the next operational area (4–6).

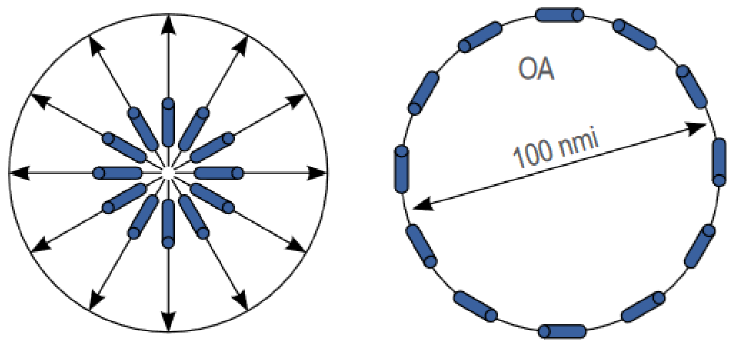

Figure 4. Screenshot of UAV Radial Sweep.
Source: Deutsch and Parry (2009).

The sweeping tactic, illustrated in Figure 4, depicts a dozen UUVs, traveling at three knots, and circulating an area with a diameter of 100 nautical miles. The article (2009) further examined the issues with size, navigation and sonar equipment necessary to detect threat submarines. Most notably, Deutsch and Parry (2009, 6) predicted the submarine's target strength (TS) "between 5 and 30 Db" as shown in Figure 5.

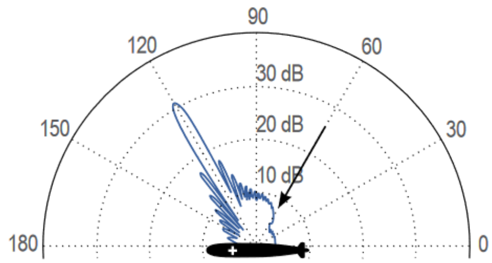

Figure 5. Estimated SSK Target Strength.
Source: Deutsch and Parry (2009).

The TS is a function of the target angle, sea state, bottom reverberation, salinity, and transmission losses. Because of these factors, their recommendation involved the use of active sonar during the UUVs' search.

Applying their concept and platform assumptions, Deutsch and Parry (2009) conducted 1000 trials in a Monte Carlo simulation. The experiment involved three diesel enemy submarines maneuvering in a designated 100 nautical mile zone while "using [an] intercept sonar" avoidance technique (Deutsch and Parry 2009, 10). Under the best-case environment, Sea State 0, the UUVs were able to find the threats with a probability of 90% in 11 hours. However, under Sea State 3, the units discovered the targets with a prospect of 90% certainty in16 hours. The experimentation concluded that the presence of the UUVs was able to alter the behavior of the diesel-electric submarines; this disruption can delay or even deter penetration of designated naval space (Deutsch and Parry 2009). The APL's study is a good benchmark to test future UUV capabilities and requirements for the fleet architecture.

Because of top-level interests in UUVs, many research projects and theses exist at the Naval Postgraduate School (NPS). Daniel W. French, a systems engineering graduate, analyzed various commercial architecture considerations for the UUV and presented the best prototype for use in the military environment (French 2010). He (2010, 41) identified five characteristics quintessential in designing a UUV platform: "1. form factor, control surfaces, propulsion, 2. Energy, 3. Pressure Hulls and Wet Volumes, 4. Sensors and Communications [and] 5. Launch and Recovery." His detailed inspection produced an optimized UUV for ISR missions; French (2010) advocated for a smaller UUV torpedo shaped prototype having several internal sensors. This paper's recommendation, consequently, suggested larger UUVs are better for non-reconnaissance missions.

In December 2017, Camacho et al. (2017), authors of "Investigation of Requirements and Capabilities of Next-Generation Mine Warfare Unmanned Underwater Vehicles," surveyed architectures of UUVs engaging in mine countermeasure mission, the second prioritized mission by the Navy. Applying systems engineering trade-off analysis, the project compared six different alternatives including, "location of data processing and communication frequency with host ship" (Camacho et al. 2017, 45). Along with these alternatives, the authors (2017, 70) discovered nine operational factors, "sensor width, UUV speed, PMA rate, on board processing rate, IC data limit, surface time, data collection rate, transit time, and replenish time," that affect mine warfare. Conducting their 18 design parameters experiment through a "discrete event simulation software, ExtendSim," the members concluded the best alternative is to have a UUV with constant communication with the host ship and onboard data processing (Camacho et al. 2017, xviii). Additionally, the team (2017) recognized the most crucial operational factors for effective minesweeping operations: UUV speed, sensor width, and onboard processing. Therefore, having more organic equipment on the UUV can speed up the process of engaging mine warfare. The implication of this project suggests speed and processing sensors are important in search and tracking missions.

The most recent study, one created by LT John F. Tanalega, surveyed the feasibility of unmanned surface vehicles in anti-submarine warfare. In his thesis, Tanalega (2018) used the Medium Displacement Unmanned Surface Vessel (MDUSV) as the platform to discover tactical capabilities of USVs in an ASW environment. Utilizing the Lightweight Interstitials Toolkit for Mission Engineering using Simulation (LITMUS) as the simulation executioner, Tanalega created a scenario incorporating manned ships with MDUSVs against several surface threats. He learned from several iterations of experimentation in LITMUS that the presence of these platforms increased the "first-to fire" rate "nearly threefold" (Tanalega 2018, 16). His work advocated for the use of unmanned maritime vehicles in hostile spaces.

1. Limitations of Litmus

While the LITMUS simulation program is a proven and popular model, this program has its shortcomings. According to Tilus (2016), the original purpose of LITMUS was to support the simulation and modeling of the littoral combat ship in a surface warfare setting. The developers adapted the program to simulate other domains including both undersea and air warfare. Tilus (2016) also noted the simulation's capability to develop scenarios through the Graphical User Interface (GUI) for testing and evaluating hypothetical events.

The GUI offers many options for experimentation; these options comprise of location, number of experimentations, the environment, and the testable units, known as agents in LITMUS. Termination of the simulation comes from two conditions: *user-defined* or *by a designated period*. One shortfall of setting up the experimentation is the creation of a user-defined random seed; this makes the simulation less random and therefore less realistic in replicating the randomness of the real world.

The production of agents in LITMUS is complex. According to Tilus (2016, 15), there are "seven modifiable characteristics." These modifications include: agent platform; sensor and weapon systems; distress signal receiver; command and control order manager; firing doctrine management; propulsion and route management; and rate of radar or sonar sweep (Tilus 2016). The requirement of in-depth agent script writing restricts randomness of encounters; each agent can only travel a certain distance with defined turn rates. Another issue with the LITMUS model is the constraints on the scenario adaptability. Rewriting the scenario is time consuming requiring the rewrite of all agents, tactics and environment. In essence, LITMUS is a single engagement, tactical simulator and does not account for the management of a long-term campaign.

The Joint Theater Level Simulation-Global Operations (JTLS-GO) alleviates some of the issues identified in LITMUS. JTLS-GO is an operational global simulation that incorporates options that cater to a long-term campaign. The comparison between the two simulation programs rests in the production of results; LITMUS has the capability to produce results rapidly while the sizeable scenario involved in a theater-level wargame needs a longer time for similar replications. However, the advantage of a large scenario is greater insight at a strategic level. Secondly, the design of LITMUS only allows for naval use; on the other hand, JTLS-GO encompasses all service branches and is suitable for all branches. Another advantage of JTLS-GO is the database; as a result, the creation of agents is less intrusive. The user can alter the attributes in JTLS-GO or choose to adjust them prior to the agent injection. Directing units is simple; instead of setting up turn rates, the user directs the agents to patrol an area; as such, the random encounters increase in JTLS-GO. Despite the added values in JTLS-GO, the model contains its set of shortfalls.

D. JOINT THEATER LEVEL SIMULATION-GLOBAL OPERATIONS

JTLS-GO is an event-driven wargaming simulation designed by Rolands and Associates that serves to test multi-sided joint campaigns and operations (Rolands and Associates 2017). JTLS-GO offers simulated operating atmosphere for the joint and coalition air, land, sea and special operations forces. The model can represent up to 10 forces with multiple players on each side. The program tests several layers of warfare including political, strategic, operational, and tactical levels; however, there is some limitation to the resolution of tactical engagements.

Because of its modularity, JTLS-GO is favorited amongst staffs as a tool for training and validating campaign strategies. This segment presents the strengths, limitations, gameplay process, and scenario in preparation for testing.

1. Strengths and Limitations

JTLS-GO has many advantages as a simulation platform; the most noticeable positive attribute is the maturity of the database. Developed in 1984, the programmers of JTLS-GO have collected decades of information on every country's order of battle (OOB) or the expected fighting components. Secondly, the scenarios and engagements are doctrine neutral; the simulation relies on the users to inject policies and to define objectives. This setup allows for exploration of different strategies and trade-off analysis. Like any model, this program does have weaknesses.

Even though the database is robust, the accuracy of unit capabilities is dependent on the classification level. The exercise sponsor establishes the classification of the exercise. Because most JTLS-GO exercises are multinational, exercise sponsors request unclassified database scenarios. As such, the JTLS-GO developers maintain an unclassified scenario database. The limitations lie in some capability imprecisions of the database at the unclassified level and updating the database at higher levels requires a lot of time. As a result, white cell interpretation of combatant results becomes necessary. Furthermore, the resolution of tactical engagements exists at broader scopes; for example, the user cannot control each action of a unit, such as turning rate of a ship.

2. Gameplay

JTLS Gameplay can be summarized in three-steps: interaction, acknowledgment, and result. Participants interact with the simulation through a web-hosted interface program called the WHIP. Within this interface, the players can generate orders for units or groups of units for action. After the submission of these orders, the combat events program (CEP), the simulation engine, acknowledges and processes the request. The resulting product is a message that reports the consequences of the injected order.

3. Limitations of Previous Works

The earlier works mentioned provided great insight in both the development and examination of unmanned maritime vehicles. They offered recommendations for optimized prototypes and expected tactics for the essential mission areas for the Navy: ISR, MCM, ASW. However, these works focused on individual engagements. The current effort intends to examine the UUV in more dynamic environments involving maritime security with surface and underwater threats while providing insight on the fleet architecture necessary to fulfill strategic objectives.

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III. METHODOLOGY

A systematic approach will be key throughout the process to ascertain the operational effectiveness of UUVs. The approach will involve the development of a conceptual prototype in an experimentation environment based on computer simulation of future capabilities in an operational context. This chapter steps through the process of creating and experimenting the UUV prototypes. The first section explains the engineering approach (MBSE) adapted for this thesis. Using JTLS-GO as a tool for the basis of the experimentation environment, the next section describes the application of the engineering approach and explains the opportunities for the injection of the UUV prototypes. After, the chapter examines how CG18 was modified (vignette) to allow repeating runs with differing UUV capabilities. Thereafter, the chapter examines the desired output, input, and design points used in the design of experiments (DOE). Additionally, the DOE section will demonstrate the reasoning behind using two DOEs for this study. Finally, this chapter shows the plan of action for the simulation and analysis that will answer the research questions mentioned in Chapter I.

A. MODEL-BASED SYSTEMS ENGINEERING (MBSE)

MBSE is the practice that entails the development of a set of related system models to aid throughout the definition, design, documentation, and the testing of a system. It is important in all modern projects because it helps immensely towards offering efficient ways to explore, modify, and update various aspects of systems to the concerned stakeholders while simultaneously striving to eliminate or reduce the dependence on the outdated traditional methods and documentation. It moves authority records from documents to digital models managed in environments rich in data. By doing so, it helps achieve efficiency and minimize complexities in any adjustments that may accrue throughout the implementation of the project. MBSE is like the traditional systems engineering approach, but orients around models including the following: the functional model, performance model, structural model and other engineering analysis models. The advantage of models is its adaptive nature; the ability to make changes in a model is simpler than rewriting or redrawing documents. Additionally, data overload is a concern; models can simplify and filter data of interest much quicker than document filtering. With the MBSE mindset, the following section examines the execution of this procedure. The efficiency that MBSE offers is the primary reason for its engagement throughout the implementation of this study.

Figure 6 shows one of the most common visualization methods of MBSE, the Vee model. The model steps through a system or product's life cycle, from creation to retirement. For this research, the focus is in the upper left echelon or the high-level perspective of a system's development. The modeling environment is vital in MBSE because the modeling results allow for the verification and validation of the conceptual system design against the system requirements. Applying this process leads to the refinement in either the design or system requirements making the product satisfy the initial deficiency. Having established the MBSE method, the next progression is to examine the implementation of the model.

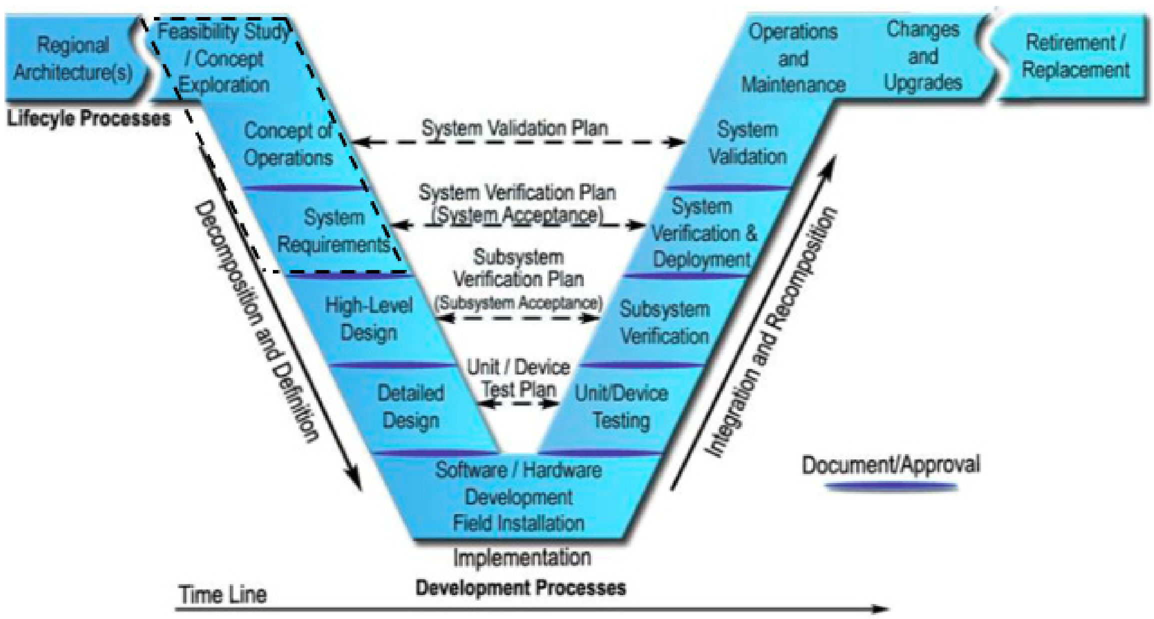

Figure 6. Typical Systems Engineering Vee Diagram. Adapted from Department of Transportation (2007).

B. EXPERIMENTAL SETUP IN JTLS-GO

Because JTLS-GO is built to represent a "decision-making environment," it is ideal for observing the effects of platform interactions and strategic level decisions (Rolands 2015). This becomes advantageous for the MBSE process since the initial MBSE stages focus on higher-level concepts that can be clearly established and analyzed through the sophisticated structures of JTLS-GO. Under conventional MBSE, the system is not identified as the solution until requirements are set, but stakeholders asked for the evaluation of integrating UUVs into the fleet.

The first step in using JTLS-GO for experimentation was to find opportunities during the unaltered CG18 scenario to inject the UUVs. Although JTLS-GO is capable of imitating complex environments, it cannot justify the capabilities and participants of an exercise. Members of Pacific Command (PACOM) created the narrative for CG18. This narrative provided the governing rules and set up for the scenario, which included the operational area, OOB, and factions. After discovering the operational deficiencies in CG18, the next step was to conduct concept exploration, done through the literature review. Combining the results of the deficiencies and the literature review led to the third step of the Vee diagram: CONOPs, which describes the application of the UUVs in the expected environment. The following sections describe the scenario and the development of the UUVs' CONOPs.

1. Scenario

CG18 is a multi-national command post exercise hosted in Thailand. The storyline occurred in a fictitious continent called Pacifica (Figure 7). The country of Sonora invaded (red arrow) a land-locked nation called Mojave, resulting in the instability of the entire continent. As a result, a United Nations coalition including Indonesia, Malaysia, Singapore, South Korea, Thailand, and the United States intervened. The objectives of the alliance included the expulsion of Sonoran forces, the enforcement of trade embargos against Sonora, the achievement of maritime superiority against Sonoran naval forces and the provision of humanitarian assistance for Mojave refugees.

Figure 7. Illustration of Sonoran Forces Attack on Mojave. Adapted from PACOM Exercise Cobra Gold (2018).

Observing the unaltered exercise led to the identification of two operational shortcomings: *limitation of maritime escorts* and *limited naval situational awareness*. The lack of maritime guards led to casualties for one U.S. and two allied vessels. More importantly, the result of these casualties transpired because of latent enemy positional information. These events provided an opportunity to uncover the impact of UUVs.

2. Concept of Operations-Vignette Description

The UUVs will operate at periscope depth around the northeast coast of Sonoran territory; their priority is to search for Sonoran units and provide a buffer zone for United Nations Task Force 1, including USS *Benfold* (DDG-65) and RSS *Endurance* (LS-207) (Figure 8). Task Force 1 will report Sonoran unit positions through Intelligence messages, displayed via the JTLS-GO message browser. If within range, the UUVs will engage the Sonoran units. At this point in the scenario, the Sonoran units are hostile, and the rules of engagements permit active offensive measures.

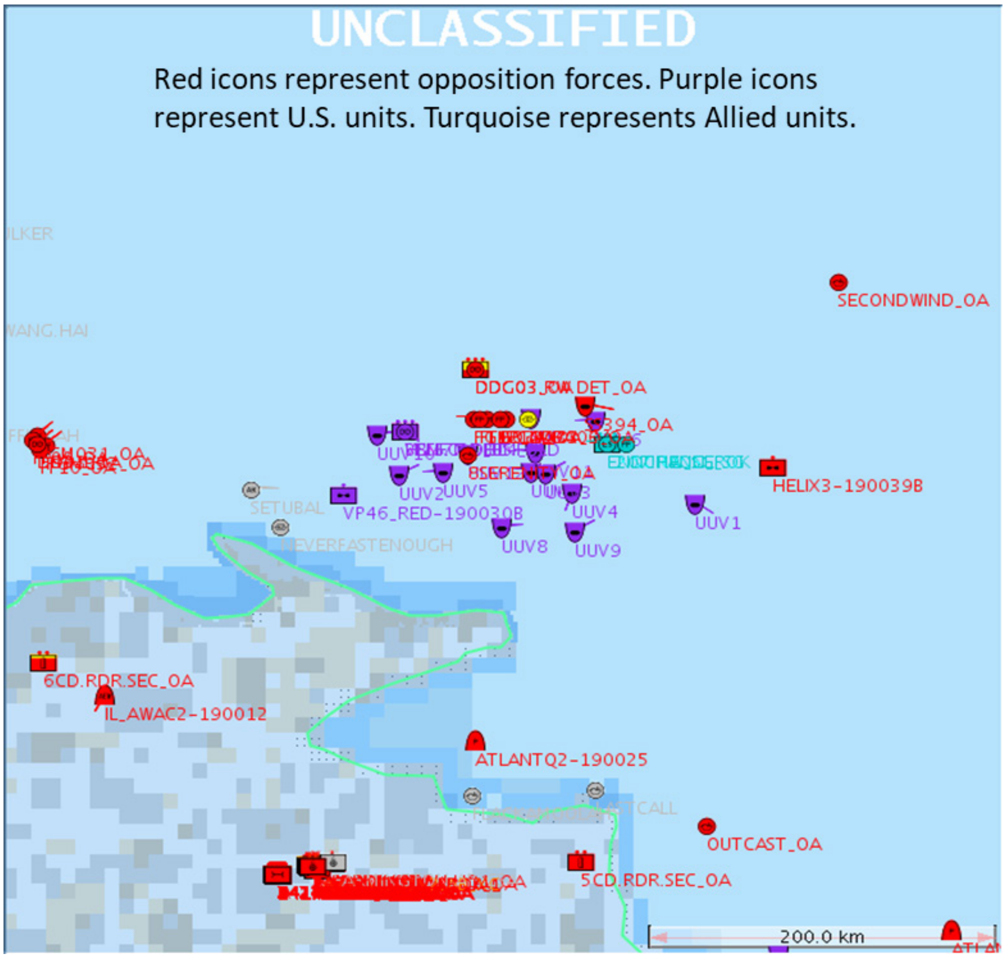

Figure 8. Screenshot of UUV Scenario.
Adapted from PACOM Exercise Cobra Gold (2018).

Opposing the United Nations Task Group, Sonoran Task Group 3.1 intends to head east to disrupt the embargo. This Sonoran task group had the following units:

- one Sovremennyy-class destroyer (Threat against air, surface, and subsurface assets),

- two Gepard-class frigates (Threat against air, surface, and subsurface assets),
- two Tarantul-class corvettes (Threat against air and surface assets),
- one Improved Kilo-class submarine (Threat against surface and subsurface assets).

The UUV's ability to interact with the Sonoran task group provides a foundation that this platform could potentially be useful in escort and embargo duties.

a. UUV Search Tactics

Undersea warfare presents a great challenge according to Admiral Gary Roughead (*Financial Times* 2011). Unlike the air or surface environment, hostile contacts are difficult to detect visually. Even with sensors, the underwater domain is difficult as more clutter exists because of the ocean current and biologicals. Thus, employing search techniques becomes paramount; moreover, applying search techniques has shown to increase the efficiency of finding vessels. Analysis of searching for U-boats in the Bay of Biscay demonstrated a significantly higher probability of sighting U-Boats, near 100%, compared to 60% with a random search pattern (McCue 1990, 88). The APL search pattern described from Chapter II will be the search pattern of choice during the experiment. The UUVs will maneuver in a circular pattern and have designated nonoverlapping areas to perform searches.

C. MEASURING PERFORMANCE AND IMPACT

To understand the impact of the UUVs, this study must find measurable characteristics that relate to the stakeholders' objectives for using a UUV in an operation. The author identified performance parameters that describe how the UUV performs, or MOPs, and how well the UUVs contributes to the operational outcomes. The performance parameters, according to the Defense Acquisition University (2018), are "quantifiable and distinct." When considering the identified operational gaps, the selection of the expected responses (performance parameters) must provide a value for analysis. Two responses come to fruition during the discovery of units: units are found, and they are found within a certain period. The expected outcome of an engagement is that there will be units killed. Hence, the MOPs for this experiment are detection numbers and Sonoran units killed.

The Defense Acquisition University (n.d.) describes MOEs as data analyzed for measuring the mission accomplishment of the system in the familiar environment. Specifically, the measurement of mission accomplishment derives from the analysis of the MOPs. As a result, the MOEs for the UUVs include the performance in detection of units and Sonoran attrition. When considering detection of units, more is better for units detected as this allows for a more complete common operational picture (COP). For Sonoran attrition values, more units killed is better since enemy kills equate to fewer threats against friendly forces. Having established the measurements for UUV success, the next progression is to identify the input parameters that will generate the desired output values. The ensuing process defines the method in distinguishing and testing those parameters.

D. FACTORS AND THE DESIGN OF EXPERIMENT (DOE)

Averill M. Law (2015) called the underlying assumptions and input parameters of a model "factors." Experimentation varies factor values to understand its influence on the measures of interest. However, there can be an infinite number of factors in a simulation and the number of values that any one factor can assume can be infinite, thereby adding to the complexity of the experiment. In most cases, exhaustively experimenting on all factor value combinations is near impossible. Tracing the results to the inputs is just as challenging. For these reasons, determining which factors to examine and what factor value combinations to use requires careful planning. The following section explains the process for selecting the variable factors and the eventual design of experiment.

1. UUV Design Factors

For the reconnaissance and engagement missions, the UUVs fill the role of modern manned submarines and so, the factors that make submarines effective are applicable to UUVs. Because the scope of this thesis is to explore the effects of UUVs on an operational mission and not create a definitive solution, we limit this study to three factors for experimentation. One design factor that makes submersible vehicles effective is its speed.

The speed, ignoring endurance limitations, correlates to the area the vessel can monitor; more speed equals larger coverage areas. Faster speed is advantageous in closing an enemy unit for prosecution. Current UUV speeds are less than 10 knots. Varying the speed can aid in finding the preferred speeds that overcome the operational deficiencies. Another factor to study is the number of UUVs to employ. The required number of UUVs to support naval operations is crucial to future fleet design. Finding the number of UUVS that can augment the future fleet to produce desired capability could be valuable in directing the Navy's expenditures. The third design factor is the use of active sonar; active sonar permits high rates of detection. However, this feature also gives away the position of the unit using active sonar.

Table 2 summarizes the range of values for each factor. The number of experimental UUVs are adapted from the John Hopkins APL's experiment with a variation of 25%. The speed reflects the typical rates from a diesel submarine. Most modern submarines have sonar capabilities: active and passive. Pinpointing the most important factors offers the ability to create the experimental matrix. The experiment will not address the factors that the user cannot control. Environmental factors and Sonoran strategies from the real exercise will not change. Thus, the experiment will address three controllable factors: UUV speed, UUV deployed (UUV composition), and sonar type. Table 2 shows the minimum and maximum ranges of these variables.

Table 2. UUV Design of Experiment Variables

DOE Factor	**Min**	**Max**	**Units**
Speed	5	12	knots
UUV Composition	8	16	vessels
Sonar	Passive	Active	

The speed of the UUV is an important factor to consider with regards to the MOEs as missions may require rapid response. The speed will determine the rate at which the Navy will be responding during its operations. The UUV composition is important because this will measure the effectiveness of the deployment of the vehicles. It is important for the Navy to confirm the deployment nature of the UUVs to be sure how effective they can be before they are put into action. Sonar is another important factor to be considered while measuring effectiveness. Sonar is a factor that uses sound propagation to navigate, communicate and detect objects under the water. This capability is critical for the Navy as it will enable the force to know or detect objects or barriers that might hinder the UUVs from being effective in their operation. While this study focuses on three primary factors, this thesis also explores attributes related to the JTLS-GO, including the simulation, basic operations, the input and output and the user participation. An understanding of various attributes related to JTLS-GO will help create a relationship between the results and the underlying process offering a better avenue for dealing with deviations, errors, and a platform for future developments and advancements.

One of the goals of testing the experimental factors is to observe their influence in the modeling environment. Law (2015, 630) labels this process of finding the factors' effect: *screening* or *sensitivity analysis*. The observable influence can be independent or mixed; to see the effects requires regression and interaction analysis. The unique value of a factor is known as a level. This screening process will be part of this research project and described in the next section. Every experimental simulation requires unique levels from the three factors; these unique set of levels is a design point (DP).

1. Design of Experiment (DOE)

The number of design points is dependent on the type of design of experiments (DOE) used for the simulation. The most ideal choice is the multi-level, full-factorial design. The benefit of a full factorial DOE is the simulation of every single design point and thus, provides the most insight because it includes all possible interactions amongst the factors. Yet, the cost lies in the time to collect the results and analyze the data of each design point. This time-consuming method is only possible with limited parameters and levels. The 2^k factorial design works well for initial experimentation when minimal information is known on how the factors affect the results and hence will be a key part of the process. Moreover, the 2^k factorial is a good design to help screen the various parameters and leads to the establishment of important ones. Thus, the experimentation for this research will be two-fold; first, the initial experiment involves the use of the 2^K

factorial to demonstrate the chosen factors are legitimate while the second experiment involving a central composite design (CCD) will provide more insight in these factors' behavior.

Incorporating the factors and levels in the UUV experiment, a full factorial is not feasible at 84 DPs or 2,520 simulations. Multiplying the number of simulations and duration of each run of JTLS-GO equates to 5040 hours or 210 days of simulation required. For the scope of this thesis, this amount of time was impractical. However, the 2^K factorial design alone is not appropriate.

Because the goal is to observe general effects at the high-level spectrum of MBSE, the CCD provides enough design points to show trends of the UUVs' behavior while not pinpointing the exact solutions. The CCD is resourceful in response surface methodology. The quadratic model helps with variable response without the compulsory inclusion of a complete 3-level factorial experiment. Using the CCD on the three factors resulted in 18 design points (Table 3). After creating the plan for experimentation, the following step involves the injection of the DPs into JTLS-GO.

Table 3. UUV Design Points

Design Points			
	Sonar	**UUVs (Units)**	**Speed (knots)**
DP1	Active	16	12
DP2	Active	16	8
DP3	Active	16	5
DP4	Active	12	12
DP5	Active	12	8
DP6	Active	12	5
DP7	Active	8	12
DP8	Active	8	8
DP9	Active	8	5
DP10	Passive	16	12
DP11	Passive	16	8
DP12	Passive	16	5
DP13	Passive	12	12
DP14	Passive	12	8
DP15	Passive	12	5
DP16	Passive	8	12
DP17	Passive	8	8
DP18	Passive	8	5

E. INJECTION OF UNMANNED UNDERWATER VEHICLES INTO THE MODEL

Often, unplanned objectives or events occur during an exercise. To accommodate these occurrences, JTLS-GO provides features to add or delete units, even units that are not organic to a faction's OOB. This element in the modeling program makes injecting future capabilities possible. But, this feature is not accessible to all factions. In JTLS-GO, controlling the scenario and units do not exist under the same GUI; because the purpose of this simulation is wargaming, each faction has its own dedicated WHIP. The white cell or referee of the game owns the controller WHIP. The experiment requires two WHIPs to create the UUV platforms (United States and Controller) with the parameters of interest. More specifically, the controller WHIP creates the UUVs and the United States WHIP provides the orders for the UUVs. This inherent design prevents unapproved advantages or disadvantages placed on any faction. The succeeding section describes the procedures on creating and controlling UUVs.

1. UUV Creation

In the current version of JTLS-GO, the UUV platform does not exist; hence, submarines will play the role of the UUVs. Subsequently, modification of the submarines became necessary to reflect the expected capabilities of the UUVs. Generating UUVs involved three steps: the first step was to change a recognized prototype from JTLS-GO's database (Figure 9); the second step was to use the create an unit order, which injects the prototype into the scenario. Finally, the prototype becomes playable when JTLS delivers it into the theater. The prototype chosen was the Agosta submarine because this prototype did not exist in the original exercise and has an Air Independent Propulsion (AIP) engine, which is considered ideal for stealth (Cai et al. 2010).

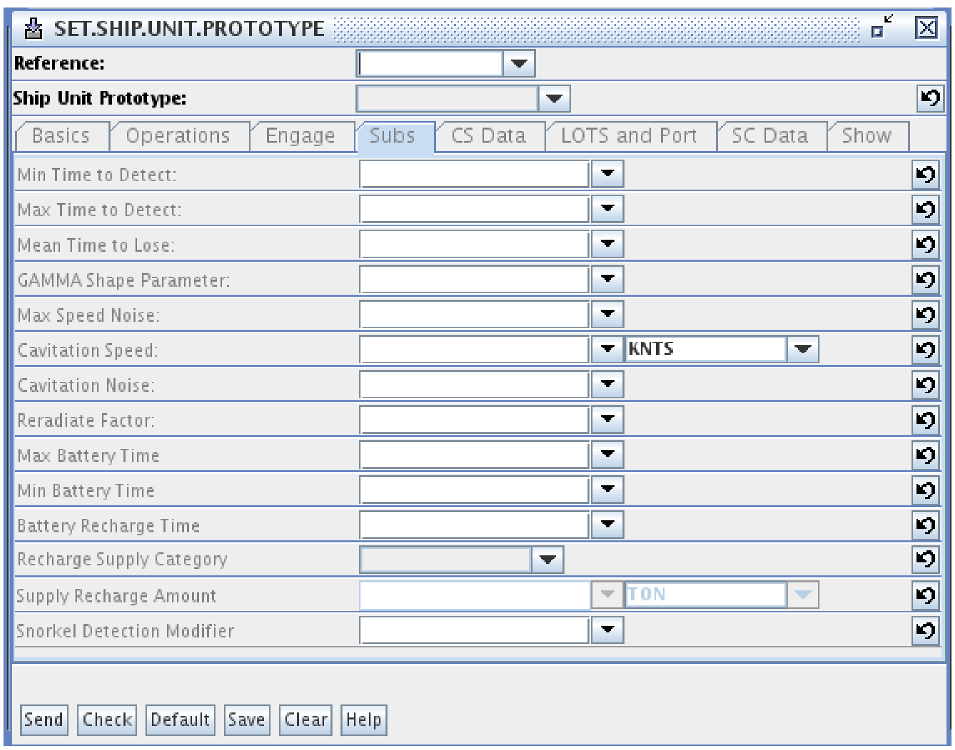

Figure 9. Screenshot of Changing Submarine Attributes.
Source: JTLS-GO Simulation

JTLS-GO offers several attributes for simulating submersible ships. These attributes include hit function, cavitation speed, cavitation speed noise, detection times, ship size, submerge time, and ship speed. Note, the modifications of the UUV prototype ignored logistical and repairing attributes of the ship because the vignette timeline is only twelve hours. Adopting the Navy Project Team's recommendation from Chapter II, the largest projected UUV platform has a displacement of 90 tons. As such, changes on the Agosta prototype replicated the attributes of a Yugo North Korean submarine.

The hit function defines the minimum amount of hits for the ship to sink, and it has the shape of a Weibull distribution. Due to the small size of the UUV platform, the alpha parameter set is 1.5, and the beta parameter is 0.8. It does not take many hits to sink the UUV. The cavitation speed describes the minimum threshold when the ship's propulsion creates cavitation. When this occurs, the addition of cavitation noise to the ships' normal operating noise occurs. For the UUV prototype, cavitation occurs at speeds greater than two knots at 63 decibels.

Detection times hold a gamma shape distribution and are a function of noise generated from the prototype. In JTLS, there are two extremes: the time it takes to detect the unit at the maximum and minimum noise. The default values are one minute at the maximum and four hours at minimum.

The submerge time describes the length of time the unit can remain underwater; this time falls under two ranges: the maximum battery time and the minimum battery time. At full speed, the UUV prototype's endurance is three hours and two days at zero knots. The UUV prototypes will have a speed range as illustrated from Table 2, five to twelve knots.

The second stage of making a playable UUV involves creating the prototype under the controller WHIP (Figure 10). In this interface, the user must choose the desired prototype. The altered Agosta prototype was chosen for this thesis. After, the user must decide which type of unit the prototype will be, submergible for this experiment. Alas, the order is ready, and the execution of this order injected the UUVs into the game.

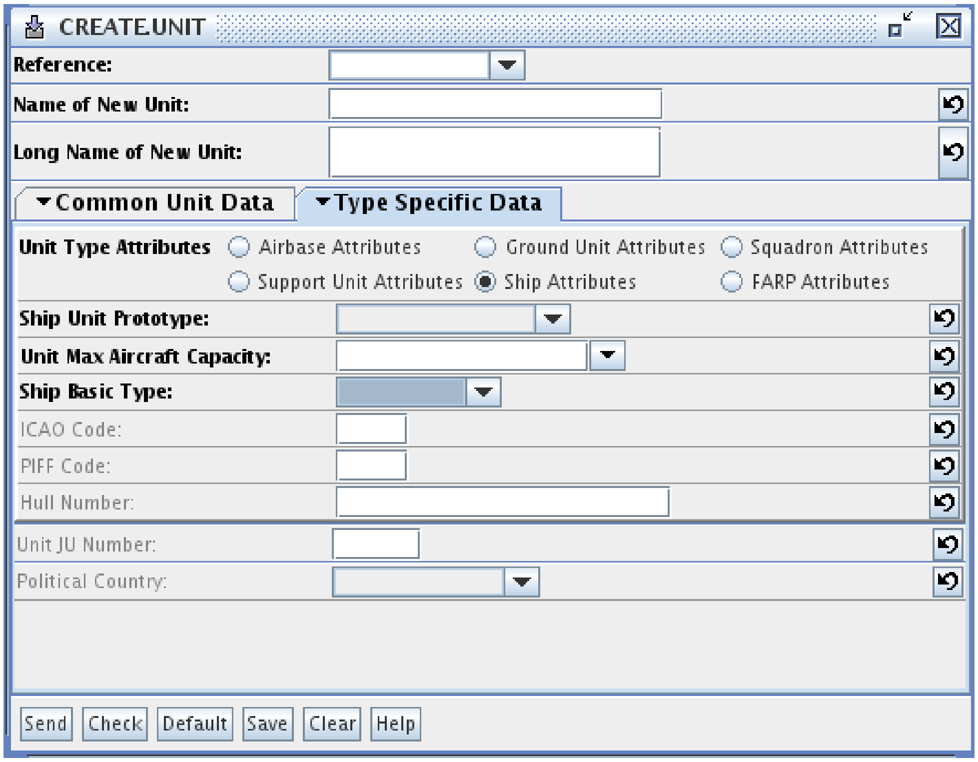

Figure 10. Screenshot of Making a Unit in JTLS-GO.
Source: JTLS-GO Simulation

The final step involved changing the delivery date of the UUVs. After the CEP acknowledges the creation orders, the UUVs will enter the game 99 days from the order acknowledgment; this is the default value, and the purpose is to simulate the logistical setup in supporting this platform in the combat theater. This logistical characteristic is known as the Time-Phased Force and Deployment Data (TPFDD). The user, through the controller WHIP, can speed up this timeline by modifying the TPFDD, (Figure 11).

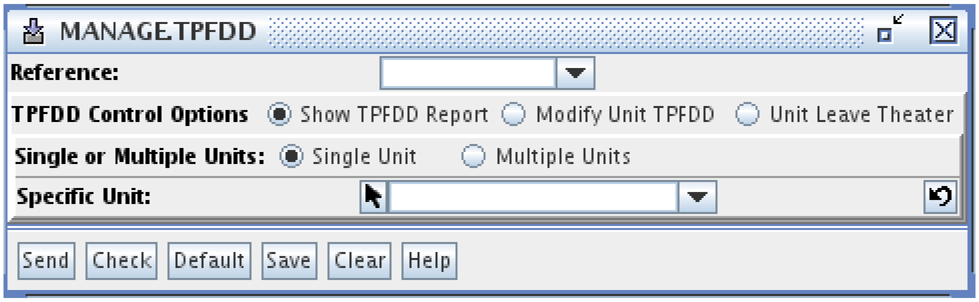

Figure 11. Screenshot of Unit Delivery Date.
Source: JTLS-GO Simulation

The user will assign the created units to a higher headquarter, select the location of injection and click submit. The acknowledgment of the order occurs, and the units are officially playable.

2. UUV Orders

Once the UUVs are in the game, the user controls the UUVs through the U.S. WHIP. Different patrol sectors assigned to the UUVs allow for searching the hostile units. Each patrol order requires the user to create a search area. The unit will randomly choose a pathway to maneuver. Additionally, the user must adjust the sensors on the platform; otherwise, all sensors are off by default. During the experiment, the UUVs will either toggle their active sonar on or off depending on the design point. Passive sonar will always be active.

F. AUTOMATED GAMEPLAY AND DATA OUTPUT

Since JTLS-GO was designed to train military staff, there needs to be constant human interaction through the GUI with JTLS-GO. This is not feasible for simulating multiple design points. This led to the development of the JTLS Farmer tool which automates the interaction with JTLS-GO. The JTLS Farmer, developed by Steve Upton of the NPS SEED Center, simulates multiple replications of each design point in the CG18 scenario. This Linux-based program becomes a requirement since each simulation needs two hours to run, which equates to 60 hours to test one design point at 30 replications. The data, resulting from the DOE and produced by JTLS-GO, is in a message format and requires time to filter the pertinent information. As such, Steve Upton and Mary McDonald programmed the JTLS Miner; this program filters the large amount of data and finds the pertinent responses from the simulation. Figure 12 presents an overview of how JTLS Farmer and JTLS Miner work. After injecting the DPs into JTLS-GO, the modeling program collects and writes the DP orders in a text file. The JTLS Farmer program imports the DP text file, replicates the real CG18 scenario, executes the simulation and produces the results in message format.

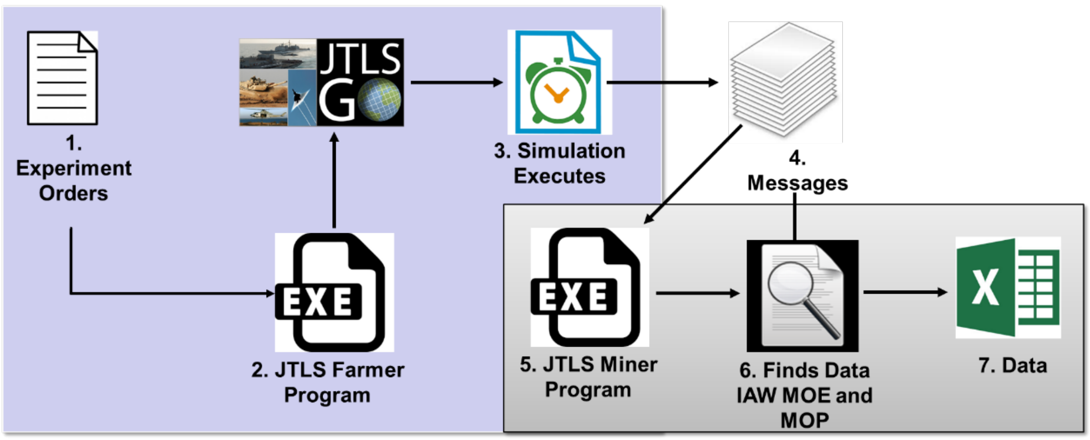

Figure 12. Automated Simulation Graphical Overview

After searching for the pertinent data, the program consolidates the data into a Comma Separated Value (CSV) file. This CSV file is now ready for use in an analytics tool such as Minitab or JMP. The analysis program for this project is JMP; the plan is to import the data from the CSV file and utilize linear regression analysis, factor interaction analysis, and partition tree analysis. The JMP analysis will be used because it offers streamlined menu interface arranged by context rather that statistical tests. The dynamic output after running the procedure will allow adding or removing the additional statistics and graphs in the results section without having to re-run the analysis program. For factor analysis, JMP will use extensive algorithm to build and refine the tables and tools for effective tabulation. The regression analysis will demonstrate the goodness or fit of a projected model and the precision of the results from the simulations. This analysis will also point to the significance of any of the factors.

G. ANALYSIS PLAN

The initial experiment with the 2^K factorial design simulates the three factors at the maxima and minima, totaling to eight design points. The resulting products (regression analysis, interaction plot, and partition tree) will provide insight to creating a second and more in-depth DOE, the CCD. This thesis will use these products to analyze the results of the two DOEs. Descriptions of the JMP products are in the following sections.

1. Regression Analysis

The regression analysis from JMP provides the Actual by Predicted Plot. The Actual by Predicted Plot (Figure 13) will demonstrate the goodness or fit of a projected model and the precision of the results from the simulations.

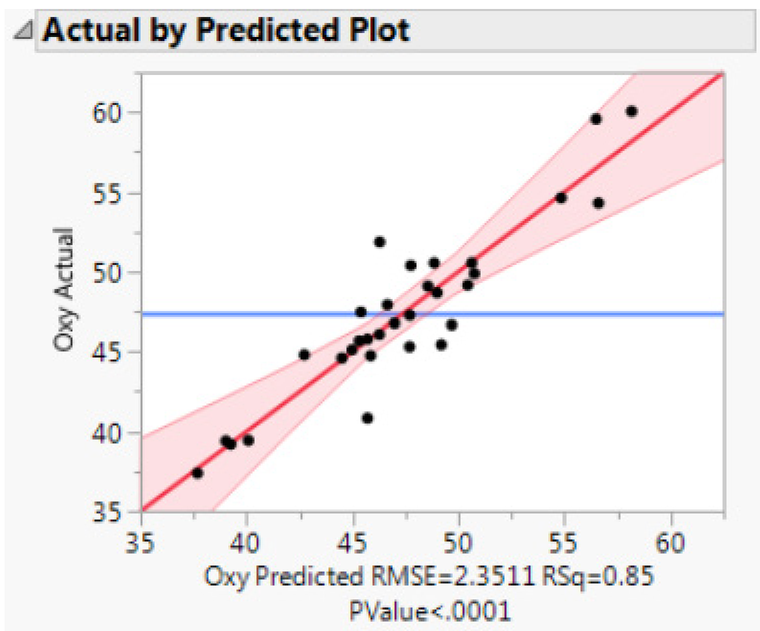

Figure 13. Example of Actual by Predicted Plot.
Source: JMP (2018a).

The black dots represent the experimental design points; the closer these points are to the bold red regression line between the horizontal-axis and vertical-axis, the better the model's fit. The blue line represents the mean of the response. The red shaded regions above and below the regression line are confidence curves, which communicate the significance of the model. The desired value is one. Quantitatively, the fit and significance of the model are expressed in the R^2 value and the p-value, respectively. When analyzing the regression data of the individual factors, they are deemed significant if their p-values are less than 0.10.

2. Interaction Plot

Another product from JMP is the interaction plot (Figure 14). This plot illustrates how a factor's influence on the response can depend on the value of another factor. The intersecting lines show that factor A positively affects the response when factor B is at its high level (B2) but negatively affects the response when factor B is at its low level (B1).

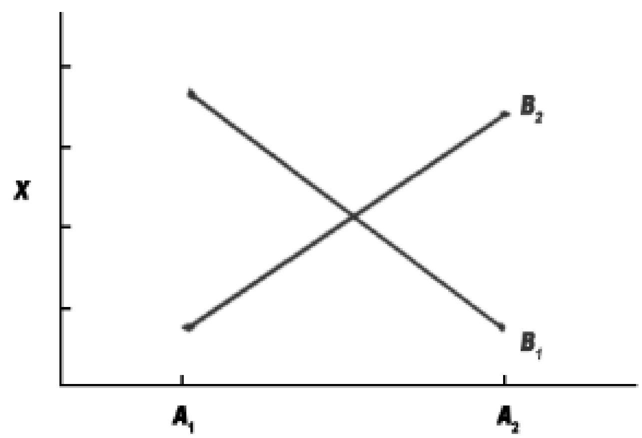

Figure 14. Example of JMP Interaction Plot. Source: Pennsylvania State University (2018).

The intersection of lines demonstrates that an interaction effect exists while parallel lines equate to no interaction effect.

3. Partition Tree

The partition tree is a data mining technique that successively splits the data according to the factor and cut-point that results in the greatest difference in the mean output. The result is a tree format that is akin to a decision tree, indicating paths through factor space that lead to the best and worst average results, shown in Figure 15.

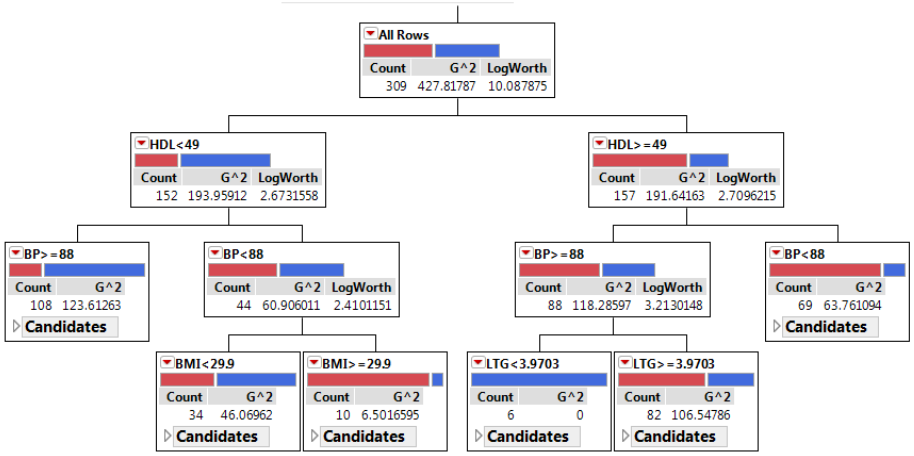

Figure 15. Example of JMP Partition Tree. Source: JMP (2018b).

In Figure 15, the desired outcome is represented with blue while the least desired outcome is represented with red. The branches from the partition tree can inform requirements for the physical prototype of the system.

H. CHAPTER SUMMARY

This chapter describes the methodology to find the effectiveness of UUVs. The development of this experiment is the result of MBSE, and through this approach, the experimentation shows the potential capabilities of UUV prototypes. Using JTLS-GO, the vignette was adapted from exercise Cobra Gold, and the unaltered version aided in finding opportunities to inject UUVs. Establishing the vignette led to the establishment of the desired outputs (MOPs) and performance rating (MOEs). These outputs resulted in forming the unique input parameters, factors. The DOE includes three factors, speed, UUV composition, and sonar type. These factors led to the creation of 18 design points which were modelled in JTLS-GO. The program produced orders that were imported by JTLS Farmer and this automated tool led to simulation results in message format. After the completion of the simulations, the JTLS Miner extracted the data pertinent to the UUVs' performance. The data from the resulting CSV files, for both the 2^K and CCD factorial designs, was analyzed with JMP. Chapter IV illustrates the results through graphics, regression and partition tree metamodels, and summary statistics.

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IV. OUTPUT ANALYSIS FROM JTLS-GO

The following chapter presents the simulation data from experimentation and the associated analyses. The initial analysis begins with validating the significance of selected factors through experimentation, using a 2^K factorial design. Next, the analysis shifts to a higher-resolution investigation of the factors with a center-composite design (CCD). The discussion culminates in exploring possible design implications for a UUV prototype.

A. RESULTS FROM UNALTERED COBRA GOLD 18 EXERCISE

We deployed no UUVs during the original CG18 exercise. The Sonoran Task Group 3.1 only had one destroyer that penetrated and caused casualties to the United Nations Task Force 1 including destruction of USS *Benfold* (DDG-65) and RSS *Endurance* (LS-207). These engagements were the motivation for injecting the UUVs with additional capabilities. Outcomes of the original gameplay establish a baseline to compare the results from simulation runs with UUVs in play.

B. 2^K FACTORIAL DESIGN SCREENING AND RESULTS

The screening process offers an opportunity to probe the effects of factors before conducting high-resolution experimentation. This approach validates the selection of the factors (sonar, speed, and UUV composition) as having impact on the MOEs. The initial experiments used a 2^K factorial DOE. This initial DOE considers the extrema of each factor, which assumes that these values will generate enough variation in the MOEs to show the significance of the factors. This experimental design totals eight design points, shown in Table 4, with ten replications each. The factors are significant if a two-sided hypothesis test on the estimated coefficients results in rejecting the null hypothesis. If none of the factors are significant, then the selection process of new factors would begin.

Table 4. Design Points for 2K Factorial Design Simulation

Design Points			
	Sonar	**UUVs (Units)**	**Speed (knots)**
DP1	Active	16	5
DP2	Active	16	12
DP3	Passive	16	5
DP4	Passive	16	12
DP5	Active	8	5
DP6	Active	8	12
DP7	Passive	8	5
DP8	Passive	8	12

1. MOE: Enemy (Sonoran) Units Detected

The following segments describe the results for the detection of Sonoran units.

a. Regression Model

A linear regression model permits a visualization of the results from the experiment. The resultant model may be studied to determine the appropriateness of the model and describes the behavior of the MOE, (Figure 16). Regression analysis provides an explanation of the correlation between the factors and UUV performance parameters. Although the intention of this study is not to create a robust prediction model, it provides a foundation for future work. The following analysis explains the adequacy of the resulting model.

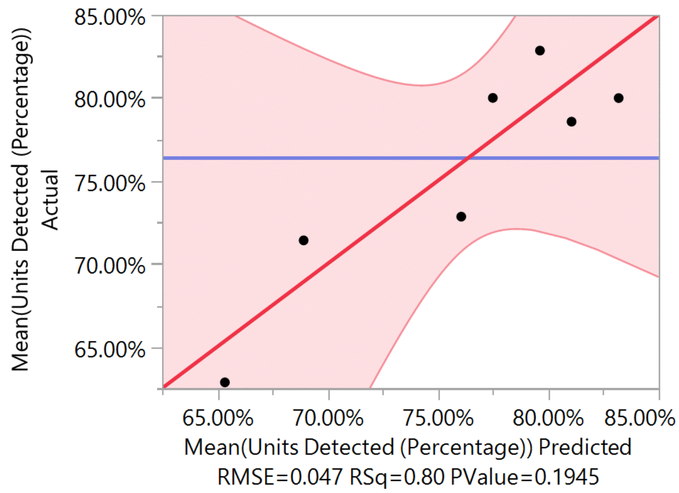


Figure 16. Actual vs. Predicted Plot: UUV Detection

b. Regression Model Interpretation

The first step in analyzing Figure 16 is to determine the appropriateness of the linear regression model. Each coordinate point is the predicted versus actual MOE value. If the model was perfect, all points would be on the red line. We see that the coordinate points are reasonably close to the red line, indicating the adequacy of the model. The R^2 value suggests that the regression model can explain 80% of the variation of the data points, which is reasonably high for this initial experiment (Minitab, Inc. 2013).

c. Regression Analysis on Design Factors

We next study the significance of each factor, Table 5. Values in the estimate columns represent the effect of each factor on the UUV detection MOE. The values under the column "Prob>|t|," or p-values, determine whether or not to reject the null hypothesis, which assumes that the associated factor has no effect on the MOE. The smaller the p-value, the more that the factor has a significant effect on the MOE. The most common p-value thresholds (significance levels) are 0.01, 0.05, and 0.10 (Filho et al. 2013, 34). We have chosen a significance level of 0.10. In this initial screening, none of the main factors were statistically significant. However, the p-value of the interaction between UUV composition and speed (0.0992) is significant. Therefore, we must consider both UUV composition and speed as factors for further investigation.

Table 5. Regression Data for UUV Detection

Term	Estimate	Std Error	t Ratio		Prob>|t|
UUV Composition*Speed (knots)	0.00280	0.00118	2.36		0.0992
Speed (knots)	0.00917	0.00474	1.93		0.148
UUV Composition	-0.00535	0.00415	-1.29		0.287
Sonar	0.0178	0.0166	1.07		0.361

d. Interaction Plot

A graphical view of the interaction between UUV composition and speed provides some insights. The plot is a three-dimensional view of two factors against one MOE. In Figure 17, the two different colors represent the UUV composition (8–red, 16–blue). As speed increases, we see that there is relatively no change in the number of enemy detections for the 8-UUV composition. However, as speed increases, the 16-UUV composition shows an increase in enemy detection (68% to 83%). The intersection of the two lines is a visual indication of significant interaction between UUV composition and speed.

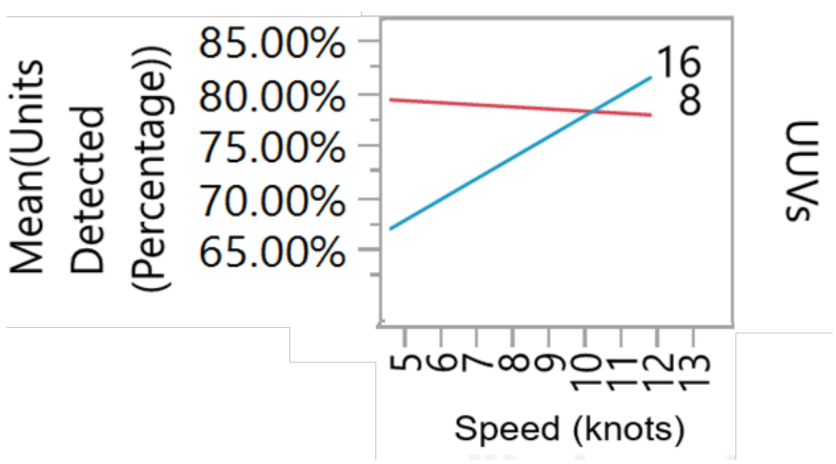


Figure 17. Interaction between Number of UUVs and Speed

The positive association of detection with an increase in speed is intuitively logical as faster units cover more area than slower units. However, traveling at faster speeds generates more acoustic noise, which JTLS does model, making it difficult to detect man-made objects. The increase in speed could have generated enough noise to disrupt the 8-

UUV composition's sensors resulting in a downward trend for detection. For the 16-UUV composition, they were able to overcome the noise by having enough units to swarm the Sonoran vessels. These results provide enough evidence to pursue these factors for more experimentation in regard to the detection MOE.

2. MOE: Sonoran Unit Attrition

The following section describes the results for the Sonoran attrition MOE.

a. Regression Model

The initial experimentation also illustrates the effects of the factors on Sonoran attrition, (Figure 18). The Sonoran attrition regression model accounts for 97% of the variation in the behavior of the data points. Additionally, the p-value of this model at 0.0137 is smaller than the 0.10 significance level. Both results indicate that the attrition regression model is adequate to explain the MOE results.

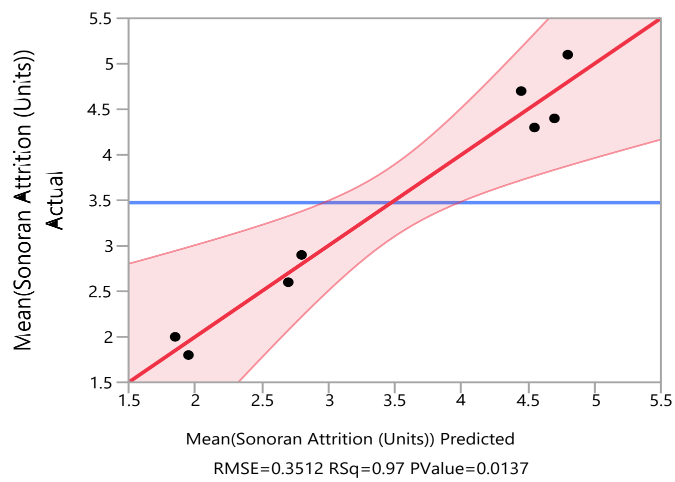


Figure 18. Actual vs. Predicted Plot: UUVs on Sonoran Units Killed

b. Regression Data

The significance of each factor for Sonoran attrition is in Table 6. The UUV composition factor shows a p-value of 0.0027, which is far below the significance level of 0.10, indicating strong significance of UUV composition effect on Sonoran attrition. From an operational perspective, this behavior is reasonable as the number of weaponized assets will affect the number of engagements; more assets equate to more engagements. The p-value for the interaction between sonar and UUV composition is greater than the significance level of 0.10, indicating that the sonar factor is not appropriate. Additionally, there is not enough evidence to support speed or sonar type to warrant further experimentation for the attrition MOE.

Table 6. Regression Data for Sonoran Attrition

Term	Estimate	Std Error	t Ratio		Prob>|t|
UUV Composition	0.287	0.0310	9.26		0.0027*
Sonar*UUV Composition	0.0687	0.0310	2.21		0.113
Sonar	-0.15	0.124	-1.21		0.313
Speed (knots)	0.0142	0.0354	0.40		0.714

C. 2^K FACTORIAL DESIGN INITIAL FINDINGS

On initial inspection, the selected factors appear to have minimal impact on the two MOEs. However, the interaction between speed and UUV composition illustrates interesting interactions; as such, more experimentation will lead to eventual significance. For the Sonoran attrition MOE, UUV composition has enough significance that affects the response of the model; this validates the selection of UUV composition as a factor for further investigation. While the p-value for the sonar and UUV composition interaction term is greater than the significance level, the value is reasonably close to the significance level, which calls for more experimentation using this term. The initial screening process established the appropriate use of linear regression analysis on the data and demonstrates interesting responses from these selected factors. Therefore, executing advanced experimentation using these selected factors is reasonable.

D. CENTER-COMPOSITE DESIGN

While initial screening did not show that all factors are significant for both MOEs, there is semblance of significant effect on one or both MOEs. Therefore, the author decided to execute the higher-resolution experiment described in Chapter III for all factors. The following section explains the insights gained about the effects of the factors on the two MOEs.

1. MOE: Sonoran Units Detected

The following segment explains the results and analyses from a higher-resolution DOE based on the detection of Sonoran vessels MOE.

a. Revised Regression Analysis on Design Factors

Table 7 presents the p-value for the factors. For this revised analysis, the significant value is 0.10. Applying this threshold, the most significant values are 0.0901 (UUV composition), 0.0929 (UUV Composition and Speed) and 0.09337 (Sonar). All factors show significance with respect to the detection of Sonoran units. Similar to the screening experiment, the interaction term between UUV composition and speed remains significant.

Table 7. Expanded Regression Data for Sonoran Detection

Source	LogWorth		PValue	
UUV Composition	1.045		0.09010	
UUV Composition*Speed (knts)	1.032		0.09299	
Sonar	1.030		0.09337	
Speed (knts)	0.873		0.13410	^
Sonar*Speed (knts)	0.846		0.14250	
Sonar*UUV Composition	0.629		0.23481	

b. Factor Effects

Further review illustrates the unique phenomena between the factors, shown in Figure 19. The figure compares the factors and their effects on Sonoran unit detection.

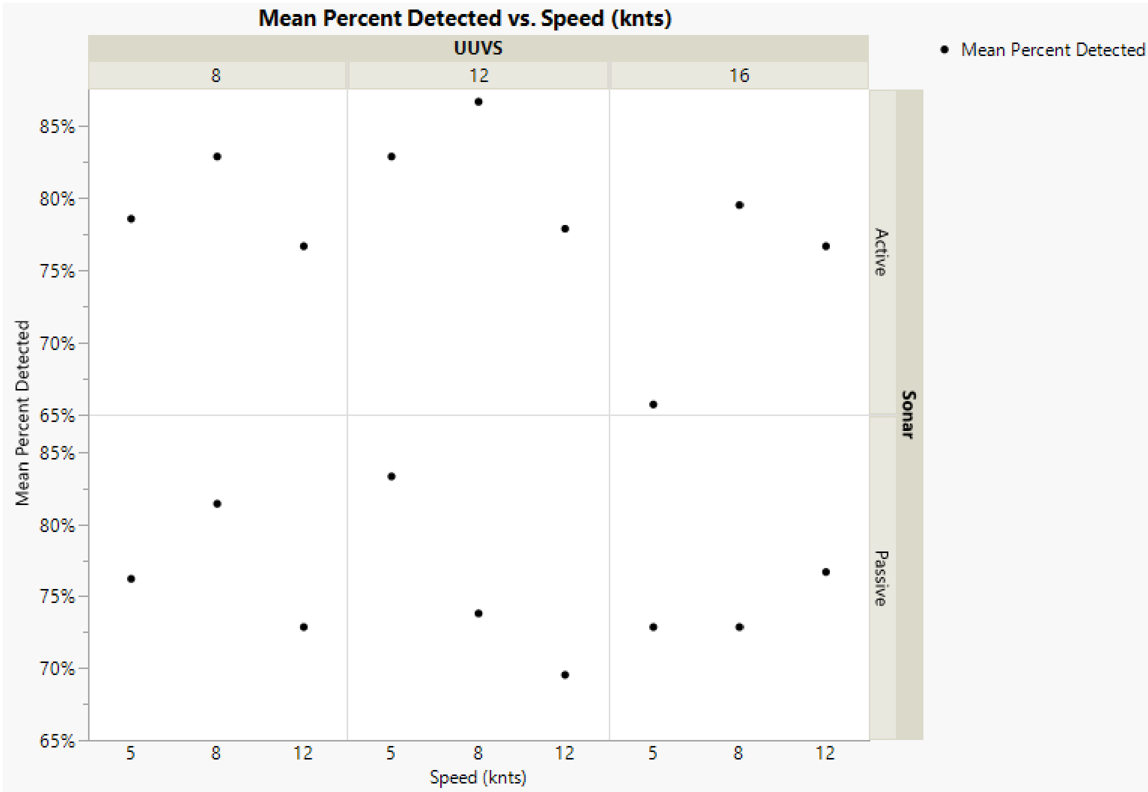


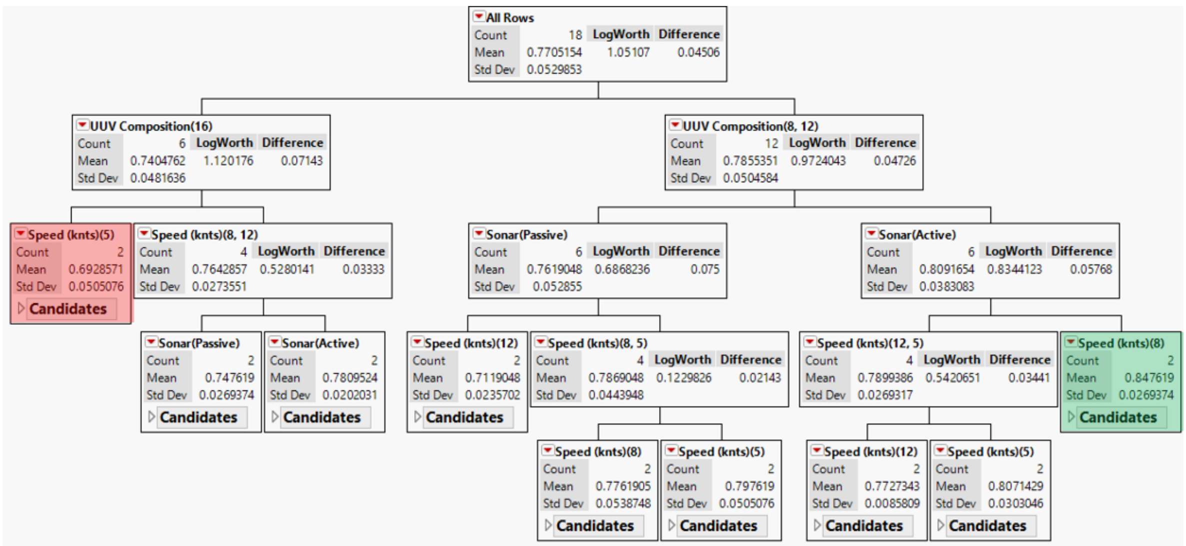
Figure 19. Mean Detection Trends Based on Speed

In the UUV composition with 12-UUVs and active sonar section, the highest detection rate among all design points is 88% when the UUV speed is 8 knots. In passive mode, the highest detection rate is 83%, which occurs at the 12-UUV composition level. However, to achieve this detection rate requires the UUVs have a slower speed of 5 knots.

From an operational standpoint, the behavior between speed and detection makes sense because more speed means more coverage area. Still, increasing speed generates more noise, and this noise interferes with active sonar. The noise becomes too loud for the UUVs to discern the units from the environment. This experiment indicates that the speed factor peaks around 8 knots. The resulting trends of the factors at various levels behave reasonably in an operational environment and provide good general guidelines. Nonetheless, analyzing a partition tree of the design points gives more resolution on what may be an ideal combination of the factors.

c. Partition Tree

The partition tree in Figure 20 reflects two dynamics. It reinforces trends from the previous plots and delineates specific values of each factor that leads to the most detection. Similar to a decision tree, this graphic is useful for trade-off analysis.



Green is ideal and Red is very unfavorable.

Figure 20. Partition Tree: Sonoran Detection

The first split occurs at the UUV composition factor where significant differences in detection are between 16-UUVs and the 8 and 12-UUV levels. This split suggests increasing the number of UUVs does not correlate to more detection. Following the 16-UUV level, the speed factor drives the next split. The 5 knots level has the least detection at 0.69 and implies that large numbers of slow UUVs are ineffective for surveillance.

On the other hand, the next split after the 8 and 12-UUV levels is based on sonar type. The detection results between active and passive sonar replicates the trends from Figure 20. Using passive sonar results in the lower detection of 0.76 while using active sonar leads to the higher detection of 0.80. Further divergence shows that a speed of 8 knots has the highest detection at 0.84. This split suggests that there is a preferred medium speed that produces the highest number of detections when using active sonar.

2. MOE: Sonoran Attrition

The subsequent section discusses the results of the refined experimentation for the UUVs' ability to engage Sonoran units.

a. Revised Regression Analysis on Design Factors

Table 8 shows the p-values for the factors. Using a similar process with the detection MOE, we identify the significant factors by computing p-values. Using a significance level of 0.10, all of the p-values associated with the factors are below the significance level. Therefore, we examine all of the factors to further explain and gain insights about the UUVs' performance in terms of this MOE.

Table 8. Expanded Regression Data for Sonoran Attrition

Source	LogWorth		PValue
UUV Composition	2.399		0.00399
Sonar	1.264		0.05442
Speed (knts)	1.169		0.06772

b. Factor Effects

Figure 21 shows the trends for attrition based on the three selected factors. The highest attrition of Sonoran units is with the 16-UUV composition section. From an operational perspective, the swarm of the UUVs sealed off escape routes allowing for maximum engagements. Comparing active and passive sonar use with the 16-UUV composition level, the UUVs with active sonar scored higher attrition numbers than UUVs using passive sonar only. Realistically, this outcome is reasonable since using active sonar will locate units of interest quicker than passive sonar. When examining the speed, the highest attrition rate occurs at the 8 knots level. Operationally, this makes sense as increasing speed allows for UUVs to get into firing range faster, yet too much speed can cause too much noise, which interferes with the firing solution. These results illustrate the advantages of active sonar and high UUV compositions in attrition. While these trends are useful, identifying a preferred combination of factor settings that impact attrition may be better visualized with a partition tree.

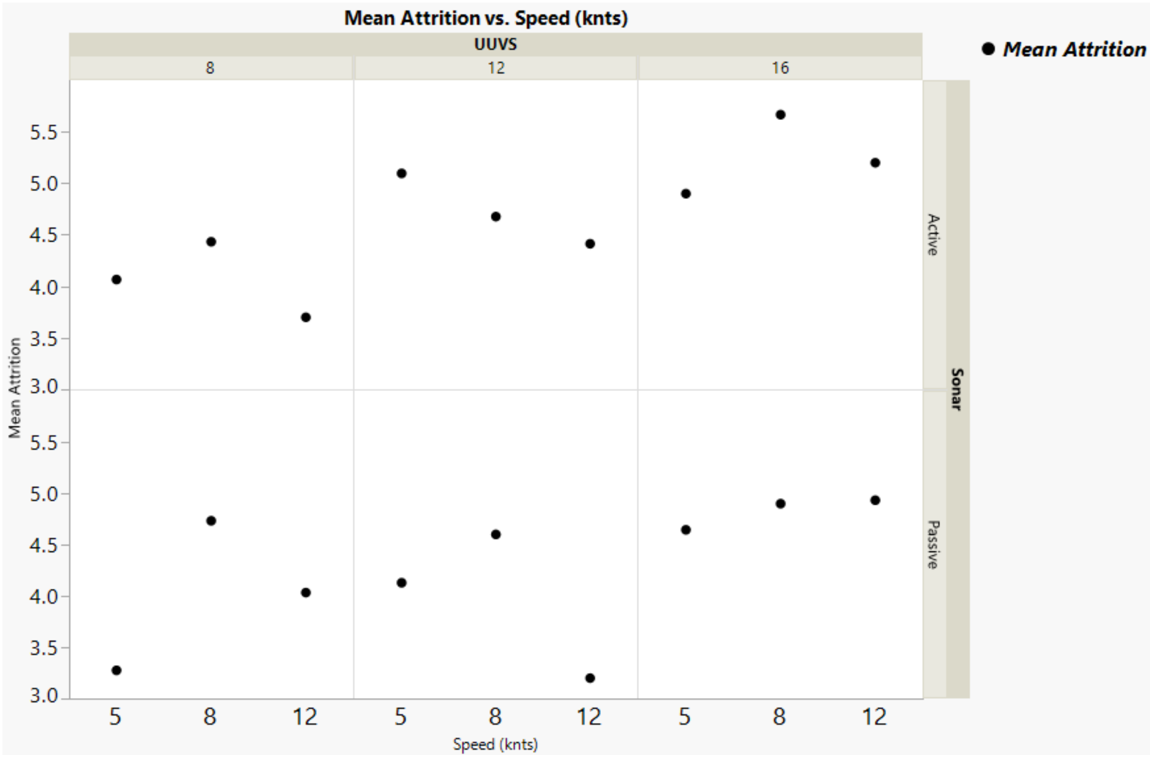
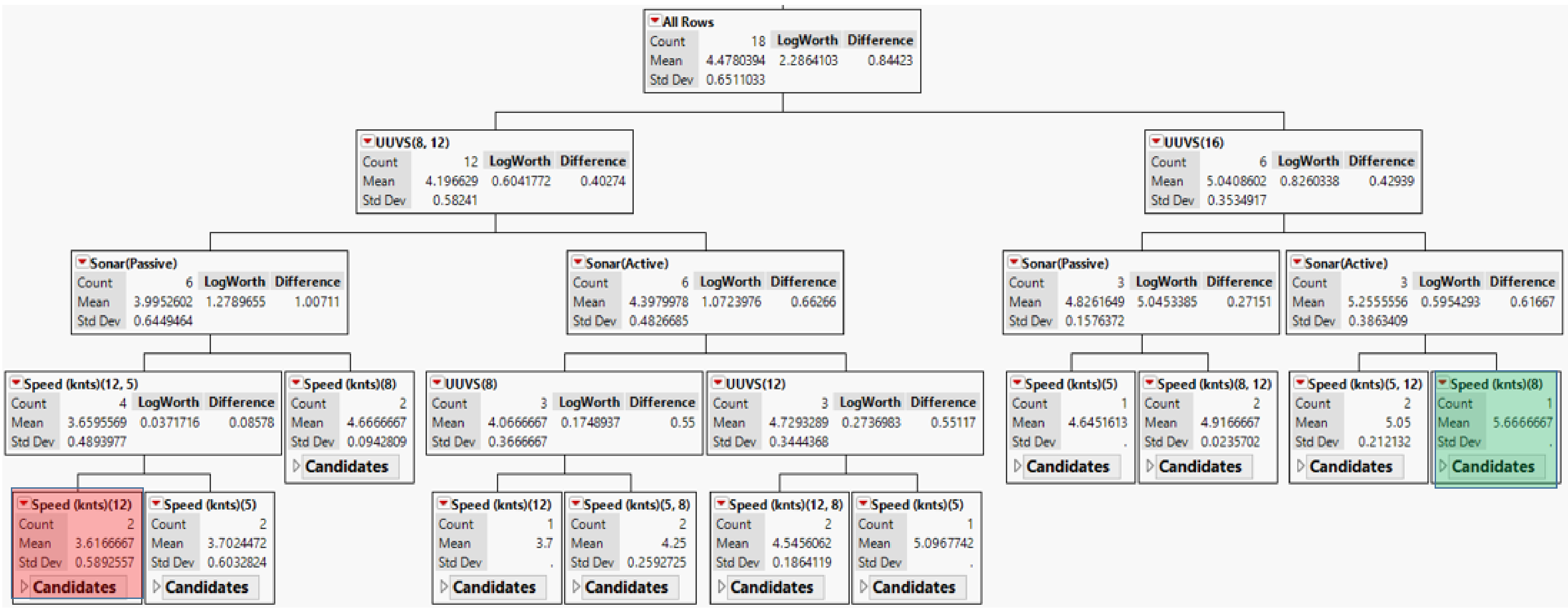


Figure 21. Mean Attention Trends Based on Speed

c. *Partition Tree*

The partition tree separates the factors in the following order: UUV composition, sonar, and speed, Figure 22. The first significant split separates the 16-UUV level from the rest; this level has more attrition (5.04) than the 8 and 12-UUV forces (4.19). Across all design points, the next substantial division in attrition occurs at the sonar factor. The configurations using active sonar caused more enemy casualties than the factor combinations using passive sonar. The final separation happens among the different speeds of the UUVs. On the whole, the 8 knots, 16-UUV composition combination has the highest attrition (5.67) while the least attrition (3.62) occurs at the design point with 12 knots and passive sonar. The result of this experiment demonstrates the importance of increasing UUV assets, limiting UUVs' speed, and using active sonar for improving engagement outcomes.



Green is ideal and red is very unfavorable.

Figure 22. Partition Tree: Sonoran Attrition

E. OVERALL FINDINGS

Regression analysis provided insights about the UUVs' value to the future Navy fleet. For both MOEs, the most significant factor is UUV composition. The preferred attributes for the detection MOE is a moderately sized fleet of UUVs at medium speed. Sonoran attrition rates, however, favor many UUVs at medium speed. There is strong indication that the use of active sonar results in higher rates of attrition than using passive sonar. The least preferred level is 12 knots because this level results in the lowest detection and attrition values. These trends can have profound implications on future design and requirements for UUVs.

After 540 simulations, utilizing 810 hours of computer time, we find evidence that the injection of UUVs is advantageous in reducing the chance of destruction of the USS *Benfold* (DDG-65) and RSS *Endurance* (LS-207). In the real exercise, both ships suffered heavy casualties. When UUVs with the most advantageous combination of UUV composition, speed and sonar setting for detection are used in the simulation, the USS *Benfold* (DDG-65) sunk twice in 30 simulation runs and the RSS *Endurance* (LS-207) sunk 12 times in 30 simulation runs. Injecting UUVs with the preferred combination of factors for attrition also led to the reduction of casaulties for the U.S. destroyer (2 casualties in 30 runs) and the Singaporean amphibious ship (10 casualties in 30 runs). These findings signify the potential value of using enhanced UUVs in an operational theater.

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V. CONCLUSIONS AND RECOMMENDATIONS

The overall objective of the study is to assess the value of UUVs on the operational effectiveness of a naval force. Supplementing the fleet architecture with a contingent of unmanned systems provides a viable option for the future Navy. Currently, the Navy has minimally integrated UUVs into the fleet, primarily to support anti-mining and reconnaissance missions. However, there are other uses for unmanned systems. Arming future UUVs with torpedoes could support anti-submarine and anti-surface operations. We examined offensive and more advanced reconnaissance capabilities in this study.

Using an MBSE approach, we developed and produced a concept of operations for an advanced UUV prototype in a disputed environment. The resulting requirements describe a UUV prototype capable of conducting reconnaissance with offensive capabilities. The next step involved the selection of three factors (attributes) and the measurements of their effectiveness. Adapting the events from CG18, an automated JTLS-GO was developed and used as an experimentation environment. Through the use of regression methods, as well as partition tree analysis, this thesis provides insights that can shape future capabilities of UUVs and their incorporation into the future fleet architecture.

A. ADDRESSING RESEARCH QUESTIONS

The following paragraphs answer the research questions that this study aimed to address.

1. How can modeling and simulation be used to assess the operational impact of future unmanned underwater vehicles' capabilities?

By establishing a modeling environment and experimentation in an automated version of CG18 in JTLS-GO, the MBSE approach provides a pathway for assessing operational impacts of future UUV capabilities.

The real gameplay from exercise CG18 and by means of JTLS-GO presented operational gaps. The MBSE approach was suitable for this study based on the research focus and availability of a recognized modeling package. The MBSE approach led to several SE products in assessing operational impacts. These products included the development of the CONOPs, a prototype, MOEs, MOPs, DOEs, and a new automated computer simulation environment for experimentation.

2. How can the addition of UUVs decrease the vulnerabilities to surface assets?

The presence of UUVs offers additional capabilities in providing situational awareness and offensive firepower.

Using UUVs in this scenario proved to be beneficial for U.S. forces. Even with the minimal fleet of 8-UUVs, the UUVs were able to detect, at worst, 60% of the units of interest. For offense, the 8-UUVs were able to sink an average of three Sonoran units. In the original gameplay, the Sonoran Task Group engaged several allied ships, causing casualties. The detection of the Sonoran units gives the United Nations commanders ample time to either strike the task group or maneuver the task group to a more secure location. Additionally, the offensive capabilities of the UUVs alleviate pressure on the single escort ship in the United Nations Task Force.

The most important aspect of adding UUVs in theater campaigns is reducing the vulnerability to allied ships. When UUVs designed for detection were escorting the UN Task Group 1, the USS *Benfold* (DDG-65) sustained casualties only twice during 30 simulation runs while the RSS *Endurance* (LS-207) suffered casualties in 12 of 30 runs. When UUVs designed for attrition are injected, the USS *Benfold* (DDG-65) sustained casualties twice in 30 simulation runs while the RSS *Endurance* (LS-207) sustained casualties in 10 of 30 runs. Had the UN Task Group 1 had UUV escorts, their risk of attack from Sonoran naval units would have decreased dramatically.

3. What are the attributes of UUVs needed to fill operational deficiencies in a theater-level campaign?

Active sonar improves both lethality and detection, but more is not necessarily better for speed and UUV fleet composition.

The analysis from Chapter IV demonstrated effects from the following factors: UUV composition, speed, and sonar sensor types (active or passive). The combination of these factors (design points) have positive and negative effects on the results. Table 9 summarizes the most and least preferred design points, ranked by the largest change in results. This table shows the trade space among the combination of factors and is useful for providing general guidelines about the performance of UUV prototypes. The recommendation for the most preferred design point based on the scope of this simulation is a fleet of at least 12-UUVs but no more than 16-UUVs. The cruising speed should be around 8 knots with active sonar engaged. The logic behind this recommendation lies in several findings. Both of the preferred design points have levels of 8 knots with active sonar engaged. The message from the worst design points (Table 9) is to avoid 5 or 12 knots for speed. When applied generally, the recommendation for future UUV prototypes includes installing an active sonar sensor and the ability to achieve between 8 and 12 knots.

Table 9. UUV Design Point Results

	Best Design Points				Worst Design Points				
MOEs	UUVs	Speed (kts)	Sonar	Results	UUVs	Speed (kts)	Sonar	Results	Δ Results
Detection-MIB (%)	12	8	Active	87%	16	5	Active	65%	22%
Attrition-MIB (Kills)	16	8	Active	5.7	12	12	Passive	3.2	2.5
Recommendation:	**12-16**	**8**	**Active**						

The abbreviation MIB equates to "More Is Better."

B. FUTURE WORK

The scope of this research project is the use of the MBSE approach with JTLS-GO to answer questions related to using UUVs in a simulated environment. The subsequent comments offer improvements and other potential work to further this study.

1. More Simulations with Higher-Resolution DOEs

The simulations conducted during this research were limited to 30 replications for each design point. As demonstrated in the analysis chapter, some of the MOEs require more replications to produce a more accurate prediction model. More replications will be necessary if the desire exists to create predictive models. Another future work idea is to expand the fleet size or the size of the UUV prototypes, which will require adjusting the application of the UUVs in the operational scenario.

2. Supportability Research

The current study ignored the supportability issues required for all naval operations. Things such as supply, replenishment, deployment, basing operations and other logistical issues did not factor into this study's UUV concept. Further research in these areas using the automated JTLS-GO modeling environment can refine the operational effectiveness of the UUVs. Future research in the supportability domain can address unforeseen issues. Furthermore, expanding the operational window and area is another option to investigate supportability issues of advanced UUVs.

3. Continued Application of Automated JTLS-GO Experimentation Environment

The MBSE approach and automated JTLS-GO simulation proved to add valuable insight for UUV future capabilities. Because there are other capabilities the Navy is considering, continued use of this experimentation environment can help reduce resources and time to conduct feasibility analysis. Advanced forms of unmanned aerial vehicles (UAVs\) or the Medium Displacement Unmanned Surface Vessel (MDUSV), can be quickly incorporated into the simulation to provide insights.

C. RECOMMENDATIONS

The desire for increasing the size of the future fleet requires the U.S. Navy to be more creative in designing the future fleet architecture. The future fleet will involve UUVs. While the construction of these unmanned systems is in progress, the Navy still seeks a credible, repeatable process for developing system requirements. The results of this study demonstrate that through MBSE and an automated modeling environment like JTLS-GO that stakeholders can observe trends and expected reactions and utilization without the need to build actual prototypes or wait for operational needs. We recommend that the Navy use the MBSE approach with an automated computer-aided exercise to conduct computer simulation experiments to develop analytically supported insights.

We recommend the integration of advanced UUVs into the fleet. The experimentation package demonstrated the potential capabilities of advanced UUVs in anti-submarine, anti-surface and reconnaissance mission areas. The advanced UUVs expanded the search and offensive capabilities of a task force when there is scarce support from aerial or other submarine assets. Therefore, future integration of these types of unmanned systems can give U.S. naval forces an edge over near-peer adversaries.

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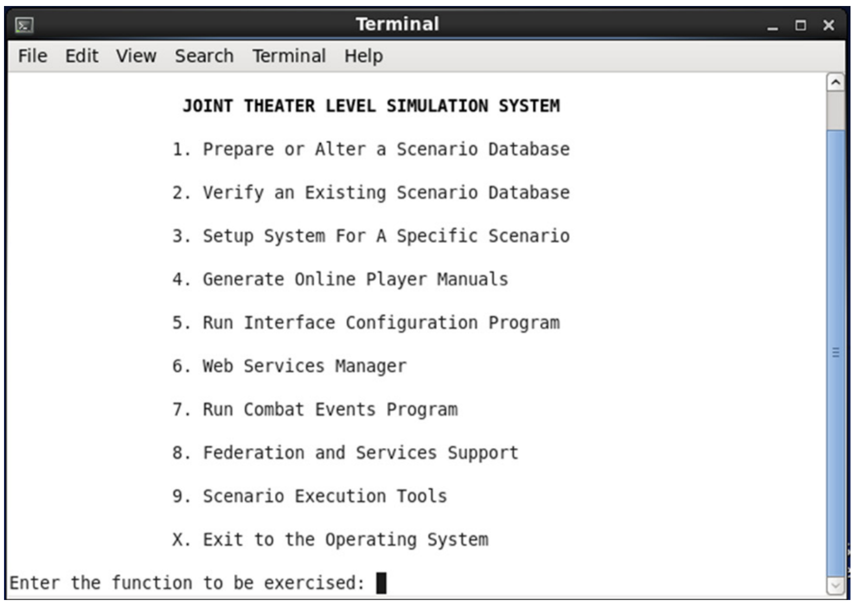
APPENDIX. JTLS-GO SET-UP

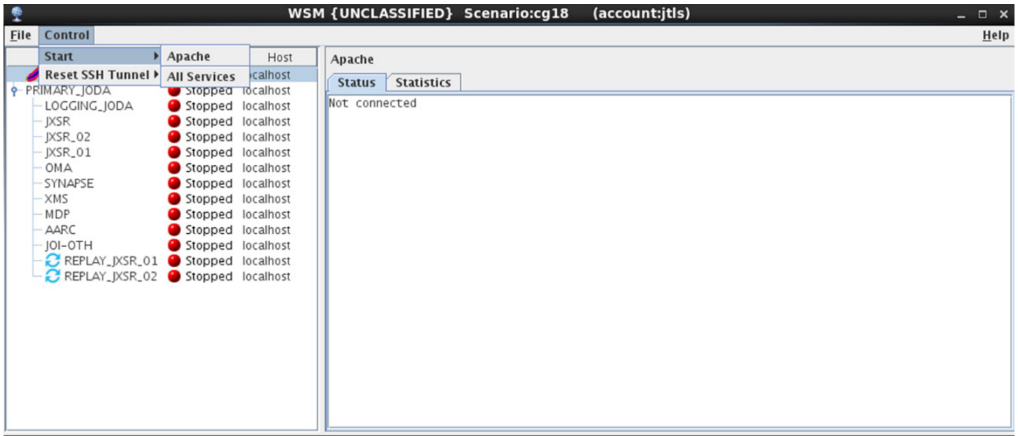
This appendix presents the steps to set up a scenario and inject advanced UUVs in JTLS-GO. All figures shown are screenshots taken from the program.

A. STARTING JTLS-GO

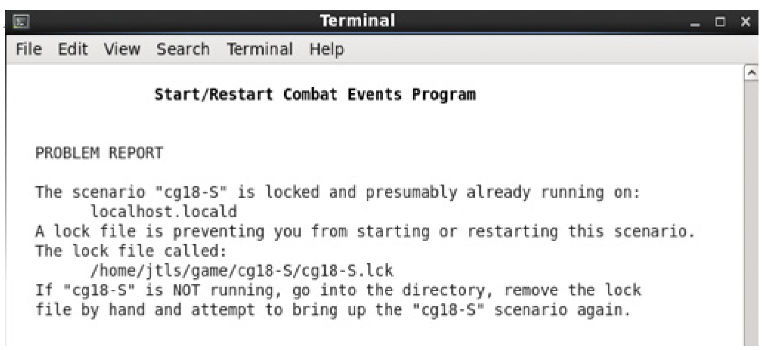
1. Start by opening a terminal window.
2. Type “jtlsmenu” and press “ENTER.” The JTLS-GO main menu will appear.



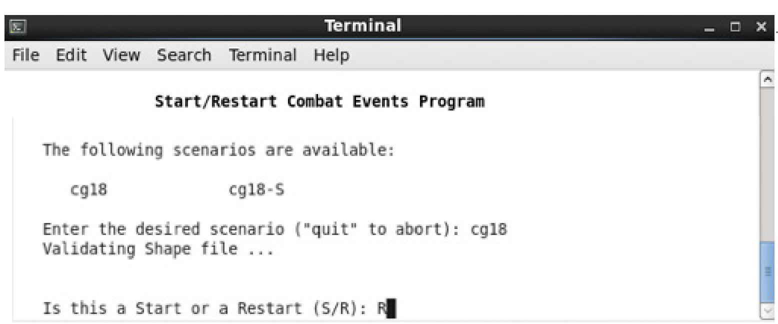
3. Enter the number “6” in the terminal window and press “ENTER” key to start the JTLS-GO Web Services Manager (WSM).
4. In the WSM, click “Control” in the menu bar and select start and all services.



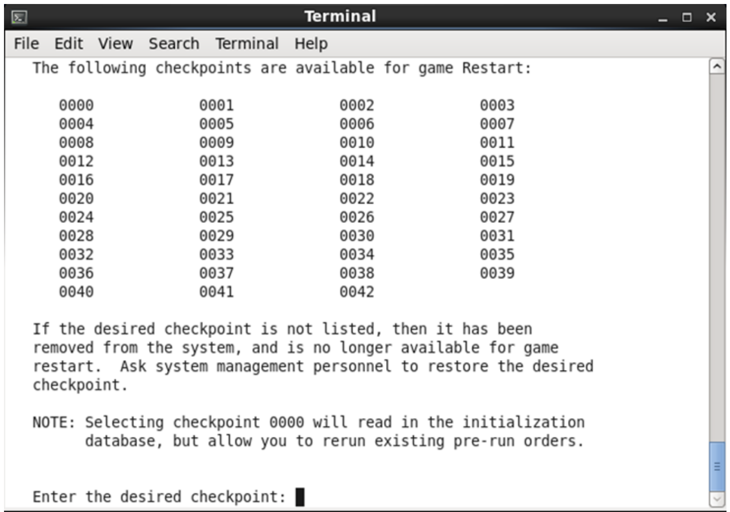
5. Make sure the indicators for JODA, OMA, and XMS all turn green. Minimize the WSM menu and return to the terminal window.
6. Enter the number "7" in the terminal window and press "ENTER." This action starts and enables the JTLS-GO Combat Events Program (CEP).
7. In the CEP window, enter the desired scenario name and press "ENTER." The scenario entered must match the scenario entered in Step 4.
8. If the message "scenario is locked" appears, enter "unlock [scenario name]" in a separate terminal to unlock the scenario. Repeat Step 7.



9. When the message "Start or Restart" appears, enter "R" and press "ENTER."

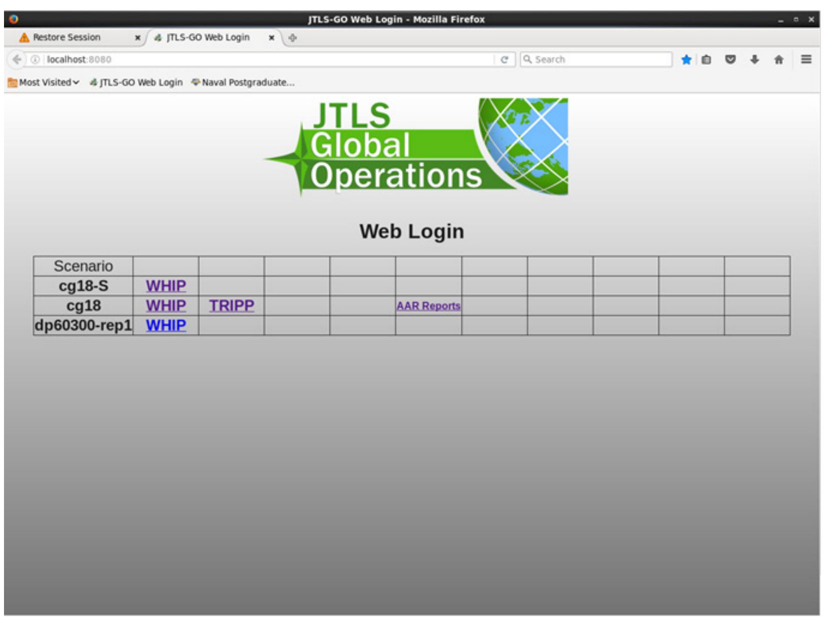


10. When asked, enter desired start checkpoint number from the available and press "enter."



11. When asked to push pre-run orders, enter "Y" for yes and press "ENTER." The program will load all of the data for the desired scenario.

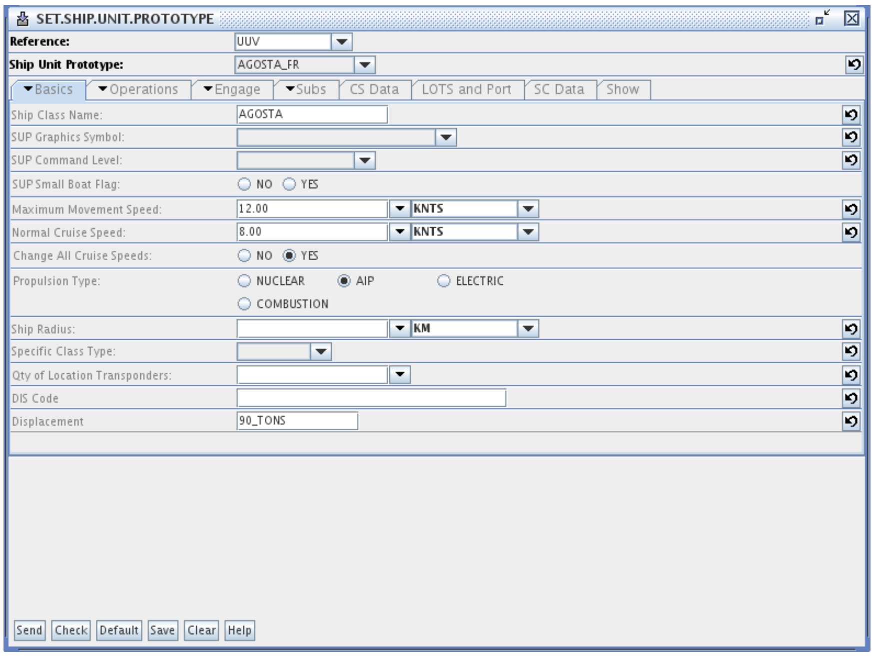
12. After the CEP completes the download to the JODA, open a web browser and type "localhost:8080"in the address box. This action will open JTLS-GO web login window.



13. Open a Control WHIP and a United States WHIP for the desired scenario. Click "Login."

B. Creating Naval Units

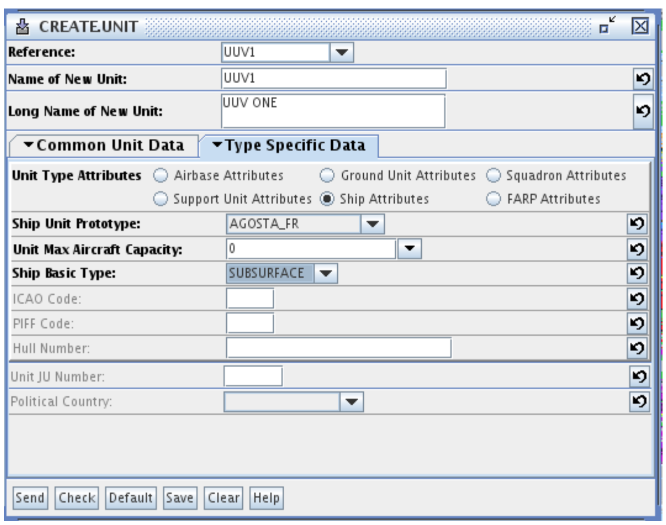
1. Creating UUV Prototypes using the Control WHIP: Click Game Control → Parameters→ Unit Prototype Parameters → Ship Unit Prototype in the menu bar. A "Set.Ship.Unit.Prototype" window should appear.



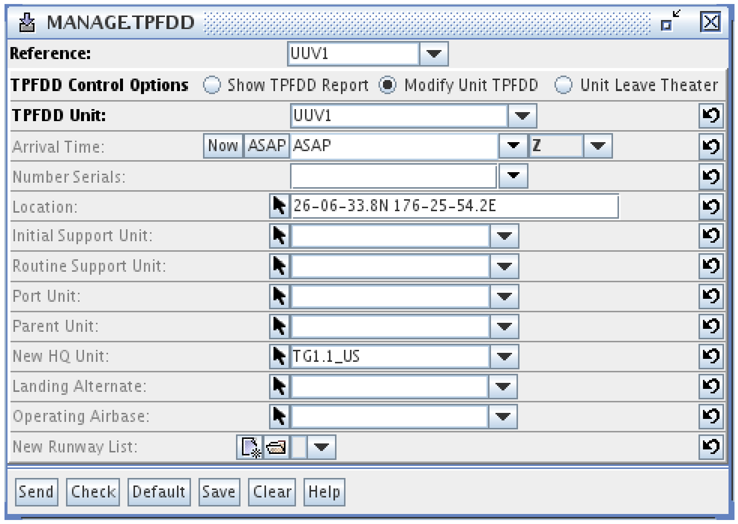
2. In the *Basics* tab, enter the pertinent information for all data fields and drop-down menus.
    a. Under "Ship Class Name" type "Agosta."
    b. Under "Maximum Movement Speed," type 12.00.
    c. Under "Normal Cruise Speed" type 8.00.
    d. Under "Propulsion Type," click "AIP."
3. In the *Operations* tab, enter the pertinent information for all data fields and drop-down menus.
    a. Under "Ship Hull Parameter 1" type 1.5.
    b. Under "Ship Hull Parameter 2" type 0.8.
    c. Under "Mean Time to Sink" click 22 minutes (M).
4. In the *Subs* tab, enter the pertinent information for all data fields and drop-down menus.
    a. Under "Min Time to Detect" click 1 minute (M).
    b. Under "Max Time to Detect" click 4-hours, 3-minutes (M).
    c. Under "Gamma Shape Parameter," type 3.0.
    d. Under "Cavitation Speed," type 2.00.
    e. Under "Max Battery Time," type 2 Days (D).
    f. Under "Min Battery Time," type 5 Hours (H).
    g. Under "Battery Recharge Time," type 4 Hours (H).

C. Creating UUV Unit using the Control WHIP

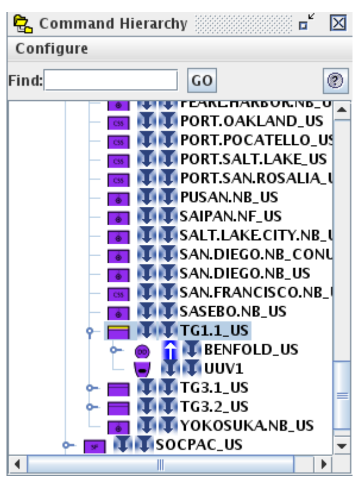
1. Click Orders→Units→ Create New Units in the menu bar. A "Create.Unit" window appears.
2. In the Common Unit Data tab, enter the pertinent information for all data fields and drop-down menus.
    a. Select "Navy" for Service and "USN" for unit faction.
    b. Enter a five-digit UIC.
    c. Select "Average-Medium" for Current CQR and Highest CQR.
3. In the Type Specific Data tab, enter the following information in the requested data fields:
    a. Select "Ship Attributes" button.
    b. Under "Ship Unit Prototype," select "Agosta_FR."
    c. Under "Max Aircraft Capacity," type 0.
    d. Under "Ship Basic Type," select "Subsurface."



4. When all the information is entered for the unit and type data, click "Send" in the bottom left corner to route the order to the CEP.
5. In the Message Browser, a "New Unit Report" will generate, verifying creation of the UUV.
6. The default arrival time for a new unit is set to 99-game days. To change this, click Orders→ Logistics→TPFDDs→ Manage TPFDD in the menu bar. The "Manage.TPFDD" dialogue box will open.
7. Click the "Modify Unit TPFDD" radio button.



8. Under "TPFDD Unit," type the unit name for the created prototype. This unit name should match that entered in the "Create.Unit" dialogue box.
9. Select "ASAP" for arrival time.
10. Under "Location" select a Location next to Task Group of interest (TG1.1_US). The latitude and longitude for the unit will auto-populate.
11. Under "New HQ Unit" select TG1.1_US from the Command Hierarchy window.
12. Click "Send" in the bottom-left corner to route the TPFDD to the CEP.
13. In the Message Browser, verify a "TPFDD Report" is generated.



14. In the Command Hierarchy window, verify the unit turns purple, signifying the unit is ready for orders from the U.S. player WHIP.

D. Setting-up Automatic Engagements.

1. The first step is to figure out which weapon you want your system to use during an engagement.

2. Under the Online Player's Manual, select Ship Unit Prototype and select the prototype of choice, "Agosta_FR" in this case.
3. Scroll down to the "Automatically Owns the Following Targets" table.

Every Unit Accessing SUP AGOSTA_FR Automatically Owns the Following Targets

KM FT

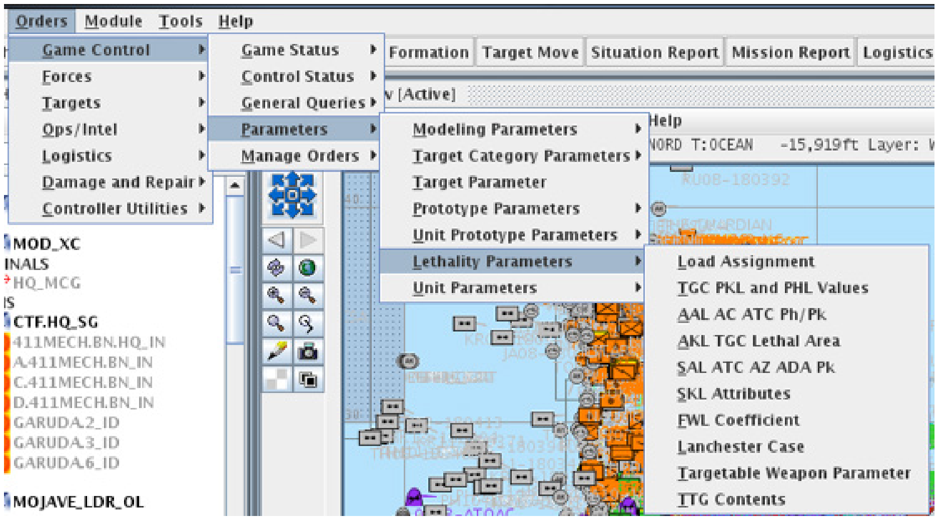
CCF Name	Long Name	Category	Subcategory	Nmbr	Antenna Ht	Range	Mobility	Pct Cap	Cat Code
533SIW.TT1	533SHORT.INT.T	SSM	TT533SI.WIRE	2	6.00 FT	0. KM	DEPLOY_ON_MOVE	1.00	87100
533SIW.TT2	533SHORT.INT.T	SSM	TT533SI.WIRE	2	6.00 FT	0. KM	DEPLOY_ON_MOVE	1.00	87100
CALYP-3.SS	CALYPSO-III.SU	SENSOR_SITE	CALYPSO-III SGN	1	49.00 FT	0. KM	DEPLOY_ON_MOVE	1.00	85400
SON.DA.HU1	SONAR.DOME.ACT	SENSOR_SITE	SONR.DOM.HA USS	1	6.00 FT	0. KM	DEPLOY_ON_MOVE	1.00	85000
SON.DA.MU1	SONAR.DOME.ACT	SENSOR_SITE	SONR.DOM.MA USS	1	6.00 FT	0. KM	DEPLOY_ON_MOVE	1.00	85000
SON.DP.MU1	SONAR.DOME.PAS	SENSOR_SITE	SONR.DOM.MP USS	1	6.00 FT	0. KM	DEPLOY_ON_MOVE	1.00	85000
SON.TP.VU1	SONAR.TOWED.PA	SENSOR_SITE	SONR.TOW.VP USS	1	6.00 FT	0. KM	DEPLOY_ON_MOVE	1.00	85000

4. Click on "TT533SI.Wire"
5. Select a weapon from the "Targetable Weapons an SSM of This Type Can Fire."

Targetable Weapons An SSM Of This Type Can Fire:

Targetable Weapon
45-56NT.AL450TP
A184.M0.533STP
A184.M3.533STP
BLAKSHRK.534STP
DM2A3.533STP
DM2A4.M4.533STP
ET-32.533STP
ET-34.533STP
ET-36.533STP
F17.MOD2.533STP
MK24.M2.533STP
MK37.M0 3.483TP
MK37.M1 2.483TP
MK48.M4.533STP
MK48.M5.533STP
MK48.M6.533STP
MN.MK60.CAPTOR
MN.MK67.SLMM
NT37C.M1.483TP
NT37CD.M2.483TP
NT37CD.M3.483TP
NT37EF.M2.483TP
NT37EF.M3.483TP
RGM84A B.HARPN1
RGM84C.HARPN1B
RGM84D.HARPN1C
RGM84G.HARPN1G
RGM84L.HARPN2
SEAHAKE.533STP
SEAHNT.M2.483TP
SEAHNT.M3.483TP

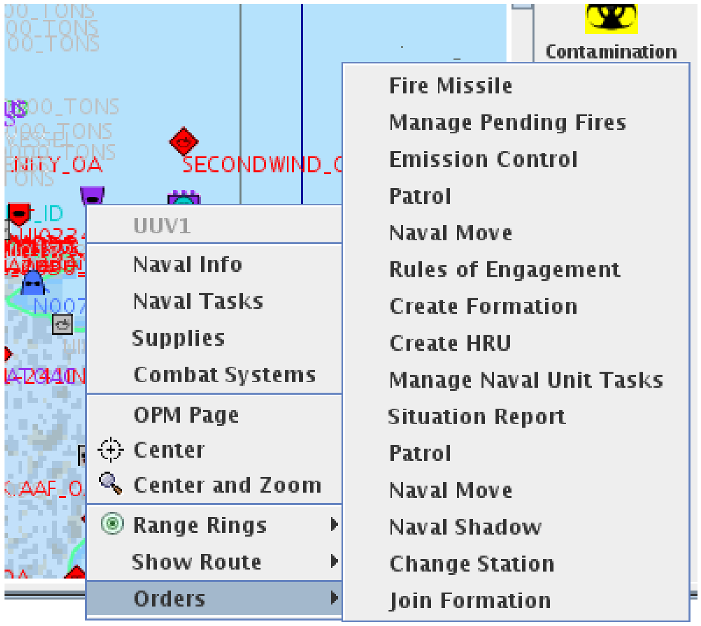
6. After deciding which weapon to use in the UUV or naval unit, go back to the Controller WHIP.



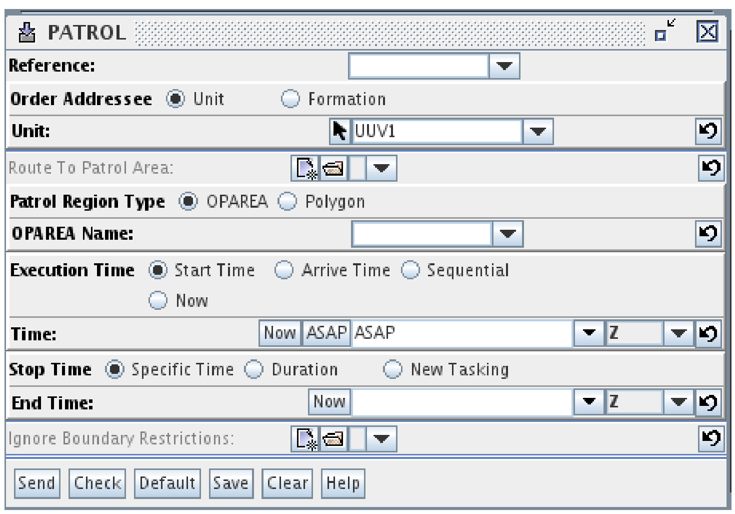
7. Click Orders→Game Control→ Parameters→ Lethality Parameters → Targetable Weapon Parameter in the menu bar. A "Set.TW.Parameter" window appears.
8. Select the Targetable Weapon of choice from 1d.
9. In the Attribute Set 2 tab and under "OKAY to Auto Fire," select yes.
10. Click send.

E. Generating orders for UUV Missions using the U.S. Whip

1. Open the U.S. Player WHIP.
2. Select the UUV and right click.
3. Select Patrol to move the unit.



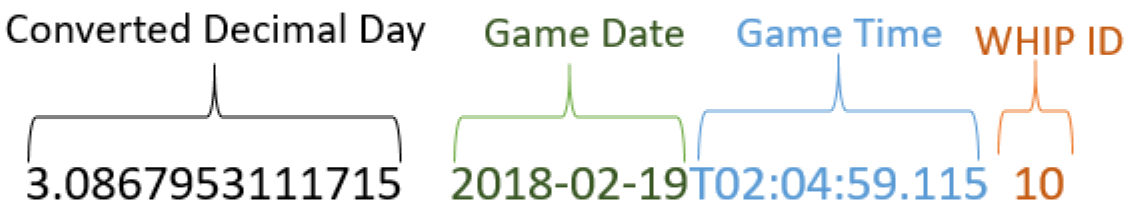
4. Selecting the Patrol command gives a Patrol window.
   a. Click "Unit" for single unit.



   b. For a new route, select the "White Paper" icon in the "Route to Patrol Area."
   c. Under the Route Location, select the route locations with the pointer.
   d. Under "Execution Time," select "Start Time" and under "Time" select ASAP.
   e. Under "Stop Time," select "New Tasking."
   f. Click send.

F. EXTRACT AND SPLICE ORDERS

1. Find and open the "Game" folder in a file browser.
2. Find the desired scenario and search for the .ci0 file. The file holds the orders created by all users during gameplay.
3. Find the appropriate UUV orders. The desired orders will most likely be at the bottom of the file.
4. Copy the desired UUV orders.
5. Find the desired starting checkpoint of the scenario. Open the .cil file within the desired checkpoint.
6. Paste the UUV orders at the end of the .ci1 file.
7. If necessary, there is an option to alter the decimal-day which determines when the orders are executed. This information is located above every order; the model reads the inputs in decimal days. The following provides steps to convert the date and time to decimal days.



   a. Dividing the game time by 24 converts hours to decimal days.
   b. Dividing the game time minutes by 1440 converts minutes to decimal days.
   c. Dividing the game time seconds by 86499 converts seconds to decimal days.
   d. The sum of steps a-c gives the 13-digit decimal value decimal day.
8. After adding the orders, save the modified ci1 file. JTLS Runner will process these orders when the scenario starts.

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