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SYSTEMS ENGINEERING CAPSTONE PROJECT REPORT

**INVESTIGATION OF REQUIREMENTS AND
CAPABILITIES OF NEXT-GENERATION MINE
WARFARE UNMANNED UNDERWATER VEHICLES**

by

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VEHICLES**

Submitted in partial fulfillment of the
requirements for the degrees of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

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ABSTRACT

This report identifies the system characteristics that have the largest impact on mine counter-measure (MCM) unmanned underwater vehicle (UUV) performance. Model-based systems engineering (MBSE) tools, including functional flow block diagrams and functional hierarchies, are used to logically define MCM UUV operations and support the development of alternative concepts of operations. A discrete event simulation is used to model operations for a design of experiments selected set of system characteristic combinations. Statistical analysis is applied to simulation outputs to identify UUV design characteristics with the most significant impact on the time taken for an MCM UUV to perform the “detect and classify” mission. The main conclusions of this study are that the most important system characteristics for MCM UUVs are UUV travel speed and sensor width, and that bandwidth limitations for subsurface communications eliminate expected benefits of constant communication between UUVs and their parent vessels.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACINT	acoustic intelligence
ACRS	Area Coverage Rate Sustained
ANSI	American National Standards Institute
AOR	area of operation
APT	average process time
ASW	antisubmarine warfare
Alt	Alternative
ATLAS	autonomous topographic large area survey
AUV	autonomous undersea vehicle
AUVAC	autonomous undersea vehicle application center
CC	constant communication
DOD	Department of Defense
DOE	design of experiments
DoN	Department of the Navy
FFBD	functional flow block diagram
FMAUV	fleet modular autonomous undersea vehicle
IC	intermittent communications
IPOE	intelligence preparation of the operation environment
IPR	in process review
ISR	intelligence, surveillance, and reconnaissance
JCIDS	Joint Capabilities Integration and Development System
JCS	Joint Chiefs of Staff
JEL	Joint Electronic Library
JP	Joint Publication
LCS	Littoral Combat Ship
LDUUV	Large Displacement Unmanned Underwater Vehicle
LFBB	Low frequency broad band
LT	Lieutenant
MBSE	model based systems engineering
MCM	mine countermeasures
MCSN	Mass Communication Specialist Seaman
MDSU	mobile diving and salvage unit
MILCO	mine-like contact
MILEC	mine-like echo
MITL	man-in-the-loop
MIW	mine warfare

MVCS	multi-vehicle communication system
NAVSEA	Naval Sea Systems Command
NC	no communication
NPS	Naval Postgraduate School
NWP	Naval Warfare Publication
ONR	Office of Naval Research
PMA	post mission analysis
REMU	Remote Environmental Monitoring Units
RMMV	Remote Multi-Mission Vehicle
RMS	Remote Minehunting System
RTA	real time analysis
SAS	synthetic aperture sonar
SLS	side look sonar
SOS	system of systems
SSAM	small synthetic aperture minehunter
TtC	time to complete
US	United States
USN	United States Navy
USNI	United States Naval Institute
USNWC	United States Naval War College
UUV	unmanned underwater vehicles
WBIED	waterborne improvised explosive device
XLUUV	Extra-Large Unmanned Underwater

EXECUTIVE SUMMARY

The current fleet of United States Navy (USN) Mine Countermeasures (MCM) ships, the Avenger class, is reaching the end of its planned service life. To fill the capability gaps left by removing these ships from the fleet, and to take advantages of technological advances in environmental sensing and unmanned underwater vehicles (UUVs), the Navy will be acquiring new systems to perform the MCM mission. The Department of Defense (DOD) acquisition process aims to fill capability gaps with materiel solutions through development of new or improved systems or the purchase of existing systems. Beginning the acquisition process with ample knowledge of potential materiel solutions and their expected performance improves the likelihood of program success.

This capstone report examines the current state of UUV technology and technological capabilities anticipated to be available within the next 10 years. The report identifies the impact to system performance based on changes to system characteristics that drive the operational performance. This report provides recommendations to MCM decision makers about system attributes that will result in capability improvements for UUVs in support of the MCM mission.

This capstone project utilized a tailored system engineering trade-off analysis process, resulting in a framework that connects current and near-term MCM mission requirements with the anticipated performance of a set of proposed system architectures. The characteristics identified for detailed assessment were communications during the mission and data processing location. We identified three possible communication states which are no communication (NC) with the command ship, intermittent communications (IC) with the command ship and constant communication (CC) with the command ship. We decided that data processing could only occur either off-board the UUV via post mission analysis (PMA) or on board the UUV via Real Time Analysis (RTA). Completing the problem space exploration and identifying key characteristics enabled the team to develop candidate system architectures. Six alternative functional architectures

were developed and detailed using model based systems engineering (MBSE) tools and summarized in Table 1.

Table 1. Proposed System Alternatives

		Communications Cadence		
		No Communication (NC)	Intermittent Communication (IC)	Constant communication (CC)
Data Processing Location	Off-board UUV	Alternative 1. Post-Mission Analysis [Status Quo]	Alternative 2. IC with Off-board Data Analysis	Alternative 3. CC with Off-board Data Analysis
	On-board UUV	Alternative 4. RTA with Physical Transfer of MILECs	Alternative 5. RTA with IC of MILECs	Alternative 6. RTA with CC of MILECs

To understand and demonstrate the benefits offered by adding communication or onboard processing to the MCM UUV, we began our analysis process by modeling each alternative in the discrete event simulation software, ExtendSim, using a set of 18 initial design parameter inputs that represent a feasible level of performance based on existing technology within the USN portfolio. Next, a design of experiments (DOE) analysis was performed to analyze the impact of individual design parameters across the system architectures. Table 2 shows the design characteristics investigated during the design of experiments portion of the analysis.

Table 2. System Design Parameters Investigated

Locomotion	Data Processing	Communication	Data Collection
Launch Time	RTA Rate	Surface Data Transfer Rate	Sensor Range
Endurance			
Speed	Off board Raw Sensor Analysis Rate	Sub-Surface Data Transfer Rate	Data Collection Rate
Track Buffer			
Surface Time	MILCO Analysis Rate	Manual Download Rate	Maximum Scan Speed
Dive Time			
Recovery Time	MILCO Data Buffer		
Replenish Time			

To assess the performance of the proposed architectures, we identified two metrics to measure system performance across a set of operating environments. The metrics chosen were:

- 1) The elapsed time between mission start and all minefield data processed
- 2) The average elapsed time between mission start and data being scanned and processed for each square meter of the minefield.

These metrics captured the operational value of the proposed UUV architectures and enabled us to asses of performance of the architectures. As an example, Table 3 shows the results, in hours, of the overall simulation in regards to the first metric of time to complete mission across three different minefield sizes. The results show the advantages of onboard data analysis and how the optimum communication capability changes depending upon the layout and size of the suspected minefield.

Table 3. Time to Complete by Minefield Size and System Architecture

Minefield Size (km x km)	Data Processing Location	Communication Capability		
		NC	IC	CC
1x10	Off board	37.1	43.5	37.1
	On board	35.3	41.7	35.3
5 x 5	Off board	85.2	82.5	85.2
	On board	81.6	80.5	81.6
10 x 10	Off board	250.8	340.4	250.8
	On board	237.2	348.0	237.2

UUVs utilizing CC for all three size minefields are able to transmit a very small amount of data during the time it takes to complete the mission, making the operational benefit of constant communications very small and nearly similar to UUVs with no communications at all. This result occurs because as the UUV returns for replenishment, the majority of data onboard that did not transmit downloads quickly through a physical connection, the same as for systems with the NC architecture. A CC capability does allow data to start arriving to the operator on board the command ship sooner, but it is not an appreciable amount to be useful.

UUVs utilizing IC offer a solution that returns a sizeable portion of data to the parent vessel while the UUV is still in the minefield, performed with mixed results depending on minefield size. Simulations showed a rise in processed data at 12 hours for both IC alternatives; nearly 3 hours before systems with no communications begin having data processed onboard the parent vessel. Depending on the neutralization system selected, this performance characteristic of an early delivery of initial data may drive superior system of system performance by allowing neutralization systems to begin their tasking earlier in the mission. However, the elapsed time associated with breaching, transmitting, and returning to scanning depth adds a delay to the scanning process for architectures with intermittent communications. This delay causes systems with IC to perform poorly for the largest minefield simulated.

In the 1km x 10km theoretical minefield, IC provides no operational advantage as the mission time is longer due to the delays mentioned. For the 5km x 5km minefield, the initial benefit of beginning the operator analysis phase earlier in the mission is maintained through the end of the mission for the lowest overall time to complete the mission of all the alternatives however, for a large minefield of 10km x10km, the delay caused by the transmission cycle (breach, transmit, dive) reduces the total sensor data throughput for a long enough period that utilizing IC is an inferior approach.

Our simulations show that total mission time cannot be reduced through the introduction of CC between the UUV and command ship. Current underwater transmission bandwidths are too low to improve performance through the transmission of scanned data, whether raw or processed. UUVs using IC offer an improvement to performance by starting the PMA process earlier in the mission, but the delay to data collection caused by the transmission process adds to mission time for larger minefields. Problem was viewed as beyond the requisite level of detail envisioned for this capstone project.

Onboard processing provides two benefits across the alternatives that implement the capability. The first benefit is that onboard processing reduces the amount of data required to be transferred resulting in faster data transfer from the UUV to the command

ship, as raw data is processed to usable data during the mission. The second benefit is that onboard processing allows parallel efforts of data collection and data processing to occur simultaneously as opposed to serially, as is the case with off board processing.

To analyze the impact of the 18 individual design parameters across the six proposed system architectures, a nearly orthogonal Latin hypercube was utilized in a design of experiments (DOE) approach. This approach reduced correlation between the inputs to near zero while generating a set of simulation inputs that sampled the entire design space within the identified design parameter boundaries.

Depending on the architecture, the impact of a parameter or interaction between two parameters varied. Across all six proposed system solutions, sensor width has the most statistically significant impact on time to complete. Increases in sensor width reduce the number of tracks required to scan the entire minefield, reducing the time required to scan the minefield and collect raw sensor data. UUV speed has a similar impact, though the benefit occurs in both the scanning portion of the mission and the transit portions to and from the minefield. Table 4 provides the top five design parameters, ranked by the statistical significance of their impact on an UUV's time to complete a 10km x 10km minefield mission.

Table 4. Design Parameters Ranked by Impact

Design Parameter	Architecture Alternative (Alt)					
	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6
Sensor Width	1	1	1	1	1	1
UUV Speed	2	2	2	2	2	2
PMA Rate	3		3	5	4	5
On Board Processing Rate (RTA)				3	5	3
IC Data Limit		3			3	
Surface Time	4		4	4		4
Data Collection Rate		4				
Transit Time	5		5			
Replenish Time		5				

Beyond UUV speed and sensor width, the rank of design parameter impact is dependent upon which architecture alternative is being simulated. The IC data limit is the third ranked design parameter, for systems with intermittent communications. For alternatives without IC, results for alternatives with the capability to perform onboard processing found the real-time analysis (RTA) rate as the third highest ranked design parameter. Alternatives without RTA see the PMA rate as third highest ranked design parameter. The design parameters that have an impact on all examined architecture alternatives offer a set of investment options for the USN that are most likely to have benefit MCM UUV effectiveness.

The design parameters that our analysis did not identify as having significant impacts on system performance offer insights as valuable as those identified do. Communications rates for CC and IC, launch time, and recovery time are all found to have no statistically significant impact on the time to complete a mission in our examined range of inputs. The absence of significance for launch and recovery time is due to the relatively small initial values, which offer little room for improvement. For constant communications, the range of examined transfer rates is beyond the likely technological capability over the next decade and still does not reach the required transfer rates to positively impact MCM UUV performance. The rate of data collection remains over 1000 times larger than data transmission using underwater acoustic modems. Interest in these technologies, and the resources invested by the USN, should not be driven based on anticipated benefits to MCM UUVs.

The PMA phase has traditionally been a bottle neck in many MCM systems, and this capstone supports this view. For minefields requiring a single UUV sortie, increasing PMA rate decreases mission time. For larger minefields, increasing PMA rate may not decrease mission time significantly due to the processor having inactive time while the UUV replenishes energy stores or scans the minefield. Improvements to processing algorithms, possibly utilizing artificial intelligence and machine learning that can consistently extract mine like echoes from the terabytes of sensor collected raw data, could reduce the elapsed mission time spent performing PMA. If this processing can occur onboard the UUV, the overall time to clear a minefield can be even further reduced

and provide an earlier start to the neutralization phase. As a result, onboard processing should be a secondary focus for decision makers.

Given the range of expected available and feasible technology for the USN to include on an MCM UUV, we found that improvements to sensor width and UUV speed have the greatest impact on expected performance. This suggests that decision makers should focus investments in capability enhancement on sensor technologies that can increase scan size and the speed at which the scanning can be efficiently performed. Increasing the speed of the UUV does not positively impact performance if the sensor cannot keep up. As the performance of communications technologies improve, this analysis should be repeated, to determine whether these relationships hold true outside the boundaries of our analysis.

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I. INTRODUCTION

The data collected by Scott Truver shows that since the end of World War II, mines have seriously damaged or sunk almost four times more USN ships than all other means of attack combined (Truver 2012). Sydney J. Freedberg estimated that there are “more than 400,000 sea mines in the hands of United States (U.S.) competitors and enemies” (Freedberg 2015). His estimate did not include waterborne improvised explosive devices (WBIEDs) that can be fashioned from fifty-five-gallon drums, other containers, and even discarded refrigerators. Mines and WBIEDs are easy to acquire or build and are cheap, but their low cost belies their potential for harm. A low-technology moored mine costs around \$1,500 (Hunt and Morison 2000) with more sophisticated mines costing several thousands of dollars. As Truver states, “they are the weapons of choice for a ‘poor man’s navy,’ providing an excellent return on investment: low cost but high effects. While mines and even WBIEDs might not be naval power–projection ‘showstoppers,’ they could certainly be ‘speed bumps’ in critical waterways and regions, slowing the movement of warships, military sealift, and humanitarian response in crisis and conflict” (Truver 2012, 32). Traditional navies as well as maritime terrorists can and have used mines and WBIED to challenge military and commercial uses of the seas (Joint Chiefs of Staff [JCS] 2016).

Unmanned systems are a relatively new technology and key enabler for Littoral Combat Ships (LCS) to address the multi-faceted mine threat. UUV systems expand the Navy’s warfighting capability by relieving the burden of existing mission tasks and introducing new possibilities (Berkof 2017). Effective use of unmanned vehicles has decreased the cost of military operations, provided advanced technical capabilities, and reduced risk (DOD 2013). This report details the results in researching improvements of current variables that will enhance future Mine Warfare (MIW) capabilities of UUVs in the next decade.

A. MINE WARFARE OVERVIEW

To summarize Naval Warfare Publication (NWP) 3-15, maritime MIW is the strategic employment of sea mines and mine countermeasures (MCM) (DoN 1996). The goals of mining listed in the NWP 3-15 are: to prevent use of sea lanes, ports, or waterways, influence adversary maneuvers, protect ports, coastal lines, destroy enemy ships, establish blockades, and deny amphibious operations (DoN 1996).

Mining has the advantage of causing damage to adversarial ships without risk to friendly ships. Maximizing the chances of a strike is accomplished by targeting high traffic areas that result from geographical constraints. These include the shortest route from one place to another, the narrowing of routes via geological formations (straits or channels), or the location of centers of commerce (cities or ports). By studying the traffic patterns of adversaries, and cross referencing that with the needs of mine warfare, including water depth and the area size, a suitable mine delivery area can often be determined.

According to Joint Publication (JP) JP 3-15 the second part of MIW, “MCM includes all actions to prevent enemy mines from altering friendly forces’ maritime plans, operations, or maneuver” (Joint Chiefs of Staff 2016, IV-5). MCM is further divided into offensive and defensive operations. Offensive MCM tactics prevent mines from being used by destroying them at the manufacturing and storage facilities or mine laying platforms (Joint Chiefs of Staff 2016).

Defensive MCM is split into active and passive methods. Passive are localization, detection, and risk reduction and active are the actual destruction of mines through sweeping or hunting (Joint Chiefs of Staff 2016). Our study focused on MCM missions and narrowed down to the specific area of active Mine Hunting via UUVs. Bold items in Figure 1 defined the area of our study to unmanned vehicles performing mine hunting.

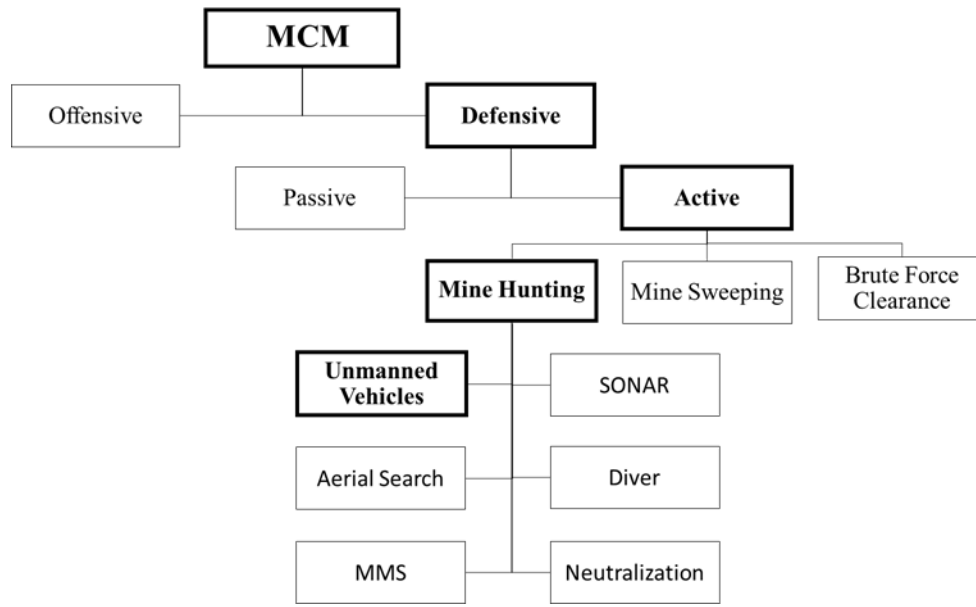


Figure 1. MCM area of study. Adapted from NWP 3-15 DoN (1996, 3–2)

John Keller recognized that “counter-mine warfare always has been a hazardous job. Until unmanned vehicles came on the scene, dedicated mine-sweeping vessels had to go in harm’s way and risk being blown up themselves in efforts to keep the sea lanes safe from hidden explosives” (2016). Today, unmanned vehicles are on the front lines in U.S. counter-mine efforts at sea. There are many potential architectures for next generation UUVs given the evolution of UUVs, sensors, and communication technologies. With the abundance of UUV MCM capabilities, identifying where the USN should focus engineering effort for next generation UUVs is a challenge.

B. RESEARCH OBJECTIVES

The current fleet of Mine Countermeasure (MCM) dedicated ships (Avenger-class) is reaching the end of its planned service life. The USN MCM fleet is shrinking. MCM-1 was decommissioned at 27 years of service (Farrington, 2014) and MCM-2 at 25 years (Minto, 2014). The unplanned decommissioning of MCM-5 at 23 years of service after it ran aground, near the Philippines (Wierzbicki, 2013), was an additional loss to MIW mission capabilities. Given an expected service life of 25–30 years, the last of the

Avenger-class MCM ships will go out of service around 2024 (Congressional Budget Office (CBO), 2015). The USN planned to replace the Avenger-class ships with UUVs designed for launch from LCS as part of the MCM Mission Package.

There is a gap between warfighters' future needs and the capabilities offered by the current USN MCM portfolio, which includes dedicated MCM vessels, helicopters, and other mission packages with varying levels of capabilities and costs. Unmanned Underwater Vehicles (UUVs) have been identified as a material solution of interest for filling the gap in the mine hunting mission. A range of UUV systems are currently in use by the DoN, and readily available technology can potentially be integrated into existing systems to improve performance. This range of potential systems and system improvements present decision makers in the MCM community with a large set of options in the UUV space.

This capstone effort examined the current state of technology for UUVs, their role performed in the MCM mission, and identified the impact of changes to system attributes on system performance. Our objective was to provide information for capability improvement to MCM community decision makers on system attributes that drive the operational performance for MCM UUVs.

C. SYSTEMS ENGINEERING METHODS

This capstone project used a tailored system engineering trade-off analysis process, resulting in a framework that connects MCM mission requirements with the anticipated performance of a set of proposed system architectures. The framework was developed iteratively, and a solution space of potential MCM unmanned underwater vehicles was proposed and then refined during the research phase of this capstone project. Figure 2 provides an overview of the major process steps that were followed in completing this project, and the outputs generated throughout the process.

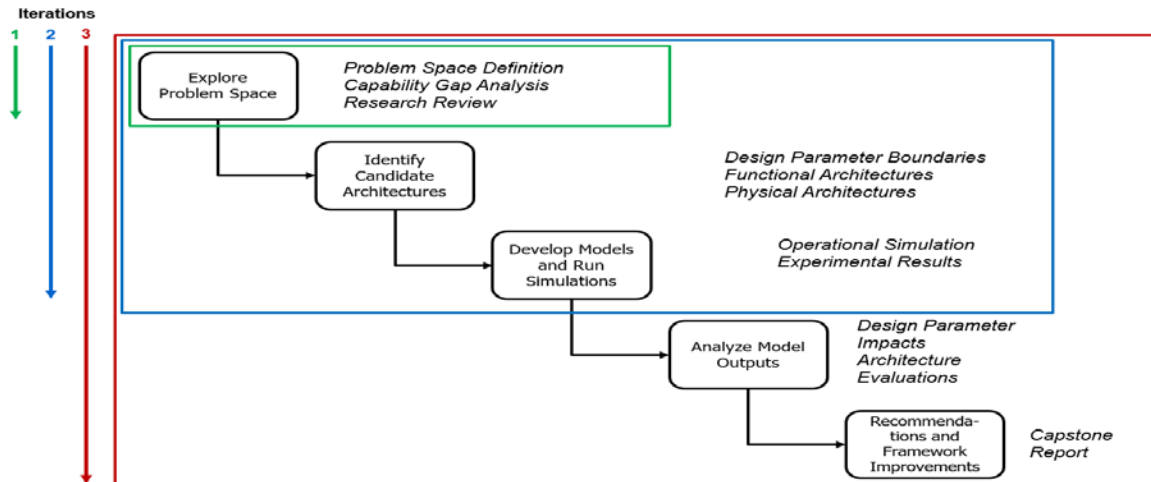


Figure 2. Tailored Engineering Trade-Off Analysis Process

1. Explore Problem Space

The capstone engineering process began with a review of current mine warfare threats and the threat of adversarial mines to restrict access, constrain freedom of navigation or disable or destroy USN and allied vessels. Following the exploration of the general mine warfare threat, our research identified current and near term available systems to perform the mine countermeasure mission, including MCM specific vessels, mission packages for vessels with a mission beyond MCM, manned aerial systems, unmanned surface, underwater and aerial systems, as well as passive methods of reducing the impact of adversary mining operations. The outputs of the initial problem space exploration include a research review, described in Chapter II. The problem space exploration was used to inform the problem space, further described in Chapter III.

2. Identify Candidate Architectures

Starting with an abstract definition of the operational mission of interest, we developed a functional architecture that described the high-level functions needed to perform the “detect and classify” portion of the MCM mission. A functional hierarchy acted as a first step to support more detailed functional analysis, and assisted in further identifying and defining interfaces and requirements, supporting the development of operational models and simulations, as well as the development of assessment criteria. A

set of potential physical architectures and associated concepts of operation were proposed that met the identified high level functional requirements. Leveraging these functional architectures, design envelopes were established to allow flexibility in design parameters and assess the impact of changes to design parameters.

3. Develop Models and Run Simulations

With initial system architectures identified, our research proceeded iteratively through the process of developing models and simulations, interpreting results, identifying primary system design attributes, and refining the system architectures. The first iteration through modeling and analysis was alternatives focused, estimating the performance for each of the proposed system architecture alternatives, and identifying the design parameter inputs required to meet desired system performance levels, following the approach used by Parnell, Driscoll and Henderson (2011). The second iteration through the modeling and analysis phase focused on changes to individual design parameters to isolate how system attributes impact system performance.

4. Analyze Model Outputs

Using the output of our operational simulation and system architecture models, we identified the primary system characteristics that drive UUV performance in the modeled MCM mission environment. Model outputs were assessed to compare the performance of the proposed system architectures throughout the MCM UUV mission, focusing on changes to communication modes and data analysis resources. Within each architecture, the outputs from the model enabled an impact assessment for a range of system parameters.

5. Recommendations and Framework Improvements

The outputs of the capstone are a framework for modeling the impact of specific system characteristics across a range of concepts of operation, and recommendations for investment areas for the development of the next generation of MCM UUVs. These results lead to a set of recommendations: first, the functional architecture with the highest anticipated performance; second, the system characteristics which have the greatest

impact on mission performance within each architecture. We concluded the effort with recommended improvement priorities for UUV system characteristics. Additionally, the team provided suggestions for further research.

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II. PROBLEM SPACE EXPLORATION

The capstone team performed a problem space exploration in order to define the scope of the architectures and models. The research focused on UUVs and mine systems. The objective of the UUV exploration was to document the different classes of UUVs that are currently used by the USN and get insight into their current capabilities. The objective for the mine systems exploration was to document the mine types that exist in the deep-water threat area.

A. UUV

This section provides an overview of select UUVs. UUVs can be categorized by their size, the categories will be defined as follows: Small UUVs are UUVs with a diameter of up to 12 inches, Medium UUVs range between 12 inches and 21 inches, Large UUVs range between 20 inches and 80 inches, and Extra-Large UUVs are anything higher than 80 inches (Clark 2015). The capstone project's scope was focused on UUVs that operate in deep-water region and were able to provide detect, classify, and identify capabilities. To identify UUVs that met that scope, the team compiled a list of UUVs and mapped them to five areas of support: battlespace awareness, detect, classify, identify, and size. Comparing the UUVs by size allowed us to see which UUVs would operate in deep water. The investigation showed that UUVs of a medium size or bigger would be inside our scope of study. The battlespace awareness, detect, classify, and identify attributes allowed us to see which UUVs could operationally perform MCM's missions. If the UUV could perform a detect, classify, and identify operation then it was part of the scope of study. The UUVs that met the criteria for the capstone project are listed in Table 1.

Table 1. Initial set of U.S. UUVs

UUV	Battlespace Awareness	Detect	Classify	Identify	Size
MK18 Mod2	-	X	X	X	Medium
Knifefish	-	X	X	X	Medium
LDUUV	X	X	X	X	Large
Snakehead	X	X	X	X	Large
XLUUV	X	X	X	X	Extra-Large
MK18 Mod1	-	X	X	X	Small
Archerfish	-	X	X	X	Small
SeaFox	-	X	X	X	Small
MDSU REMUS 100s	X	-	-	-	Small
IVER 2	X	-	-	-	Small
SandShark	X	-	-	-	Small
GhostSwimmer	-	-	-	-	Small
FMAUV	X	-	-	-	Medium
LBS UUV	X	-	-	-	Medium
NAVO Seahorse	X	-	-	-	Small

The following provides an overview of the UUVs in the capstone project’s problem space.

1. Small UUVs

Brian Clark states that “small UUVs (about 12" in diameter) are commonly used today for surveys and minehunting, such as the Navy’s Mk-18 UUV. They will be able to take on other surveillance or attack missions as part of the Fleet Modular Autonomous Undersea Vehicle (FMAUV) program and operate from submarines as well as surface ships and aircraft” (2015). The small size and relative lower cost make FMAUV ideal for shallow water or neutralizer missions (Clark 2016). The threat area of the report is focused on the deep-water and to exclude neutralizers, therefore there were no small UUVs that fit under the capstone project’s problem space.

2. Medium UUVs

As the size of the UUV grows, so do other of their capabilities, such as endurance and payload weight limits. The two UUVs that fall under this category are the Kingfish and the Knifefish. The UUVs in this section, although still going through testing, are the most mature of the groups. Their slightly larger bodies allow them to be deployed from submarine torpedo tubes, but yet they are small enough to be deployed on a wider range

of crafts of opportunity. They both have plans for short term improvements, so their stakeholders would be the ones that would benefit the most from the results of the capstone project.

a. *Kingfish – MK18-Mod 2*

Phillip Bernstein noted that “The Kingfish MK18-Mod 2 UUV is based on the Kongsberg Maritime owned Hydroid REMUS 600. Its dimensions are 12-¾ inches in diameter and a length of 11.5 feet. MK 18 Mod 2’s operating depth is between 5 meters (16 feet) and 100 meters (328 feet) the family of systems is up to 300 meters (984 feet)” (2014, 4–5), its targeted operating zone is for the Very Shallow Water, Shallow Water, and Deep-Water regions. The Kingfish UUV has detect, classify, and identify capabilities. Its main sensor is the “Edgetech 2200, 850kHz Dynamic Focus Side Look Sonar (SLS)” (Bernstein 2014, 4). From Lorene Adams’ brief on Kingfish specifications we learned that it has the “Small Synthetic Aperture Minehunter II (SSAM II) and the Autonomous Topographic Large Area Survey (ATLAS) modules. Both modules are under testing, but the SSAM objective is to decrease Post Mission Analysis (PMA) time and the ATLAS increases the detection range to approximately 3200 feet” (2016, 8).

b. *Knifefish*

From Adams’ brief we also found that:

The Knifefish UUV uses the General Dynamics owned Bluefin-21 as its frame. Its measurements are a 21 inches diameter, 21 feet long, and weighs about 1,700 lbs. Its detection capabilities focused on the Low Frequency Broadband Synthetic Aperture Sonar (LFBB SAS). Its main platform is on LCS with two UUV onboard, as it supports the MCM Mission Package (2016).

Knifefish can hunt mines in cluttered areas and can detect, classify, and identify floating and bottom (proud or buried) mines. The Knifefish UUV is positioned to take the place of the RMMV and therefore should focus its future upgrades on any gaps like endurance to cover large minefields.

3. Large UUVs

“Large UUVs (about 80 inches¹ in diameter) such as the Navy’s Large Displacement UUV (LDUUV) are designed to use the planned Virginia Payload Module (VPM) tubes in Block V Virginia-class submarines. The LDUUV will provide a way for submarines to increase their sensor reach, expand their payload capacity, or deliver payloads into areas that are too risky or constrained for the submarine to reach” (Clark 2015, 7). The two UUVs that fall under this category are the LDUUV and the Snakehead UUV. Both of these systems are under development, so these stakeholders could also benefit from reviewing the results of the capstone project.

a. Large Displacement Unmanned Underwater Vehicle Program

The LDUUV are prototype efforts ran by the Office of Naval Research (ONR) designed to provide increased endurance, range, and payload capabilities. Its focus areas are for Intelligence Preparation of the Operation Environment (IPOE), Antisubmarine Warfare (ASW), Acoustic Intelligence (ACINT), Intelligence, Surveillance, and Reconnaissance (ISR), MCM and offensive operations and payload deployments. It is being designed to work in a variety of platforms, such as LCS or Virginia and Ohio class submarines, or even dry-dock (Keller 2015).

The LDUUV demonstrated an endurance of about 30 days, but the desired threshold endurance was 70 days (Keller 2015). Aside from the intrinsic capability of obstacle avoidance that it needs to have, it also has to address data transmission rates between the host and the UUV, and runtime endurance. The LDUUV reached the technology maturation and risk reduction phase in 2015 with initial operating capability planned in 2020 and a full rate production in 2025.

b. Snakehead UUV

The Snakehead UUV is the result of development led by the ONR LDUUV team. This effort focused on autonomy and software as part of the acquisition program of the Snakehead UUV. “The Phase 1 Snakehead LDUUV will focus on intelligence and preparation of the environment (IPOE) and intelligence, surveillance and reconnaissance (ISR) mission sets, and Phase 2 would seek to add extended ranges to both missions. The

eventual program of record Snakehead Increment 1 would include additional payloads, potentially including electronic warfare, mine warfare MCM, anti-submarine warfare and anti-surface warfare...” (Eckstein 2017).

4. Extra-Large UUVs

“Extra-Large UUVs (more than 80” in diameter) in development would be designed to launch from shore or very large ships with well decks or “moon pools.” They could be used for long-endurance surveillance missions or primarily as “trucks” to deliver other payloads and UUVs. Experience with LDUUV will help inform concepts for using XLUUV” (Clark 2015). There was only one UUV in this category and that was the XLUUV. The Extra-Large UUV is still in early stages of design, but has the most potential for capability due to its high endurance and bigger payload weight capacity. The XLUUV stakeholders would also benefit from reviewing the capstone project’s results to help prioritize their product improvement needs.

a. Extra Large UUV (XLUUV)

The USN is currently receiving bids for the design of an XLUUV. There are some requirements of the capabilities it is expected to perform. For example, it should be able to deploy from a shore site, it does not need to deploy from another platform. It should be modular and be able to be configured with different payloads. The XLUUV design was expected to travel about 2,000 nautical miles and be able to periodically establish communications (NDIA 2017). This could open new areas for the USN, such as possibilities of undersea network communications.

B. MINE SYSTEMS

This section describes the types of mines the USN generally expects to encounter. Mines are developed based on a variety of requirements including their target type, delivery method, and geological area being placed.

1. Mine Delivery Methods

Three methods used for Mine Delivery are Aircraft, Surface, and Subsurface.

- Aircraft-laid mines: Used to rapidly deploy mines in areas for offensive actions. Most mines in the current U.S. Naval arsenal are aircraft laid mines
- Surface-laid mines: A variety of ships can deploy mines. While other nations commonly use ships to deploy mines, the United States does not maintain a stockpile of surface-delivered mines.
- Subsurface-laid mines: Mines deployed subsurface designed to be deployed torpedo tubes (NAP 2000).

This report focuses on deep-water zones because our research indicates that is where the use of UUVs provide the most benefit. Mines are classified according to three characteristics: Position in the water column, method of delivery, and method of activation (NAP 2000). These three characteristics will be discussed in the subsequent sections.

2. Mine Types

There are four categories of mines: bottom, moored, rising, and drifting. The capabilities of each mine are constrained by its location in the water column position. Water depth influences the type of mine that can be used and if an area can be mined at all. Traditionally water depth of more than 600 feet means the detection of seagoing targets becomes difficult, and their destruction even more difficult. However, in recent years, technology advancements have facilitated the emplacement of mines in depths beyond 600 feet, which makes mine hunting and sweeping difficult. Despite some advantages, placing mines at these extreme depths are not desired. As can be seen, water depth must be considered when deploying mines (NAP 2000).

The method of activation is typically dependent on the adversary laying them and the geological area being mined. For instance, a wealthy country with a capable naval presence may have specialized ships while a poorer country may rely on converted merchant ships. In regards to geographical location, camouflaged boats masquerading as fishing boats may be utilized to stealthily drop mines in enemy waterways. Geographical

areas also exhibit specific water depths that affect the method of mine delivery chosen. Since this report focuses on deeper water depths, only those delivery methods employed within those areas will be discussed.

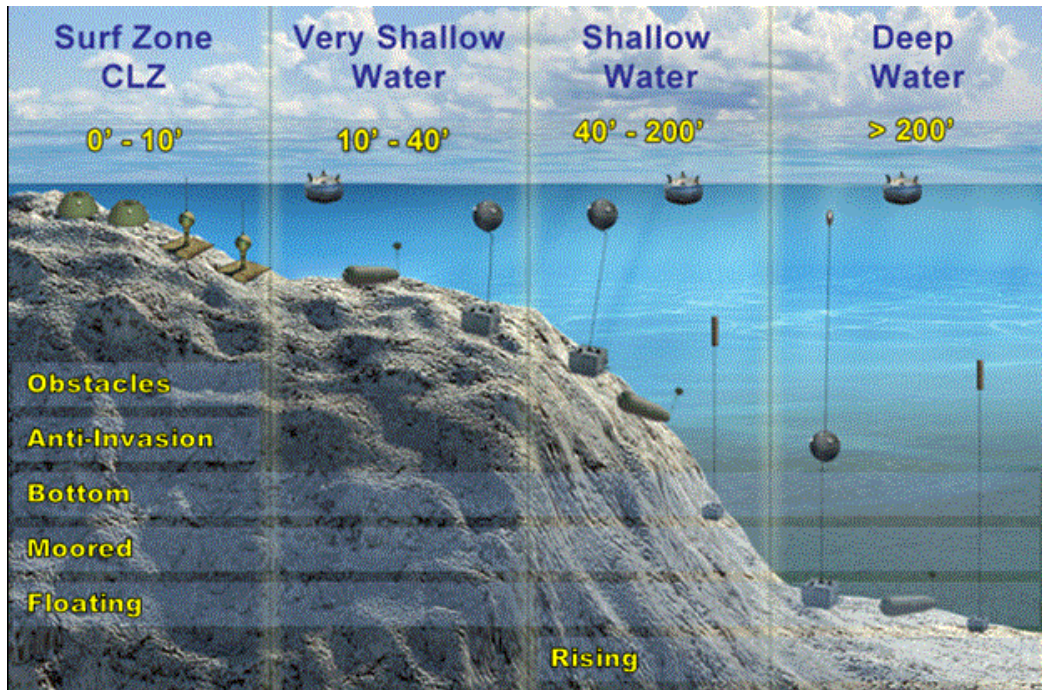


Figure 3. Overview of Mine types (Brief NPS).

- Bottom Mine – Generally found in shallow water where either surface craft or submarines can easily trigger them (NAP 2000). They can be buried or on top of the ocean floor.
- Moored Mine – Also known as tethered mines, are found in deeper water and are highly effective against both surface ships and submarines. As their name implies, they are moored to the ocean bottom, typically with a weight or anchor. Based on the water depth, they can have either fixed length, or adjustable length mooring cables as to precisely position themselves in the water column. Some moored mines contain weapons that have the ability track and engage targets (NAP 2000).

- Drifting contact mine – Move with the currents at water level or just below. Drifting mines were banned in 1907 by The Hague Convention. However, many “rogue” nations still utilize drifting mines because of their low cost and easy deployment (NAP 2000) in addition if a moored mine’s tether breaks it become a drifting mine as well Figure 3 displays an example of a floating mine.
- Rising Mine – Behave similarly to bottom mines or moored mines until triggered. Rising mines are designed to float back to the surface when triggered by a specific influence from an enemy ship. They change from negatively buoyant to positively buoyant by jettisoning its ballast upon being triggered. This mine category can be especially effective because it combines the capabilities of bottom mines at rest and floating mines when activated. This makes the floating mine difficult to identify and neutralize. By moving to the surface, rising mines can exert significant damage to its target by being in close proximity (Slade 2000).

3. Methods of Activation

Three primary methods of activation exist: contact, influence and controlled.

- Contact activation represent the oldest mine activation technology and the simplest. These must have close proximity to the surface if the target is a surface craft since contact with the hull is required. They detonate when a “horn” contacts something hard, which bends it, activating a chemical reaction to set off the explosive (NAP 2000).
- Influence activation is the most common activation method today. Detectors are used to sense changes in fluid pressure or acoustic, magnetic, and electric fields (or a combination of all four). Sensors are designed to distinguish between different types of vessels or to have delays before detonating to ensure maximum damage to the adversarial vessel (NAP 2000). By detecting one of these influences from a distance,

and not requiring contact with the ship, the mines can be positioned deeper in the water column.

- Controlled activations are used for coastal defense. Unlike influence mines or contact mines, controlled mines are typically under observation and triggered remotely, using a tethering system. The mines can be activated or deactivated when needed to allow ships to pass through the mined area or restrict access. This type of mine is typically used defensively and is particularly effective in preventing entrance to straits or confined areas.

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III. ARCHITECTURE DEVELOPMENT

To paraphrase Crawley, Cameron, and Selva, well architected systems meet stakeholder needs and deliver value, while integrating easily, evolving flexibly, and operating simply and reliably (2016). They further define system architectures as “abstract descriptions of the entities of a system and the relationship between those entities. In systems built by humans, this architecture can be represented as a set of decisions” (2016, 3). The development of a system architecture establishes a baseline set of systems entities and relationships that can be used to establish a decision space that represents the range of solutions that meet mission needs. Some benefits of systems architecture are: early systems decisions can be analyzed and used to structure creativity, “the focus on decisions enables system architects to directly trade the choices for each decision, rather than the underlying designs they represent, thus encouraging broader concept evaluation” (Crawley et al. 2016, 4). Rather than comparing previously defined discrete solutions to an identified capability gap, the development of a system architecture allows the analysis of changes to all design parameters and the assessment of substantially more alternative designs. While well-defined system architecture does not guarantee system success, it does establish a sound foundation for the execution of capability-focused system development.

A. MODEL BASED SYSTEMS ENGINEERING TOOL SELECTION

Team Cleansweep selected SPEC Innovations’ cloud application Innoslate as the tool to support our MBSE process. Innoslate possessed several features that supported development of the system architecture for this capstone project. The Innoslate application simplified the development of the system architecture by enabling clear visualization of potential functional structures, functional flows and multiple design concepts. This visualization capability streamlined the process of identifying architectural decisions that shaped the approach to operational and design parameters. Innoslate allowed the team to evaluate the logical consistency of proposed functional architecture models and address design issues of the proposed concepts prior to development of the

detailed simulation. Innoslate's cloud access and real-time collaboration contributed to team members' ability to work on the architectural design in disparate physical locations.

B. FUNCTIONAL ARCHITECTURE WALKTHROUGH

In developing a system architecture for the next generation MCM UUV, we identified a set of operating concepts the system could follow. These operating concepts, along with system design parameters and environmental inputs, determine system performance. To avoid letting an appeal to tradition limit the range of potential approaches investigated, we examined the objectives of the mine hunting mission in the abstract, finding that the essence of the MCM mission is in transforming an unknown battlespace into a known battlespace. This can be portrayed as the collection and transformation of environmental data collected by sensors. Figure 4 depicts the modeled progression of data during the mine hunting mission.

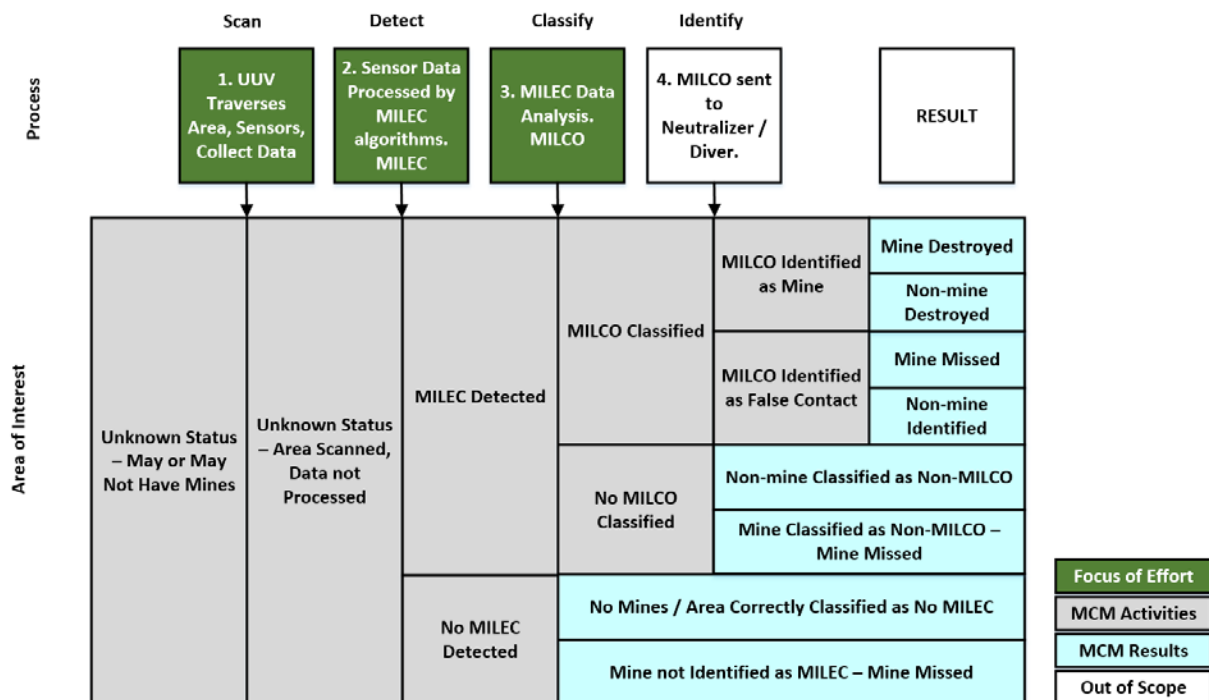


Figure 4. Battlefield Awareness Progression – MIW

Battlespace awareness of a potential minefield increases in the figure from left to right. In Process 1, that knowledge progresses from unknown and uncollected to unknown and collected, as raw sensor data is collected. This raw sensor data needs to be transformed and analyzed before providing value. In Process 2, algorithms and purpose-built software analyze the collected raw sensor data and create an output consisting of areas without suspected mines and areas where sensor data indicates the presence of something mine-like, referred to as a Mine-Like Echo (MILEC). In Process 3, MILECs are analyzed by trained individuals with the assistance of analysis tools to determine which echoes may represent actual mines; these echoes are called Mine-Like Contacts (MILCOs) once identified. Within our model, the man-in-the-loop (MITL) process of assessing MILECs to identify MILCOs represents the termination of the portion of MCM UUV mission under investigation. While outside the scope of our modeled and analyzed environment, the last step in this basic mine hunting flow, Process 4, would be the neutralization of mines, which we believe will not be done by the same system as Process 1 and 2, due to the requirement of a man-in-the-loop. In concert with neutralization systems and supporting equipment, the MCM UUV is part of a system of systems (SoS) with the purpose of clearing mines from a minefield, but the MCM UUV we are interested in contributes only to the data collection and processing portions of the mission, called “detect and classify.” Once the “detect” of a mine-like object has happened “the next step involves separation of mine-like objects from objects that are mines” (NAP 2000, 46).

The current generation of MCM UUVs involved in the “detect and classify” mission rely on a physical transfer of sensor data for processing via capabilities not resident on the UUV. Previous NPS capstone projects studied the impact of changes to UUV design parameters such as speed and sensor range, and analyzed their intended impact on performance of the MCM mission. Per the literature review presented in Chapter II, the recent progression of UUV technology suggests that this capstone expand the area of study to include alternative approaches to the mission of collecting, analyzing, and transmitting sensor data from within the minefield. The first potential change to the concept of operations identified was performing the detection phase onboard the UUV.

The second potential change to the concept of operations was the introduction of communication modes between the UUV and the ship or system performing the MITL analysis of MILECs. We chose the communication options of no communication and constant communication, as well as a middle-ground of intermittent communication. Table 2 depicts the resulting six architectures.

Table 2. Concept of Operations Alternatives

		Communications Cadence		
		No Communication (NC)	Intermittent Communication (IC)	Constant Communication (CC)
Data Processing Location	Off-board UUV	Alternative 1. Post-Mission Analysis [Status Quo]	Alternative 2. IC with Off-board Data Analysis	Alternative 3. CC with Off-board Data Analysis
	On-board UUV	Alternative 4. RTA with Physical Transfer of MILECs	Alternative 5. RTA with IC of MILECs	Alternative 6. RTA with CC of MILECs

C. FUNCTIONAL ARCHITECTURE WALKTHROUGH

To aid in communicating the consistencies and differences between the six alternative approaches to performing the “detect and classify” mission with a UUV, a functional hierarchy and functional flow block diagrams were created. A single model was developed within Innoslate that captures the functions required for each of the six alternatives. The Innoslate tool includes internal logic that was leveraged to ensure that each modeled architecture performed only the functions necessary and required by the associated communications mode and data processing location.

A functional hierarchy was developed to aid in understanding the functions that are performed in completing the mission, and the required lower level functions that decompose them. We built a functional hierarchy down to the level of detail that was needed to capture the differences between the suggested alternative communication and data processing methods. Figure 5 shows the highest level of the functional hierarchy, representing the processes that need to be completed throughout the life cycle of the

MCM UUV. The functions shown in green are the areas of interest for this report. While the entire life cycle offers potential for improvement, our focus at this time lies in the operational aspects only. The highest level, Perform MCM Operations, is decomposed by the entire MCM UUV life cycle, of which only the MCM Mission is further decomposed. Within the MCM mission, there are a number of functions again ruled out of scope, such as the embarkation and disembarkation of the system, maintenance, and standby periods. The primary areas of interest are the UUV MCM mission operations and data analysis, either onboard or off-board the UUV.

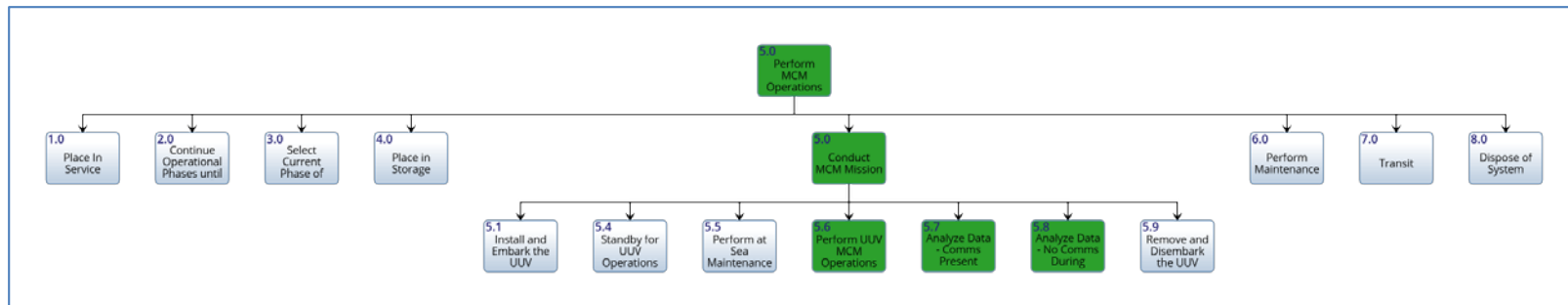


Figure 5. Functional Hierarchy

The function Perform UUV MCM Operations is further decomposed in Figure 6, showing the functions required while the UUV is operating away from its parent vessel. The UUV must be launched and retrieved from its parent vessel, it must transit to and from the minefield, and it must reach and return from mine hunting depth. The primary function of interest for this capstone project is set of functions that are performed in the minefield. These include locomotion across the minefield, scanning the local area, onboard processing when included in the architecture, and communications with the parent vessel when included in the architecture. Within the communications functions, the data being transmitted is determined to be either raw sensor data or MILECs by whether the data has been processed onboard or not.

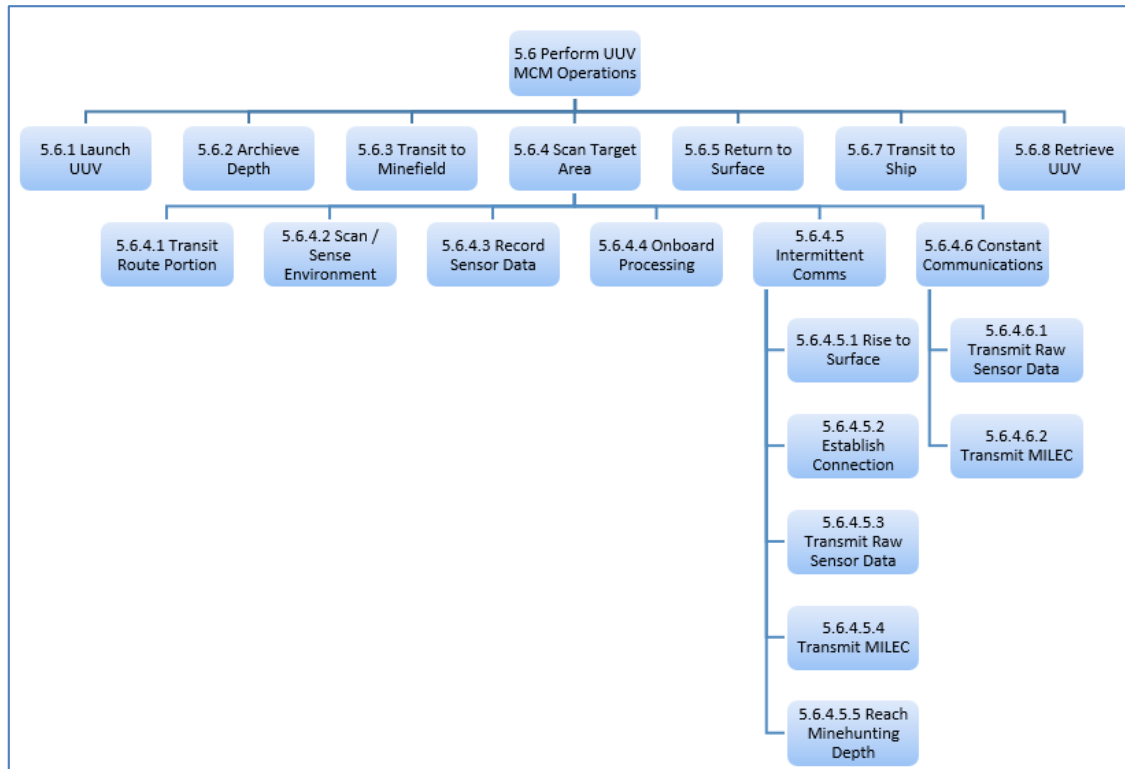


Figure 6. Perform UUV MCM Operations Functional Hierarchy

The functional hierarchy shows the functions required to perform the mission, but does not provide enough information to simulate operations, because the order that functions are performed and the logic determining this order are not part of a functional hierarchy. To enable simulation and further understanding of the MCM UUV operations, we leveraged the functional hierarchy to create a set of functional flow block diagrams representing the operations of all six proposed system architectures.

Multiple functional flows were represented in this single model by implementing a decision point at the start of the functional architecture. This decision point is represented by the function 0.1 Choose MCM System in Figure 7, and allows a user to select one of the six alternative architecture of interest, and the selection is leveraged by the tool to determine the functional flow within the model. The function 0.2 Set Environmental Conditions represents the modeled battlespace being established. The

function 0.3 Perform MCM represents the UUV system life cycle from the moment the vehicle is placed in service to disposal, and is the area within the model that internal logic is applied. This level of the functional architecture exists only to support modeling and interim simulation, while the remainder of the model, described below, represents the system architecture of the UUV(s) of interest.



Figure 7. Perform Mine Countermeasure Operations

Figure 8 depicts the life cycle process from system fielding in 1.0 Place in Service to 9.0 Dispose of System, the end of the system life. Functions 1.0 Place in Service and 9.0 Dispose of System occur a single time during the life cycle, at the beginning and end, between which the UUV exists in a set of states represented by the functions 4.0 Place in Storage, 5.0 Conduct MCM Mission, 6.0 Perform Maintenance, and 7.0 Transit. Functions 4.0 Place in Storage, 6.0 Performance Maintenance, and 7.0 Transit are active functions that the vehicle must perform outside of the operating cycle. 8.0 Influence UUV with Environmental Feedback represents the interaction of the UUV with the environment – including risk of damage due to nearby friendly operations, adversarial action, and passive conditions such as corrosion. The focus of this analysis is on the operational portion of the system life cycle, represented by function 5.0 Conduct MCM Mission and decomposed in Figure 9.

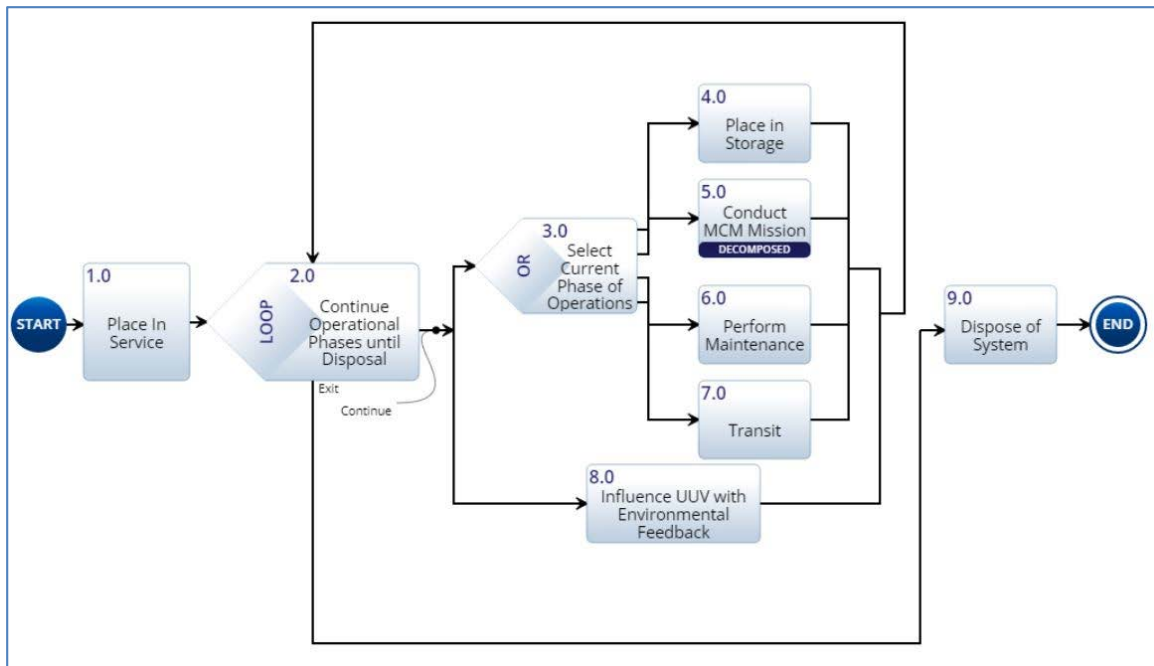


Figure 8. Perform MCM UUV Operations

Due to the five to ten-year time period of interest for this capstone project, we assumed that next-generation MCM UUVs will be launched from a separate parent vessel near the MCM operations area. We believe that it is unlikely that a near-term UUV will have the power capacity necessary to operate without a parent vessel. To do so, a UUV would have to transit to minefields from a home station and still have the power stores necessary to run sensors and send and receive tasking once on-station. The MCM mission is inherently responsive to how the U.S. Navy moves the fleet and where threats emerge. Meeting the MCM requirement would demand extreme endurance beyond what is feasible for the next generation of assets.

The Function 5.0 Conduct MCM Mission, shown decomposed Figure 9, consists of the functions performed from the time the MCM UUV embarks for mine-hunting missions until the time the MCM UUV is disembarked. To set the scope for the capstone project it was assumed that the next-generation MCM UUV of interest would perform the

“detect and classify” portions of the mission, with the neutralizer system performing the identification of the MILCOs and the destruction of targets.

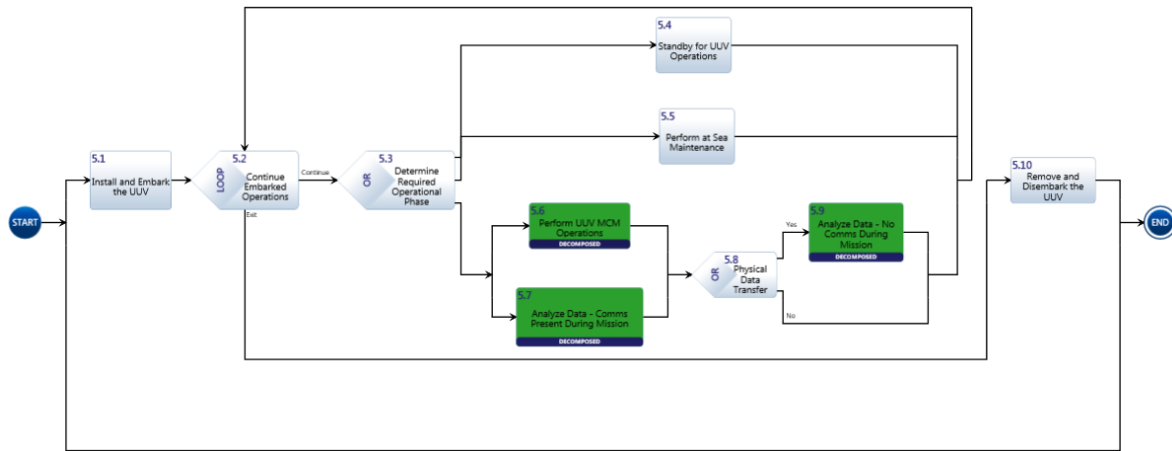


Figure 9. 5.0 Conduct MCM Mission

The MCM mission starts with system installation at function 5.1 and ends with system removal at function 5.10, between which the system will alternate between functions 5.4 Standby for UUV Operations, 5.5 Perform at Sea Maintenance, and actively performing the mine hunting mission. The tasks associated with the active portion of the mine hunting mission are represented by functions 5.6 Perform UUV MCM Operations, 5.7 Analyze Data – Communications Present, and 5.9 Analyze Data – No Communications Present.

Function 5.6 Perform UUV MCM represents the functions performed while searching the minefield and collecting sensor data. Function 5.7 Analyze Mission Data – Communications Present represents the data analysis performed in parallel with UUV operations to capitalize on the ability of an MCM UUV to communicate with a parent vessel during the MCM mission. Four of the proposed UUV architectures identified are able to transmit either raw sensor data or data that has been analyzed for MILECs. This data is passed to an off-board control location for further analysis and potential relay to neutralization systems. MILCOs will be identified with man-in-the-loop analysis,

necessitating that sensor data cannot be processed beyond MILECs on the MCM UUV. The function 5.9 Analyze Mission Data – No Communications Present mirrors the capabilities of MCM UUVs as they generally exist currently – the UUV has to return to the parent vessel and the data must be transferred to the PMA subsystem for further analysis, which is the case for the remaining two alternative architectures modeled. This level of functional decomposition captures the highest level of the focus of our analysis – the operational performance of an MCM UUV and supporting equipment performing the “detect and classify” mission with respect to the collection, analysis and transmission of sensor data in an area with potential mines.

The differences in operating functions between the six alternatives becomes apparent at lower levels of functional decomposition. Function 5.6 Perform UUV MCM Operations represents the core mission of the MCM UUV - providing battlespace awareness by collecting data that describes a potential minefield from which potential mines can be identified through the analysis of sensor data. Function 5.9 Analyze Data – No Communications During Mission represents the data transfer and analysis process for UUVs with no method of communicating during the mission. Function 5.7 Analyze Mission Data – Communications Present is modeled in parallel to function 5.6 to represent the ability of the UUV to transmit data, either raw or analyzed, to an off-UUV location for further analysis. The introduction of parallelism between data collection and data transfer could represent a significant potential opportunity to reduce the overall MCM mission time by allowing for the time required to analyze the data to begin while the minefield is still being scanned. While environmental data about a particular area needs to be collected before it can be analyzed, data collection and data analysis can occur simultaneously for sensor data collected for different areas of the minefield.

Function 5.6 Perform UUV MCM Operations, decomposed as shown in Figure 10, represents the required actions that the MCM UUV must conduct from the time the UUV leaves the host platform until the time the UUV returns to the host platform. This includes interaction with the host platform at launch and retrieval, locomotive processes

to reach the target mine hunting depth and area, and the scanning operations while in the target area.

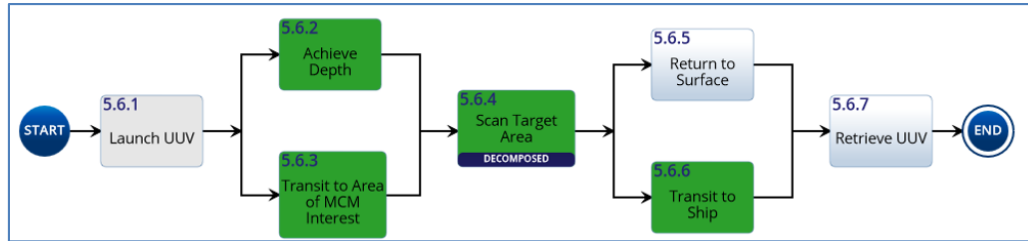


Figure 10. 5.6 Perform UUV MCM Operations

Within the modeled system architecture, 5.6.4 Scan Target Area is initial point of deviation between the suggested system alternatives. System capabilities – onboard versus off-board data processing, and communications – determine the operating approaches followed. Figure 11 shows the decomposition of 5.6.4. The functions involved with scanning the target area are repeated, with the set of functions blocked in orange and expanded in Figure 12, dedicated to the transit, data collection, and potential onboard data analysis of a given area, and the functions highlighted in green and expanded in Figure 13 dedicated to transferring data (processed or unprocessed) over the available communications models. For the purpose of our simulations, the intermittent communications paradigm is modeled to require a period during which the UUV will breach the surface in order to communicate and then return to mine hunting depth after the communications are complete. The constant communications paradigm does not require this breach-to-transmit process.

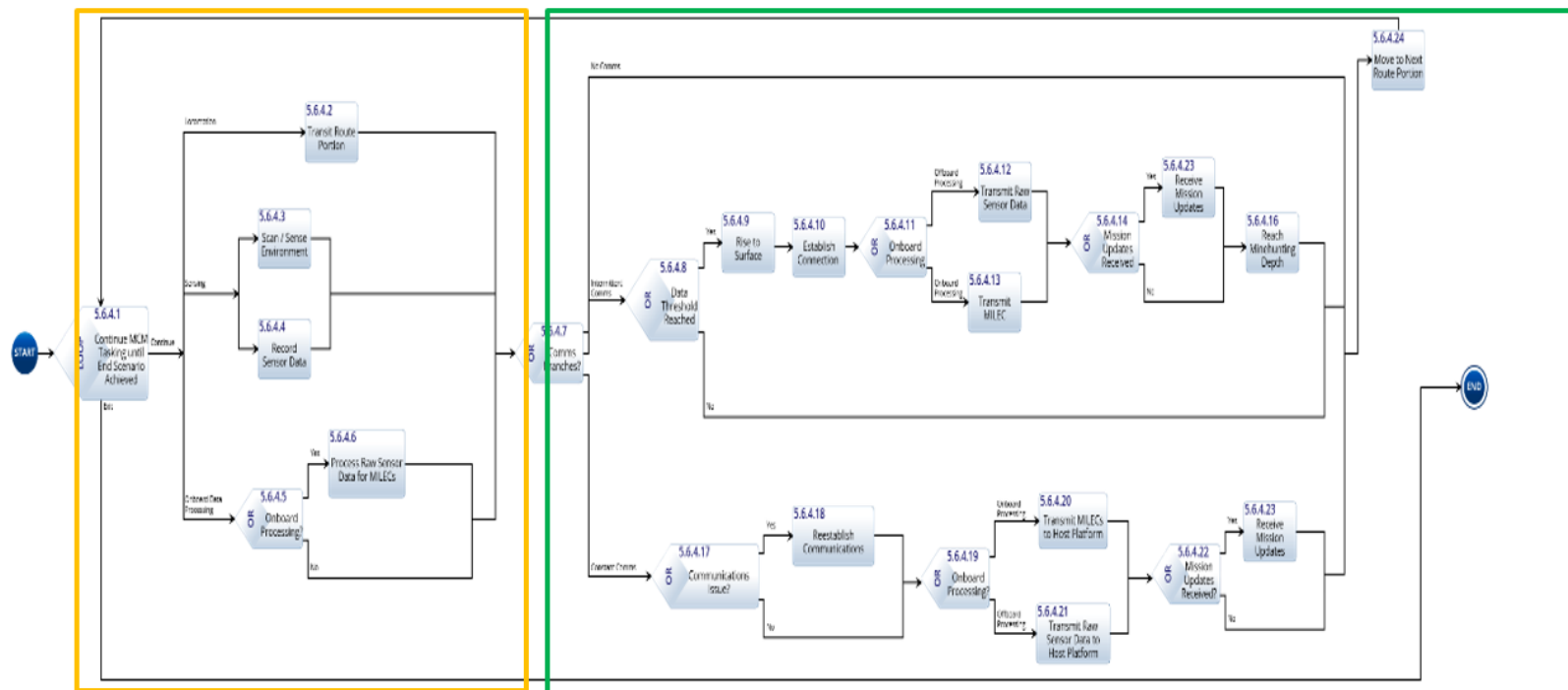


Figure 11. 5.6.4 Scan Target Area

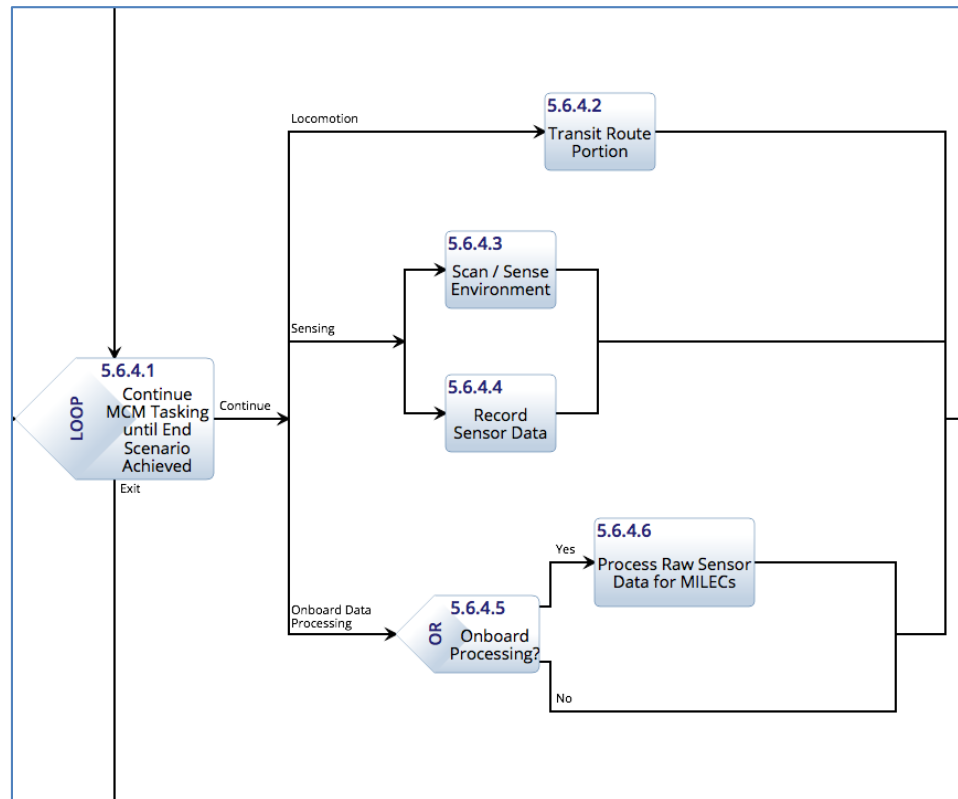


Figure 12. 5.6.4 Scan Target Area - Sensor Data Collection Portion

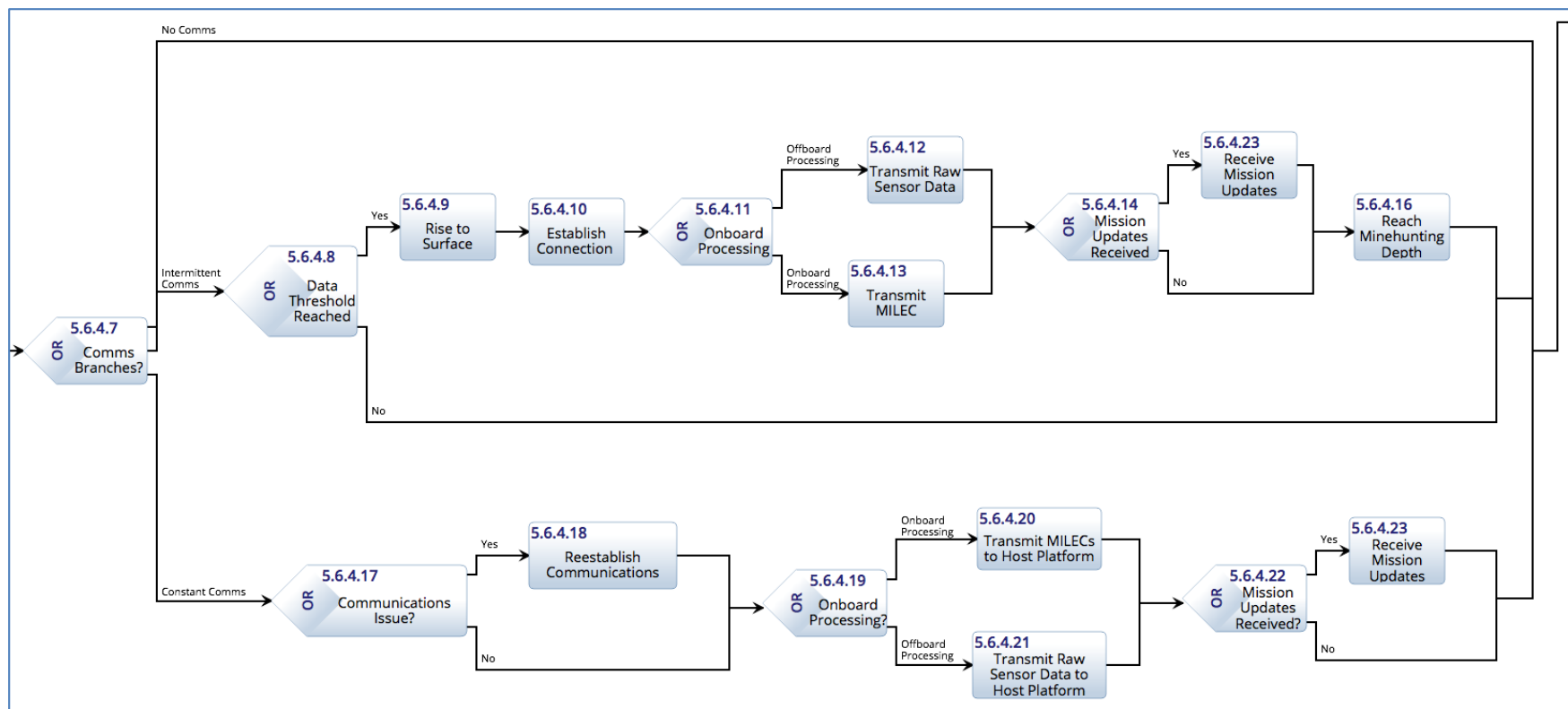


Figure 13. 5.6.4 Scan Target Area - Communication of Data

For Alternatives 1 and 4, data transfer is performed manually. Function 5.9 Analyze Data – No Communications During Mission, shown in Figure 14, the transfer of data for the entire scanned area occurs simultaneously as the MCM UUV is retrieved. The data arrives as raw sensor data if the UUV lacks onboard processing, or identified MILECs if onboard processing is available, as represented by functions 5.9.2 and 5.9.3. For Alternative 1, where no onboard processing is available, function 5.9.4 Analyze Raw Sensor Data identifies MILECs from raw sensor data, analogous to the onboard function Figure 14. After MILECs are identified, the core operations of the next generation MCM UUV is completed – the analysis of MILECs to identify MILCOs and targets is done manually, while neutralization is performed by a separate system.

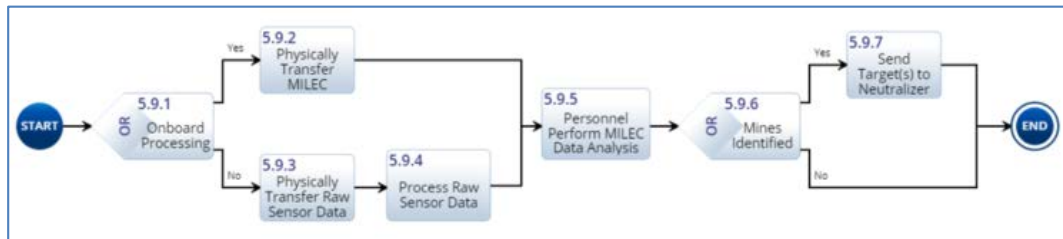


Figure 14. 5.9 Analyze Data - No Communications During Mission

For the remaining four alternatives, communication capabilities enable data transfer between the MCM UUV and the host platform. Figure 15 shows the decomposition of Function 5.7 Analyze Data – Communications Present During Mission. For all communications-enabled alternatives, data is processed in batches smaller than the complete scanned area. Alternatives with constant communications receive and analyze sensor data for smaller portions of the scanned area than alternatives with intermittent communications. For systems with onboard data processing, the data communicated to the host platform is MILECs, while architectures without onboard processing transfer raw sensor data. After data is off-board the MCM UUV, the process reflected in Function 5.7 mirrors that discussed in Function 5.9 – unprocessed data are processed by algorithms to detect MILEC, and MILEC data are manually processed to identify MILCOs to be sent to

neutralizers. The primary impact of enabling communication is that information about the minefield is gained piecewise throughout the mission, rather than all at once at the end of the mission, as is the case with physical transfer of data. This piecewise battlespace awareness may enable earlier processing of data for MILCOs and/or MILECs and significantly reduce the overall time required to fully evaluate and clear a potential minefield.

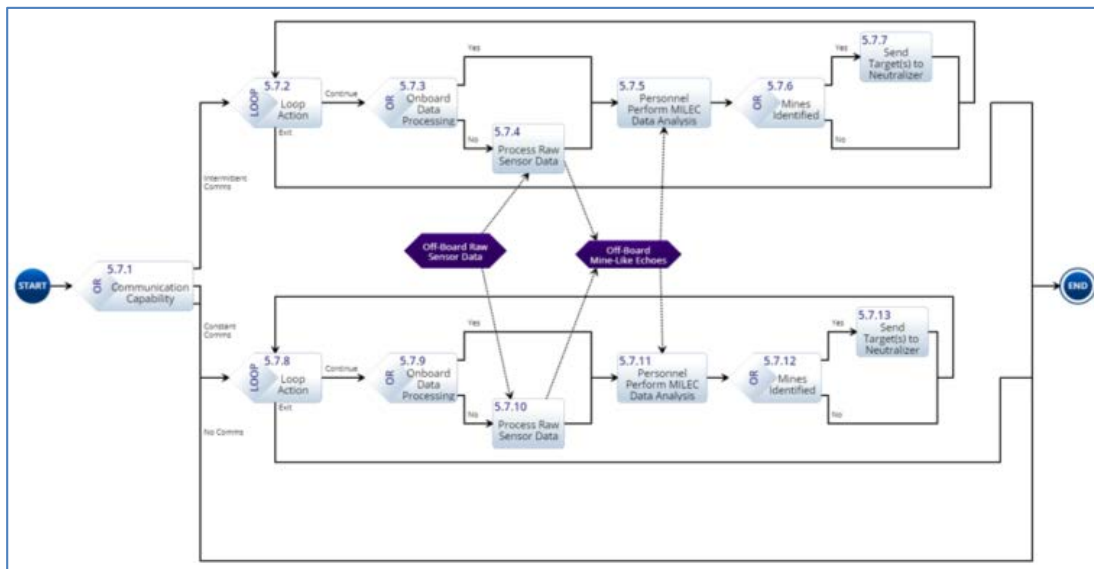


Figure 15. 5.7 Analyze Data - Communications Present During Mission

The construction of a functional architecture in Innoslate allowed for a basic simulation of operations to ensure that the modeled functions are logically consistent. Appendix C provides modeling results from the six alternatives using notional performance inputs and the Innoslate simulation tool. A logically consistent functional architecture acts as a foundation for the remaining capstone tasks of building an operational simulation, and identifying the ideal alternative and the design parameters that have the largest impact on system performance. Chapter III Section C uses the proposed system architectures to identify the design parameters which impact system performance, and proposes simulation boundaries for these parameters. Chapter IV

describes the modeling process in ExtendSim, which simulates a more realistic and representative operating environment based upon the described architectures.

D. DESIGN PARAMETER SELECTION

The functional flow block diagrams in Sections A and B were developed to demonstrate the functional flow and logical consistency of the proposed operations but do not represent the operational environment or required activities or define the system parameters with enough detail to assess the performance of the six proposed alternative architectures. There are a large number of system characteristics that impact the performance of a UUV that were not specified by system architectures. For example, the functional architecture specifies that the UUV must traverse to and from the minefield but does not provide information regarding the speed at which the UUV should be able to move or enumerate the distance from the minefield to the location of launch and recovery operations. These specific parameters would be aspects of the physical design of the system selected in such a way to optimize the performance of the design with respect to specific measures of the effectiveness of the overall system. In order to simulate operations and analyze the performance of the proposed architectures, further information was required. In this capstone project, aspects of the simulated environment were represented as variables. These simulation variables were selected to represent design parameters which virtually instantiated the desired system characteristics in order to determine and assess the ways in which the proposed UUV performs the functions identified in the functional architecture. The simulation of the design parameters allowed for controllable system characteristics that impacted the length of time required to perform each function, the likelihood of a function being performed, or the frequency of performing a function. These simulated design parameters, combined with the framework provided by the functional architecture, enable the development of an operational simulation.

We categorized the functions performed in the system architecture into four groups based upon the most closely related primary function: locomotion, data collection, communication, and data processing. This categorization assisted with the identification of design parameters and eliminated duplication of inputs. The system design parameters that influenced the time to complete each function are listed in Table 3.

Table 3. System simulation design parameters

Design Parameter		Description
Locomotion	Launch Time	The amount of time necessary to launch the UUV into the water from parent vessel
	Endurance	The amount of time the UUV can operate in the water before its energy needs to be replenished
	Speed	The propulsion speed of the UUV
	Track Buffer	The additional length of track necessary for the UUV to turn to the next track.
	Surface Time	Time taken for UUV to rise to surface from mine hunting depth
	Dive Time	Time taken for UUV to dive to mine hunting depth from surface
	Recovery Time	Time needed to remove the UUV from the water to the parent vessel
	Replenish Time	The amount of time necessary to replenish the energy of the UUV before it can be relaunched
Data Collection	Sensor Range	The width of the UUV's sonar swath. Will influence how many tracks are necessary based upon twice the size of the sensor range and the search area width
	Data Collection Rate	The rate at which the UUV sensors collect data while searching
	Maximum Scan Speed	The maximum movement speed at which the UUV can move while searching
Communication	Surface Data Transfer Rate	The rate at which the UUV can transmit data while on the surface of the water
	Sub-Surface Data Transfer Rate	The rate at which the UUV can transmit data while under the water with acoustic communications
	Manual Download Rate	The rate at which the UUV can physically transfer data to the PMA subsystem while it is docked on the parent vessel
Data Processing	RTA Rate	The rate at which the UUV can process raw sensor data and recognize MILEC while performing its mission
	Off board Raw Sensor Analysis Rate	The rate at which off board analysis can process raw sensor data and recognize MILEC
	MILCO Analysis Rate	The rate at which MILEC data can be analyzed and MILCO identified
	MILCO Data Buffer	The amount of data before and after a detected MILEC that is transferred to host vessel.

The identified design parameters and the functional architecture are not the sole determinants of system performance or operational simulation results. Operational characteristics, either real or simulated, also have the potential to impact system performance. While exhaustive literature exists regarding the impact of the environment on locomotion, data collection, and communication, the scope of this capstone limits the environmental inputs of interest to the length and width of the search area.

The simulations described in Chapter IV provides the level of detail to represent and assess UUV performance, and the simulation output was analyzed to determine the relationships between design parameters and system operational performance. Because the functional architecture provides only a framework for the actions within the operational simulation, values for the length of time required to perform each function within an operational simulation demand supporting inputs which drive system performance. Chapter IV defines the variables included in the simulation, while Chapter V analyzes the impact of changes to these design parameters on system performance.

Prior to running the operational simulation, we identified initial values for each of the design parameters based upon existing UUVs. We selected bounding high and low values for each design parameter, representing the potential for improvement or degradation in specific system characteristics and enabling an assessment of the impact of changes to a given design parameter. The list of parameters are detailed in Table 4. The initial values are based upon best estimates for current UUV performance from publicly available data. Upper bound values were based upon best in class related commercial capabilities, and lower bound values were set to establish an equal difference from the related initial value. For design parameters where the difference between current USN UUV capabilities and commercial best in class capability is an order of magnitude, lower bounds were set an order of magnitude below the initial value. When USN and commercial best in class capabilities were of a similar magnitude, lower bound values were set so that the initial value is the midpoint between the high and low boundaries. If

existing military UUVs did not detail a parameter, for example underwater communications, then parameter ranges for commercial acoustic modems were used.

Table 4. Design Parameter Values

	Design Parameter	Units	Initial Value	Low	High
Locomotion	Launch Time	Minutes	30	15	45
	UUV Endurance	Hours	20	10	40
	UUV Speed	Knots	5	1	10
	Surface Time	Minutes	5	2.5	10
	Recovery Time	Minutes	30	15	45
	Replenish Time	Hours	6	3	9
	Transit Time	Hours	2	0	4
Data Collection	Sensor Width	Kilometers (KM)	0.1	0.005	0.2
	Data Collection Rate	Megabits (Mb) per second (Mbps)	100	10	200
Communication	Surface Data Transfer Rate	Mbps	10	1	25
	Sub-Surface Data Transfer Rate	Kbps	14	5	35
	Manual Download Rate	Mbps	500	50	5000
	IC Data Limit	Mb	250,000	100,000	500,000
Data Processing	RTA Rate	Mbps	50	10	200
	PMA Rate	Mbps	50	10	100
	Data Reduction Rate	Ratio	0.5	0.1	0.95
Environmental Parameters	Search Area Width	Kilometers (KM)	10	5	20
	Search Area Length	Kilometers (KM)	10	5	20

To assess the impact of changes to these design parameters, the operational simulation described in Chapter IV was run repeatedly using a range of inputs for each design parameter, and for each alternative architecture. Chapter V reports on the results of these simulated runs and analyzes outputs using a design of experiments (DOE) methodology. Chapter VI provides recommendations for the next generation of MCM

UUVs with regards to the efficacy of the six alternative architectures, as well as the impact of improvements to each design parameter of interest.

IV. SIMULATION OF MCM UUV OPERATIONS

Chapter III detailed the approach taken to simulate UUV operations, including assumptions made in order to simplify the simulation design, simulation inputs, simulation structure, and the outputs of the simulation. The functional architecture and design parameters in Chapter III defined the process and impact of system design parameters on a UUV performing the mine hunting mission. The functional architectures and design parameters offered limited insights into system performance. We developed the operational simulation to represent MCM UUV operations and generated predicted operational outcomes based upon design parameters and environmental conditions provided as inputs.

Figure 16 shows the relationship between the area of interest and the simulation environment developed to model it. Design parameters and environmental conditions are represented by simulation variables. The functional architecture and composing functions are represented by events in a discrete-event simulation. The outputs from the discrete-event simulation can be analyzed to generate predictions of MCM UUV performance of the Detect and Classify mission.

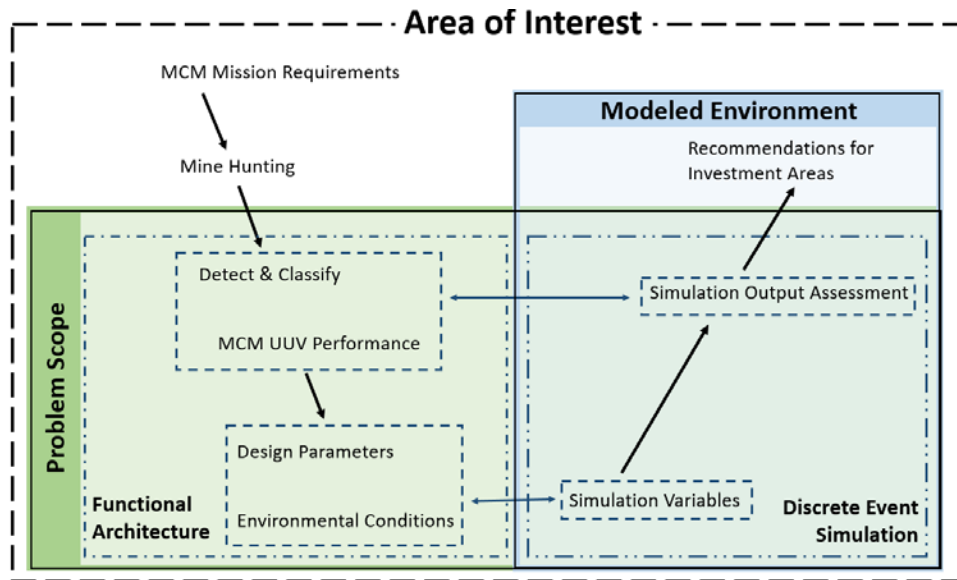


Figure 16. Simulating the Area of Interest

A. DETERMINING LEVEL OF DETAIL IN OPERATIONAL SIMULATION

We established a set of constraints and assumptions to place reasonable bounds for the level of detail in the model and configurations based on the results of initial capstone research. These constraints include the level of detail captured in the operational simulation. Figure 17 represents a typical DOD modeling pyramid that illustrates the four levels where a model can exist. At the bottom of the pyramid, the physics level, models created focus on material performance, the physics behind the subsystems, and answer the question “Is this system feasible?” Moving up a level in the pyramid to the engagement level, the models focus on weapon or sensor performance, single engagements, and answer the question “Will this system perform?” The next level in the pyramid, the mission level, the models focus on system performance, are mission based, and answer the question “Will this system be effective?” At the top of the pyramid, the campaign level, the models deal with mission capabilities, have a theatre perspective, and answer the question “Will this system achieve operational objectives?” In the DOD modeling and simulation pyramid, the results of models are aggregated and passed up the

pyramid, not the models themselves. This information apprised the establishment of the capstone project’s modeling assumptions and level of detail.

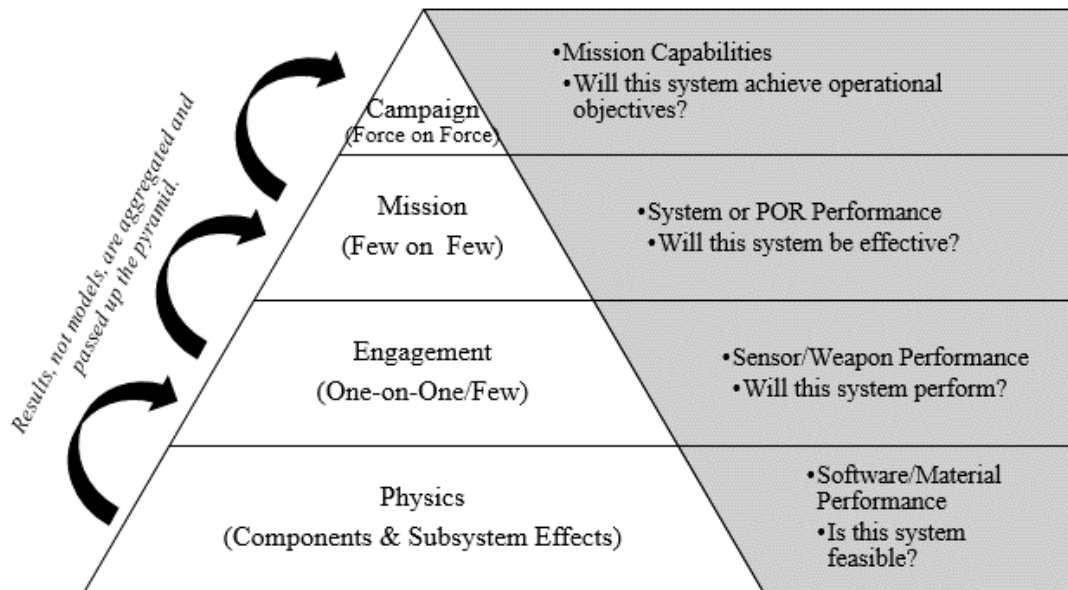


Figure 17. DOD Modeling and Simulation Pyramid. Source Tatum (2014).

This capstone project’s research was developed with the intention to fall within the engagement level of the modeling pyramid. There was an additional constraint on the scope from our focus on a portion of the MCM mission – the role of an MCM UUV – rather than the entire MCM mission. The current MCM mission leverages airborne, surface, and sub-surface vehicles in operations. Bounding our research to strictly unmanned underwater vehicles allowed the capstone project to collect and filter the level of detail gathered from resources to approach a problem with both a feasible scope and a useful level of definition. Parameters typically found at the mission level were excluded from our simulations, for example percent clearance and number of UUVs. Similarly, the capstone project did not consider water characteristics or quality of sensors, because those types of variables would fall lower in the pyramid, at the physics level.

B. SIMULATION DEVELOPMENT

The team followed an iterative and incremental process to develop the operational simulation. The functional flow block diagrams created within Innoslate were leveraged for the creation of a single simulation in ExtendSim that represent the six architectures identified. ExtendSim is a simulation program which can represent multiple processes in its modeling. ExtendSim uses unique blocks from a library that can be connected to represent the architecture of a model and simulated based upon different customizable input and output variables. At first, the use of multiple models to represent the six architectures was considered. However, the overlap between models may have led to errors when assumptions or approaches changed. As a result, a single operational simulation model was developed.

To represent the design parameters and environmental alternatives identified in Chapter III, an input and output database was created for use in ExtendSim. The database facilitated simulating operations with changes to design parameters, and captured model outputs from each simulated scenario. With the database established, the Post-Mission Analysis model (Alternative 1) was selected as the initial scenario to have its functional architecture represented in the operational simulation. The status quo represents the current mine hunting architecture, and was best understood by the simulation development team, who found that the model naturally lent itself as a starting point for simulation development and verification.

With the first architecture alternative tested and functioning, the model was modified to allow for the simulation of constant communications and intermittent communications when data processing was handled off-board. As the final step, the on-board data processing capability was incorporated into the simulation. By mixing and matching these capabilities, the remaining five alternative architectures were effectively developed. Sample parameters inputs were used and the model verified for functionality for all six architecture alternatives.

Using the selected input variables, the initial output parameters were analyzed. After no abnormalities were seen with all the output parameters, the design of experiment DOE process, explained in Chapter V commenced. A DOE utilizing all the input parameters to be varied was created in Minitab, resulting in a matrix of input parameters to be fed into the ExtendSim input database. Minitab is a statistical software package which was used to provide all the calculations for the input parameters based upon the range of possible values presented in the model. This DOE process is explained in depth in Chapter V. The model was then run for each identified scenario, with the complete database of inputs and outputs captured for analysis. The methods and results of this analysis are detailed in Chapter VI.

C. REPRESENTATION OF FUNCTIONAL ARCHITECTURE IN THE OPERATIONAL SIMULATION

This section describes the connection between the Innoslate functional flow block diagrams and the ExtendSim operational simulation. During the development of the simulation in ExtendSim the plan to mirror the functional architecture in Innoslate could not be followed exactly. The deviation from the plan was due to the limitations presented by the tools used to develop the flow block diagrams and the simulation. This deviation resulted in ExtendSim representing the diagrams differently in structure and order, but the same in overall functions completed. Although different, the simulation included the major components of the functional flow block diagrams and represented all six configurations of architecture in a single simulation, with a higher level of fidelity within the outputs.

As mentioned at the start of this chapter, the design parameters and the environmental conditions of the functional architecture were captured within the simulation variables of the discrete event simulation. Appendix A provides two examples of how a functional flow block diagram function dealing with choosing specific design parameters (location of data processing and communication types) was implemented within the discrete event simulation as simulation variables. These examples show not

only the differences between the functional diagrams and the simulation, but the similarity of both accomplishing the common goal of the selected function. Ultimately, the simulation results in quantitative outputs that can be analyzed to describe the performance of the MCM UUV functional architecture as described within the functional flow block diagrams.

D. MODEL OVERVIEW

This presents a review of the simulation highlighting the major functions of each hierarchy block as shown in Figure 18.

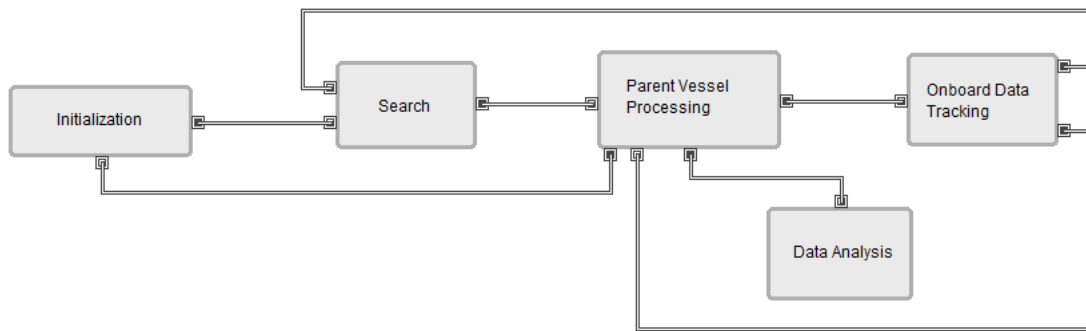


Figure 18. Top-level Simulation Diagram

The six system alternatives represented by the functional architecture were combined into a single model using a simulation program called ExtendSim. A list of these alternatives can be seen in Chapter III, Table 2. The team chose a discrete-event simulation to model the operational simulation of the UUV. The simulation follows a single item, the UUV, through the simulation while tracking the time it takes to move through each activity. As a discrete-event simulation, the time between the activities can be considered to be zero and the only time that will be added to the mission will be that of each activity the UUV performs. Time is the major output of the simulation tracking both the time the UUV spent searching for MILCOs and the time the PMA team spent analyzing the data collected. The simulation (and UUV mission) will only be considered

complete once the UUV has completed searching all its required tracks, as well as the PMA team completing its analysis.

The first hierarchical block in the simulation is Initialization. This block starts with the creation of the UUV “item” which is what the program tracks throughout the simulation. The UUV then reads in the input parameters from the database and converts these parameters into “attributes” which assign the database values to the UUV item for the remainder of the simulation. The values of the input parameters were created from a DOE that will be discussed further in the next section of this paper. The specific UUV alternative is assigned during this step. A full list of the database parameters and mapped attributes can be seen in Appendix A. The block then continues initializing the mission by creating and assigning additional variables that need to be used for future calculations. Once these initial calculations are complete, the rest of the block is used to track the time it takes for the UUV to leave the staging base and prepare for its search. After the UUV has completed a sortie, it will return to the initialization block to reset some of its parameters and track the time to retrieve, replenish, and return to the mission area.

Leaving the Initialization block, the UUV enters the Search hierarchy block which handles the majority of the detection mission performed by the UUV. This block represents a single segment of the track run by the UUV. The tracks can be split into specified sized segments so data can be tracked at multiple points along each UUV track. This gives a more flexible output which will help draw a more dynamic conclusion when comparing each alternative. The Search block calculates how many segments the UUV has completed during this sortie and its current position inside the search area which it uses to know when the UUV should turn or how long it will take to return to the staging base. Using this information, the Search block checks if the UUV can continue to search based on its current endurance level and passes this information to the next block, Parent Vessel Processing.

The Parent Vessel Processing block is the next step for the UUV and contains the data calculations based on the UUV’s specific alternative during the sortie. The equation

blocks consume input parameters of the specific mission and the mission times calculated from the Search block to compute most of the data manipulation including data collected, processed, and transmitted with the associated time it took to complete these tasks. Depending on the UUV alternative, terrestrial transmission time or acoustic transmission time will be utilized to transmit some of the processed data to perform PMA in parallel with the mission before the UUV returns to the staging base. These calculations are then sent to the Onboard Data Tracking block where they can be used to finalize the times necessary to transfer and process the remaining data on the UUV. Once the UUV no longer has endurance to continue the sortie, it will take a different path through this block which will add the processing and transfer times performed on the staging vessel to the total mission time using the data collected from each segment. If there are still tracks to be completed in the mission, the UUV will return to the Initialization block to replenish and continue its mission. If all the tracks have been completed by the UUV, this block will route the UUV to the Data Analysis block to finalize any remaining calculations and complete the mission

The UUV moves into the Onboard Data Tracking hierarchy block to complete any data processing and transfer calculations that happen on the UUV itself. If the UUV alternative is using intermittent communications, this is the block that will track the time taken to surface, transmit data, and dive back down to continue the mission. Depending on the UUV alternative, all or some of unprocessed and unanalyzed data may remain on the UUV. The UUV will then be routed to perform another search segment of its sortie. If the endurance of the UUV, calculated in the previous Search block, is not enough to continue the mission, it will be routed through the Parent Vessel Processing block to finalize sortie calculations. This block will also add the logistic times of transiting and retrieving the UUV back at the staging base and add these times to the mission.

The final block of the simulation is the Data Analysis hierarchy block. This block collects the final sortie and mission times completed by the UUV and combines them into total sortie time, total PMA time, and total mission time. This data is then written to the output database for each run of the UUV for export and analysis. The data collected at

this block and throughout the simulation will be used to analyze the benefits of each UUV alternative. The variable inputs created by the DOE should give a dynamic view of the advantages and disadvantages of each alternative given multiple mission and UUV parameters.

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V. ASSESSING SIMULATED OPERATIONAL PERFORMANCE

We provide a ranking of the most impactful design parameters for system performance and make suggestions regarding the direction of investments related to improving MCM UUV performance. DOE was used to determine the impact of changes to design parameters. The results of the discrete event simulation were generated for a wide range of design parameters to support analysis to determine that the operational model accurately represents the expected performance for various system architectures and to generate results that can be used to assess the impact of changes to design parameters on the effectiveness of UUVs.

The proposed system alternatives are all modeled and compared in Section C of this chapter using the same design parameters across all proposed architectures. The results are used to provide recommendations regarding future MCM UUV architecture planning given current technology and the likely state of technological development over the next decade. Section C of this chapter looks at each system architecture and determines the alternative-specific impact on performance associated with changes to each design parameter. DOE was used to measure the impact of changes to individual design parameters, and enabled the identification of significant interactions between design parameter impacts on operational performance. Section D combines and communicates the impact of each design parameter across all proposed system architectures, focusing on trends and inconsistencies between system architectures. Section E offers suggestions regarding investment decisions for increased system performance through investments in individual design parameters.

A. SIMULATION RESULTS FOR PROPOSED SYSTEM ARCHITECTURES

The results of the simulation we created for this analysis are communicated as a measured time to complete, as well as a timeline of the status of data collection, transmission, and processing. This timeline, while difficult to communicate in raw form, lends itself well to visualization, and serves as a tool to explain the relationships between

design parameters and system performance. The following six figures provide a short description of the data outputs of the simulation for each alternative, performing the “detect and classify” mission in a 10km x 10km minefield.

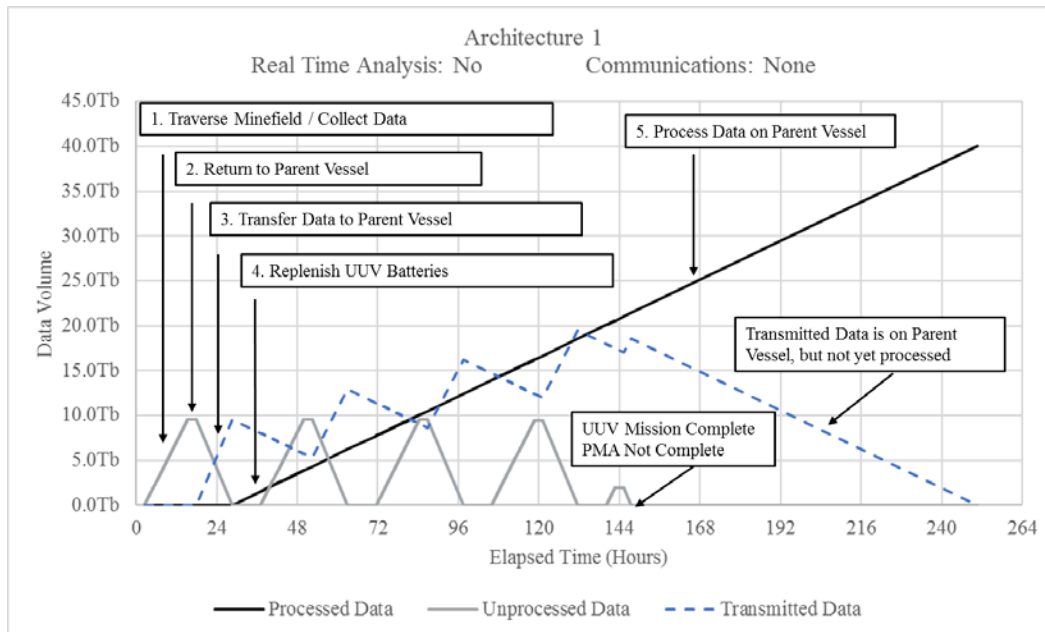


Figure 19. Simulation Output – Alternative 1

Figure 19 shows the progression of data collection and processing throughout a mission performed by a MCM UUV that does not have the capability to perform RTA or communicate data with a parent vessel. The lines represent data in its distinct forms throughout the mission, aligning to the data transformation process explained in Chapter III. The UUV scans the environment and collects raw sensor data (action 1) until the UUV batteries reach an identified level, at which point it returns to the parent vessel (action 2) and transfers data (action 3) through a manual connection to the parent vessel. Upon completion of the data transfer, the energy stores on the UUV are replenished (action 4). As data is transferred from the UUV to the parent vessel, it is transformed from Unprocessed Data to Transmitted Data, data that is on the parent vessel, but not processed. This data is then transformed to Processed Data through the PMA process of

the parent vessel, which occurs in parallel with UUV operations as long as the parent vessel has a cache of Unprocessed Data. The UUV repeats actions 1–4 until the entire minefield has been scanned, and the parent vessel continues to process Transmitted Data until all data from the minefield has been processed.

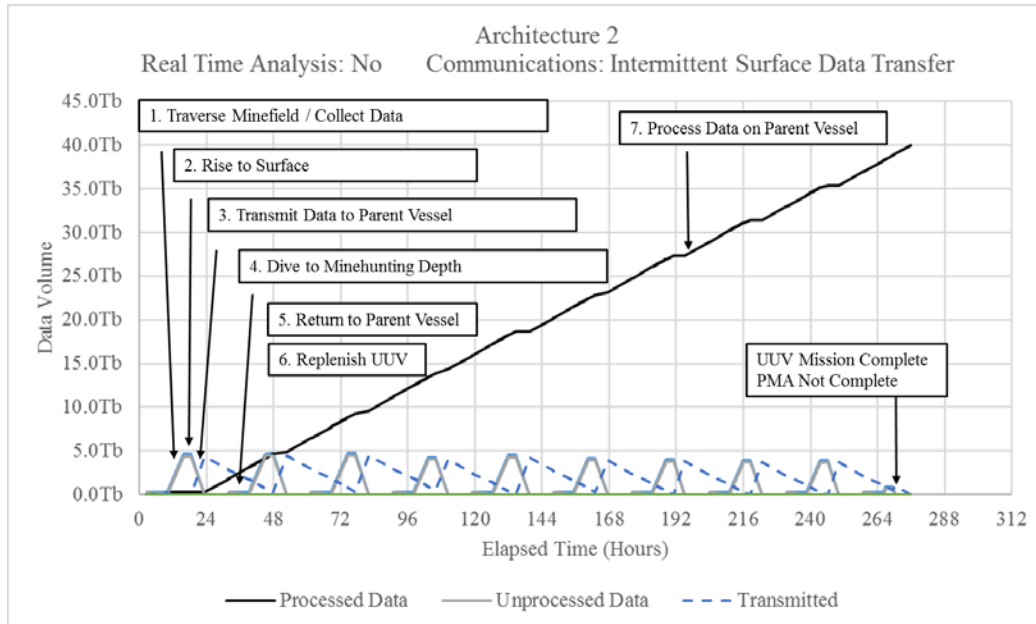


Figure 20. Simulation Results – Alternative 2

Figure 20 shows the progression of data collection and processing throughout a mission performed by a MCM UUV that does not have the capability to perform RTA, but communicates data with a parent vessel through surface level data transfer. The UUV scans the environment and collects raw sensor data (action 1) until the UUV data stores reach an identified level, at which point the UUV rises to the surface (action 2), transmits data (action 3) and returns to mine hunting depth (action 4). The UUV repeats this process until batteries reach an identified level, at which point it returns to the parent vessel and transfers remaining data (action 5) through a manual connection to the parent vessel. Upon completion of the data transfer, the energy stores on the UUV are replenished (action 6). Transmitted Data is transformed to Processed Data through the

PMA process of the parent vessel, which occurs in parallel with UUV operations as long as the parent vessel has a cache of Unprocessed Data. The intermittent communications reduces the time elapsed between initial UUV launch and the start of the PMA process. The UUV repeats actions 1–6 until the entire minefield has been scanned, and the parent vessel continues to process Transmitted Data until all data from the minefield has been processed.

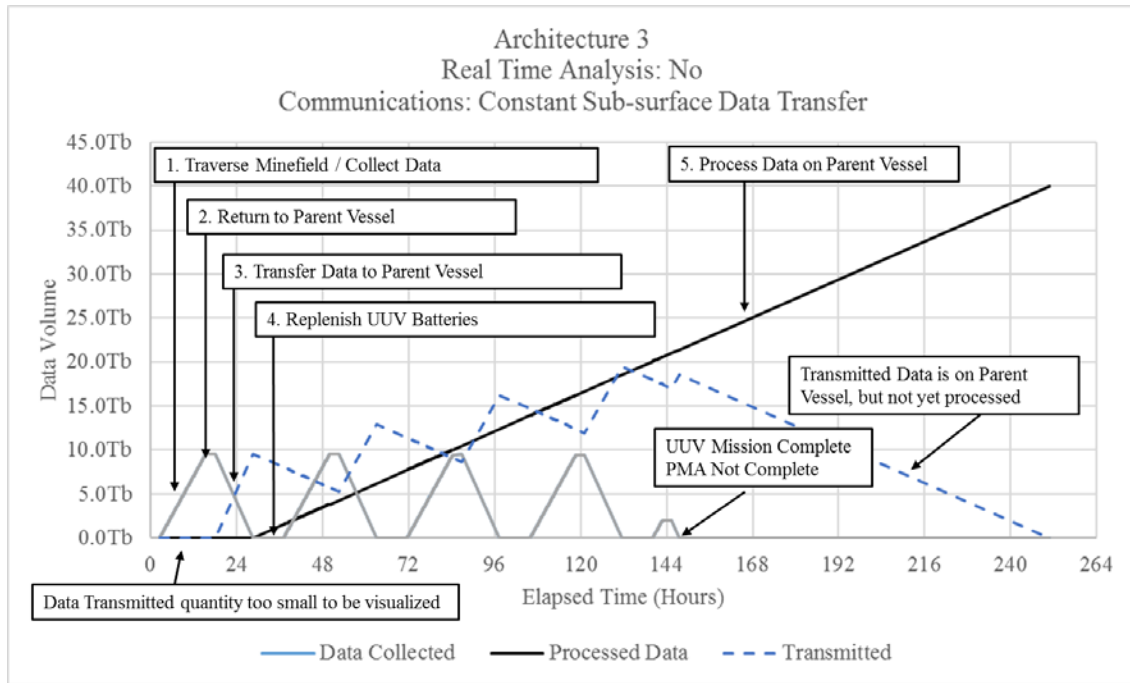


Figure 21. Simulation Results – Alternative 3

Figure 21 shows the progression of data collection and processing throughout a mission performed by a MCM UUV that does not have the capability to perform RTA, but communicates data with a parent vessel through constant sub-surface level data transfer. The UUV scans the environment and collects raw sensor data (action 1) until the UUV batteries reach an identified level, at which point it returns to the parent vessel (action 2) and transfers data (action 3) through a manual connection to the parent vessel.

At all times the UUV has collected data onboard and is not transferring it manually to the parent vessel, constant communications enable transmission of data through an acoustic modem. The bandwidth used in this simulation is so low that the amount of data transmitted while the UUV is in the minefield is not visible on the chart above. Upon completion of the data transfer, the energy stores on the UUV are replenished (action 4). Data transmitted through either constant communications or manual transfer is transformed to Processed Data through the PMA process of the parent vessel, which occurs in parallel with UUV operations as long as the parent vessel has a cache of Unprocessed Data. The UUV repeats actions 1–4 until the entire minefield has been scanned, and the parent vessel continues to process Transmitted Data until all data from the minefield has been processed. The slow rate of data transfer possible through constant communications leads to very little impact of adding the capability to constantly transfer data.

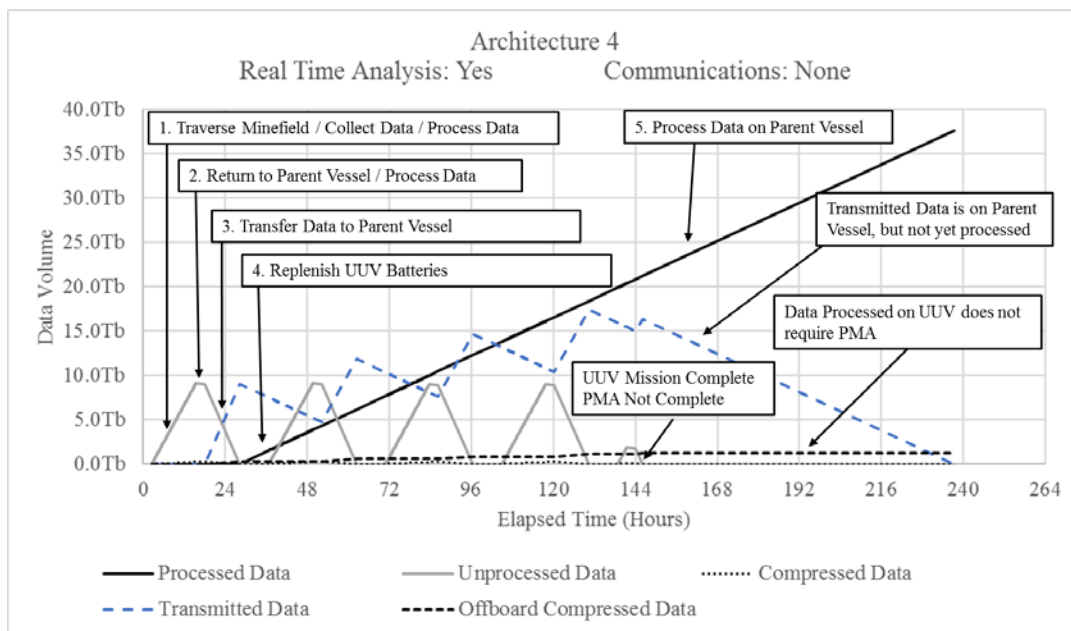


Figure 22. Simulation Outputs – Alternative 4

Figure 22 shows the progression of data collection and processing throughout a mission performed by a MCM UUV that has the capability to perform RTA, no ability to

communicate data with a parent vessel from within the minefield. The UUV scans the environment and collects raw sensor data, while processing data it has collected (action 1), until the UUV batteries reach an identified level, at which point it returns to the parent vessel (action 2) and transfers data (action 3) through a manual connection to the parent vessel. Upon completion of the data transfer, the energy stores on the UUV are replenished (action 4). Unprocessed Data transmitted through the manual transfer is transformed to Processed Data through the PMA process of the parent vessel, which occurs in parallel with UUV operations as long as the parent vessel has a cache of Unprocessed Data. Data that has been processed by the UUV during operations is shown as Compressed Data, due to the fact that this data is reduced aside from areas with expected MILECs. After Compressed Data is transferred to the parent vessel, the chart shows this data as Offboard Compressed Data, which does not require PMA processing. The UUV repeats actions 1–4 until the entire minefield has been scanned, and the parent vessel continues to process Transmitted Data until all data from the minefield has been processed. By processing a portion of the collected data onboard the UUV, the amount of time dedicated to PMA after the UUV has completed scanning the entire minefield is reduced.

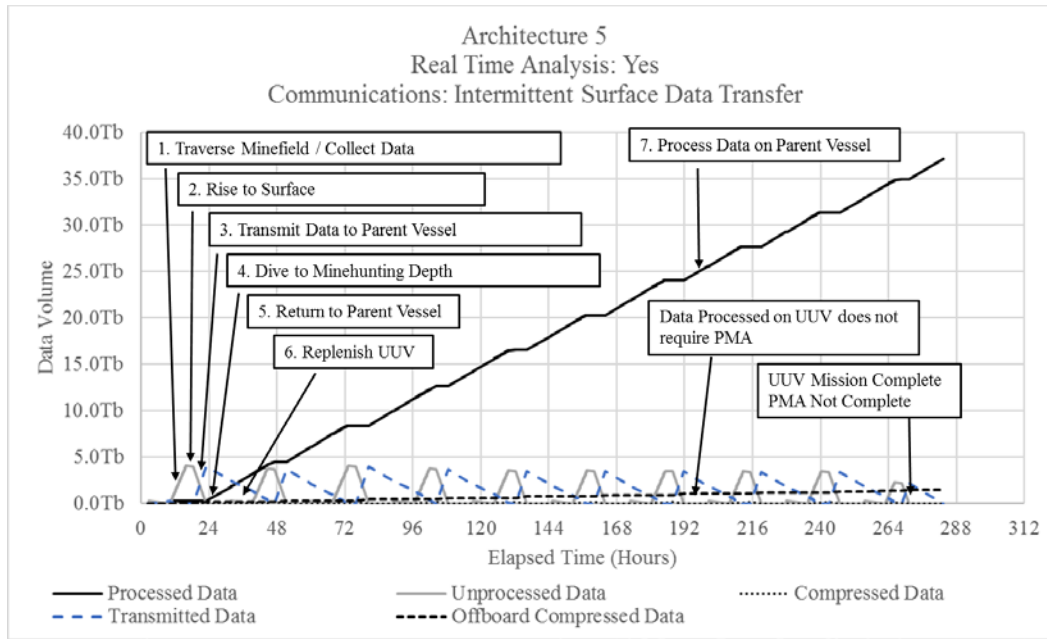


Figure 23. Simulation Outputs – Alternative 5

Figure 23 shows the progression of data collection and processing throughout a mission performed by a MCM UUV that has the capability to perform RTA, and communicates data with a parent vessel through surface level data transfer. The UUV scans the environment and collects raw sensor data (action 1) until the UUV data stores reach an identified level, at which point the UUV rises to the surface (action 2), transmits data (action 3) and returns to mine hunting depth (action 4). While not transmitting data, the UUV processes raw sensor data through a similar, but slower, process to that performed during PMA. The UUV repeats the scan and transmit process until batteries reach an identified level, at which point it returns to the parent vessel and transfers remaining data (action 5) through a manual connection to the parent vessel. Upon completion of the data transfer, the energy stores on the UUV are replenished (action 6). Transmitted Data is transformed to Processed Data through the PMA process of the parent vessel, which occurs in parallel with UUV operations as long as the parent vessel has a cache of Unprocessed Data. The time elapsed between initial UUV launch and the start of the PMA process is reduced with Intermittent communications, and enables

processed data to be transferred to the parent vessel during the operation. The UUV repeats actions 1–6 until the entire minefield has been scanned, and the parent vessel continues to process Transmitted Data until all data from the minefield has been processed. RTA allows the UUV to scan a larger portion of the minefield before reaching the intermittent communications data limit.

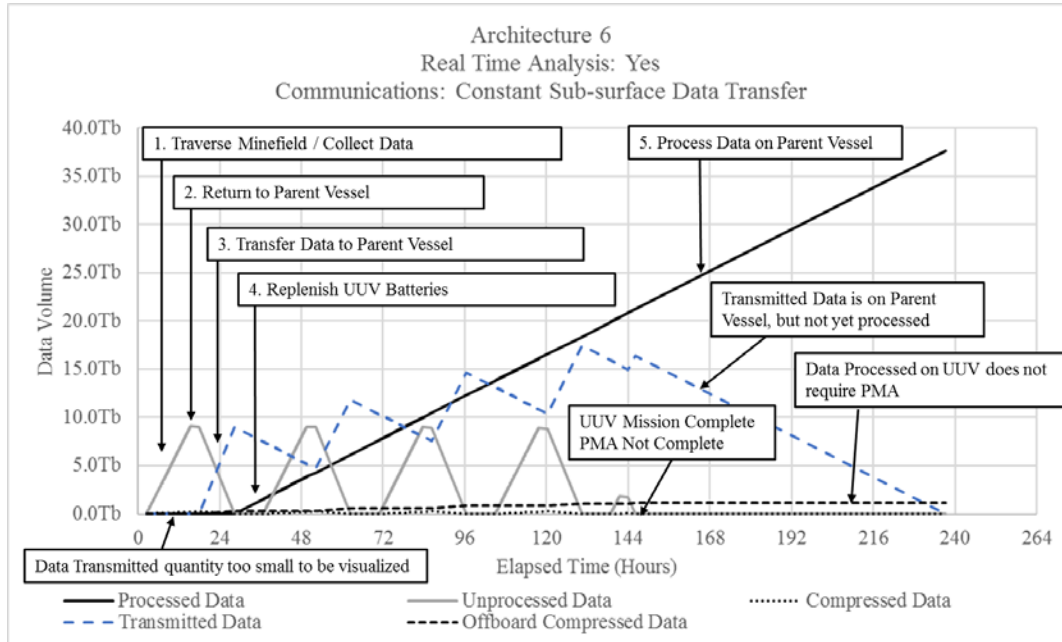


Figure 24. Simulation Outputs – Alternative 6

Figure 24 shows the progression of data collection and processing throughout a mission performed by a MCM UUV that has the capability to perform RTA, but communicates data with a parent vessel through constant sub-surface level data transfer. The UUV scans the environment and collects raw sensor data (action 1) until the UUV batteries reach an identified level, at which point it returns to the parent vessel (action 2) and transfers data (action 3) through a manual connection to the parent vessel. At all times the UUV has collected data onboard and is not transferring it manually to the parent vessel, the UUV processes data through onboard RTA, while constant communications enable transmission of data through an acoustic modem. The bandwidth

used in this simulation is so low that the amount of data transmitted while the UUV is in the minefield is not visible on the chart above. Upon completion of the manual data transfer, the energy stores on the UUV are replenished (action 4). Unprocessed data transmitted through either constant communications or manual transfer is transformed to Processed Data through the PMA process of the parent vessel, which occurs in parallel with UUV operations as long as the parent vessel has a cache of Unprocessed Data. The UUV repeats actions 1–4 until the entire minefield has been scanned, and the parent vessel continues to process Transmitted Data until all data from the minefield has been processed. The slow rate of data transfer possible through constant communications leads to very little impact of adding the capability to constantly transfer data.

While the visualizations above allow for the details of the proposed concepts of operation to be communicated, they do not aid in assessing which alternatives are preferable. To aid in this effort, one or more performance metrics is needed. Area Coverage Rate Sustained (ACRS) is a performance metric, generally paired with a confidence level that is used to measure the area that a MCM unit can clear of mines in a given period of time with a certain level of certainty. ACRS as a performance metric is ideal for a mine hunting SoS, but measures operational performance at too high of a level to assess the performance of the MCM UUV that is the focus of this capstone project. To isolate the performance metrics to the portion of the MCM mission that is performed by the MCM UUV of interest, our assessment is based on the time at which the UUV can complete its portion of the mine hunting mission – detecting and classifying mines. Viewing the UUV mission as a battlespace awareness problem, we can measure operational performance in two ways: the time to detect and classify mines for an entire minefield and the time at which neutralization systems can begin their mission. As a system within a SoS, the MCM UUV provides value to warfighters as soon as data is processed for a portion of the target minefield. Though measuring these outputs does not represent the end-to-end mission of mine hunting, it captures the portion of the mine hunting mission that is directly impacted by the MCM UUV.

Unfortunately, measuring the time to detect mines and time to determine an area is clear of mines is not a straight forward task due to the complexity of the process involved. The value of the MCM UUV system is not based upon a single mine or small area, but instead upon clearing minefields of various sizes with various environmental characteristics. A single operational concept or system architecture may experience superior performance under some mission conditions and objects and degraded performance under others. The flexibility of the operational simulation described in Chapter IV allowed our team to model performance in a limited range of environmental conditions. In order to assess performance using our DOE, we identified a pair of metrics to represent system performance for a given environment. To best capture the operational value of the proposed UUV architectures, we identified that the elapsed time between mission start and all minefield data processed and the average elapsed time between mission start and data being scanned and processed for each square meter of the minefield were the two metrics by which UUV performance can be assessed, shown in Table 5, and three minefield sizes across which the alternatives would have their simulated performance compared, shown in Table 6.

Table 5. Assessment Metrics

Metric	Description	Units
Time to Complete	Elapsed time between mission start and all minefield data processed	Hours
Average Time to Process	The average elapsed time between mission start and data being scanned and processed for each square meter of the minefield	Hours

Table 6. Assessment Environments

Minefield Environment	Minefield Size (km x km)
1	1 x 10
2	5 x 5
3	10 x 10

B. PERFORMANCE COMPARISON OF ARCHITECTURE ALTERNATIVES

The intent of modifying the methods of operation through the proposed architectures and the proposed changes with respect to data analysis and transfer is to reduce the overall timeline of the MCM's detect and classify capabilities. The concept of operations employed by existing MCM UUVs (modeled in Alternative 1) has a UUV transit to a suspected minefield from a parent vessel, collect data using sensors while traversing the target location, and then return to a host platform where the data is offloaded for further analysis. In Alternatives 2 through 6, there is either communication from the UUV to the host platform during the collection of the data (Alternatives 2, 3, 5, and 6) or analysis occurring onboard the UUV during the collection of the data (Alternatives 4 through 6). The goal of both the data analysis and transfer is to decrease the delay between sensor collection of data and when that data is both converted to a usable form (the identification of MILECs) and in the hands of the individuals making decisions regarding target neutralization. The value of the detect and classify mission performed by the MCM UUV is found in increasing the knowledge of the suspected minefield such that follow-on assets can be deployed to confirm the identities of any suspected mines and then neutralize those mines as necessary. By reducing the period of time elapsed between when a portion of the minefield is scanned and when the resulting data is passed to the neutralization system, the total time to clear a minefield is reduced, and the likelihood that a suspected floating mine has moved, and will require a difficult reacquisition.

To understand and communicate the benefits offered by adding communication or onboard processing to the MCM UUV, we modeled each alternative using a set of initial design parameter inputs, as defined in Chapter III, Section C. These design parameter values were selected to represent a feasible level of performance based on existing technology within the USN portfolio. Comparing the six alternatives provides a baseline value across which performance can be compared and allows for visualizations to communicate the impact that changes in concepts of operation have on mission outputs.

Table 7 provides the time to complete the “detect and classify” mission for each of the six alternatives across three minefields with different characteristics.

Table 7. Time to Complete (hours) by Minefield Size and System Architecture

Minefield Size (km x km)	Data Processing Capability	Communication Capability		
		NC	IC	CC
1x10	No RTA	37.1	43.5	37.1
	RTA	35.3	41.7	35.3
5 x 5	No RTA	85.2	82.5	85.2
	RTA	81.6	80.5	81.6
10 x 10	No RTA	250.8	340.4	250.8
	RTA	237.2	348.0	237.2

The advantages of onboard data analysis and communications options change depending upon the layout and size of the suspected minefield. For smaller minefields, such as 1km x 10km, systems operating with our initial design parameter inputs that leverage constant communications are able to transmit a very small amount of data during the time it takes to complete the mission, making the operational benefit of communications very small. Architectures 3 and 6 send a relatively small amount of data back throughout their scanning routes, with the amount of data transmitted limited by bandwidth capabilities of underwater communications. Current underwater communication technology is limited to kilobits per second compared to the megabits per second offered by surface level communications or hundreds of megabits per second offered through physical data transfer. In Figure 25, the amount of data transmitted by the end of the scanning mission is so insignificant that it could be processed in under a minute if had not been transmitted, reducing overall mission time by a negligible amount. The current bandwidth of underwater communications limits the value of constant communications to the point of irrelevance.

UUVs utilizing IC offers a solution that returns a sizeable portion of data to the parent vessel while the UUV is still in the minefield. Figure 25 shows a rise in processed

data at 12 hours for both Alternative 2 and Alternative 5, nearly three hours before Alternatives 4 or 6 transfer data processed onboard to the parent vessel. Depending on the neutralization system selected, this performance characteristic of an early delivery of initial data may drive superior system of system performance by allowing neutralization systems to begin their tasking earlier in the mission. However, the elapsed time associated with breaching, transmitting, and returning to scanning depth add a delay to the scanning process for architectures with intermittent communications. This additional elapsed time in the minefield increases the total time to complete the “detect and classify” mission in a 1 km x 10 km minefield, in spite of the superior performance through hour fifteen.

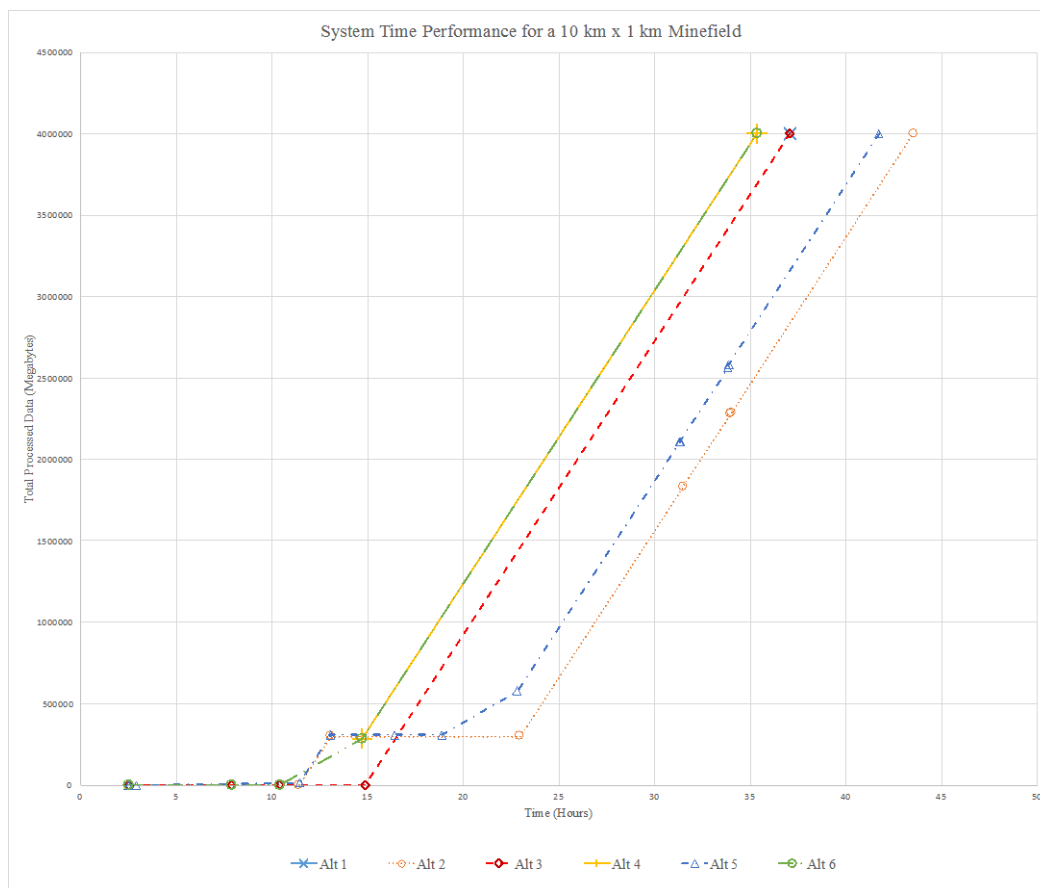


Figure 25. 1 km x 10 km Minefield Data Processed vs. Time to Complete

The benefit of onboard processing can be seen in the reduced time to generate initial processed data for Alternatives 4 and 6 relative to Alternatives 1 and 3, as well as the improved time to complete of 1.8 hours. The rate at which the UUV is able to process data is slower than the rate at which data is collected, resulting in the need to process data in the PMA phase, shown as the continuous lines starting at hour 15. The benefit of onboard processing is the 100GB of data that is already processed upon return to the parent vessel.

When operating in the larger area 5km x 5km minefield for which results are shown in Figure 26, the rank of alternatives changes from those seen for a 1km x10km minefield. While all six alternatives complete the mission within the range of 80–85 hours, Alternative 5, with intermittent communications and onboard processing, is the superior system architecture. The transmission of data to the parent vessel early in the mission, coupled with the slow rate of PMA, means that a constant supply of unprocessed data is available to feed the PMA phase starting, and therefore ending, in a shorter timeframe than systems without intermittent communication. The visible plateau in processed data for Alternatives 2 and 5 around hour 45–55 occur when the PMA process completes processing available data and idles until additional sensor data is returned. The sensor downtime associated with breaching, transmitting, and returning to scanning depth for intermittent communications allow alternatives without this downtime to eventually surpass the total data scanned and processed in a given period, but that point only occurs in larger minefields.

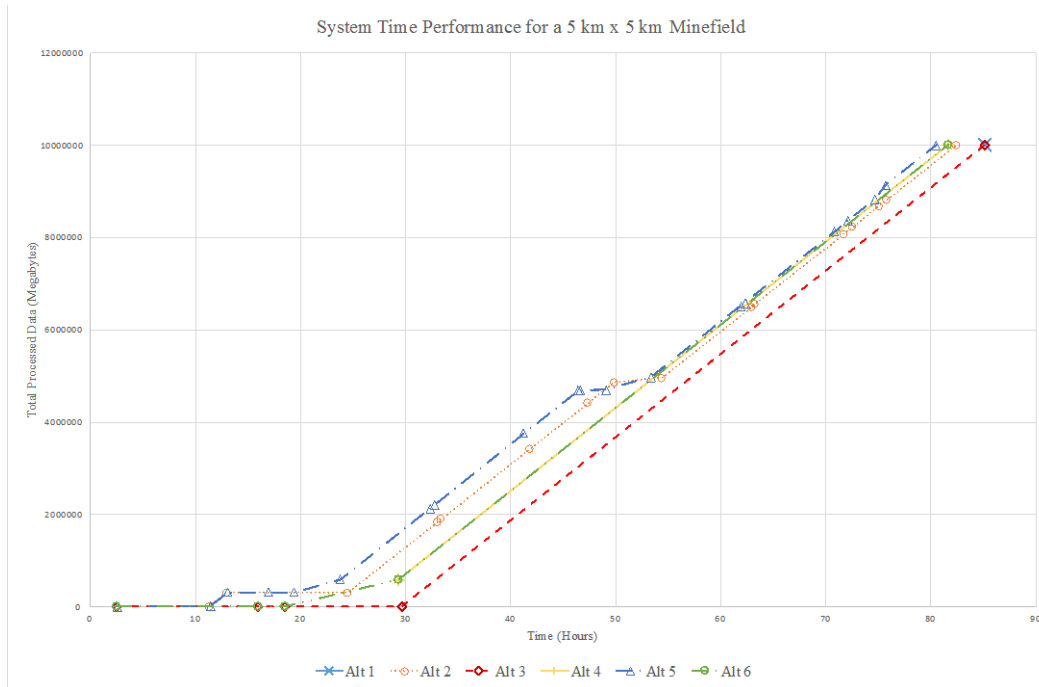


Figure 26. 5km x 5km Minefield Data Processed vs. Time to Complete

As the size of the minefield increases, the initial advantage of the intermittent communications in Alternatives 2 and 5 is quickly eclipsed by the capability to process data onboard, available for Alternatives 4 and 6. For a 10km x 1km theoretical minefield, there is almost no advantage in employing IC as the time required to breach and transmit is such a large portion of time with respect to the time required to analyze the minefield. For the 5km x 5 km minefield, the initial benefit of beginning the PMA phase earlier in the mission is maintained through the end of the mission. For a minefield of 10km x 10 km, the delay caused by the transmission cycle of intermittent communications (breach, transmit, dive) reduces the total sensor data throughput for a long enough period that intermittent communications is an inferior approach. As seen for both other size minefields, the difference between no communications and constant communications is negligible, because the bandwidth for constant communications given current technology is completely dwarfed by the scale of the data collected when scanning a minefield. The majority of data will be transferred through a physical connection at the end of each

sortie when subsurface data transmission rates are small enough. Figure 27 shows the results of all six alternatives in a 10km x 10km minefield, with a clear and significant disadvantage for designs with intermittent communications, and a slight advantage for alternatives with onboard processing over communications-matched architectures without onboard processing.

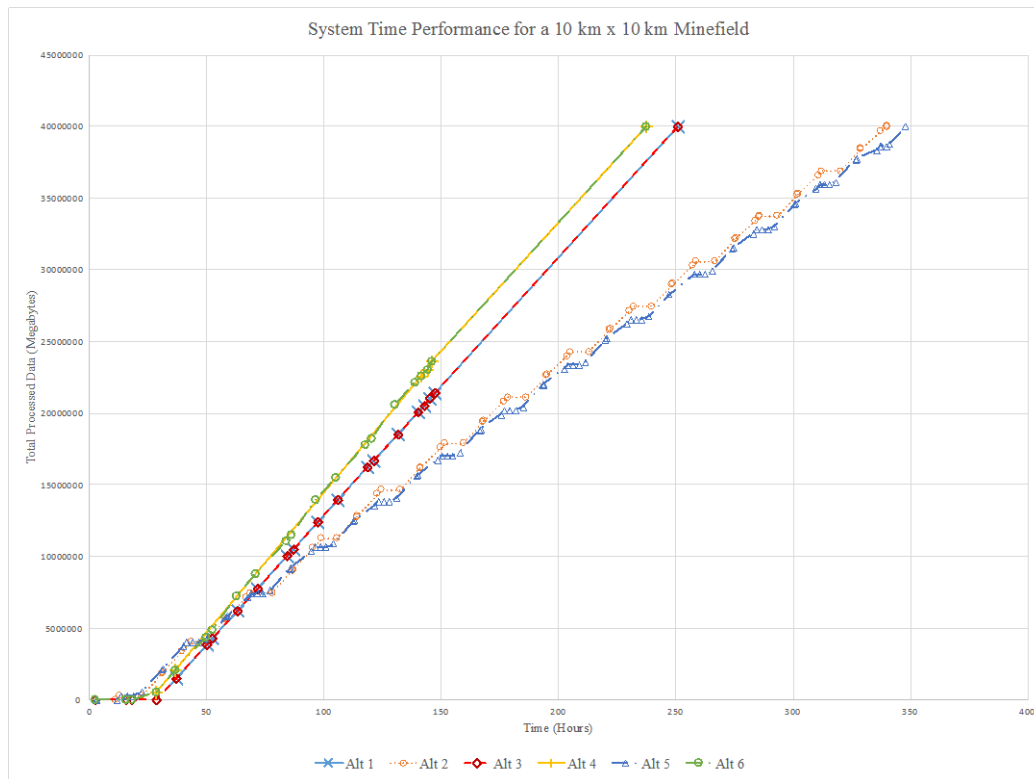


Figure 27. 10 km x 10 km Minefield Data Processed vs. Time to Complete

The changing relative performance of the six identified system architectures can be seen in Figure 28, which plots the time to complete (vertical) a simulated mining mission for square minefields of various sizes, from 1 km² to 400 km². Given the initial design parameters representing available and feasible technology for the USN to include on an MCM UUV, onboard processing and

either constant communications or no communications is the ideal system for larger minefields. IC and onboard processing is competitive or has a slight advantage for certain minefield sizes closer to 25 km². One notable attribute of architectures with intermittent communications is that the cadence with which the transmission process is initiated is flexible and likely not design-constrained by technology. Running an optimization process could determine the optimal times to breach and communicate, but that problem was viewed as beyond the requisite level of detail envisioned for this capstone project.

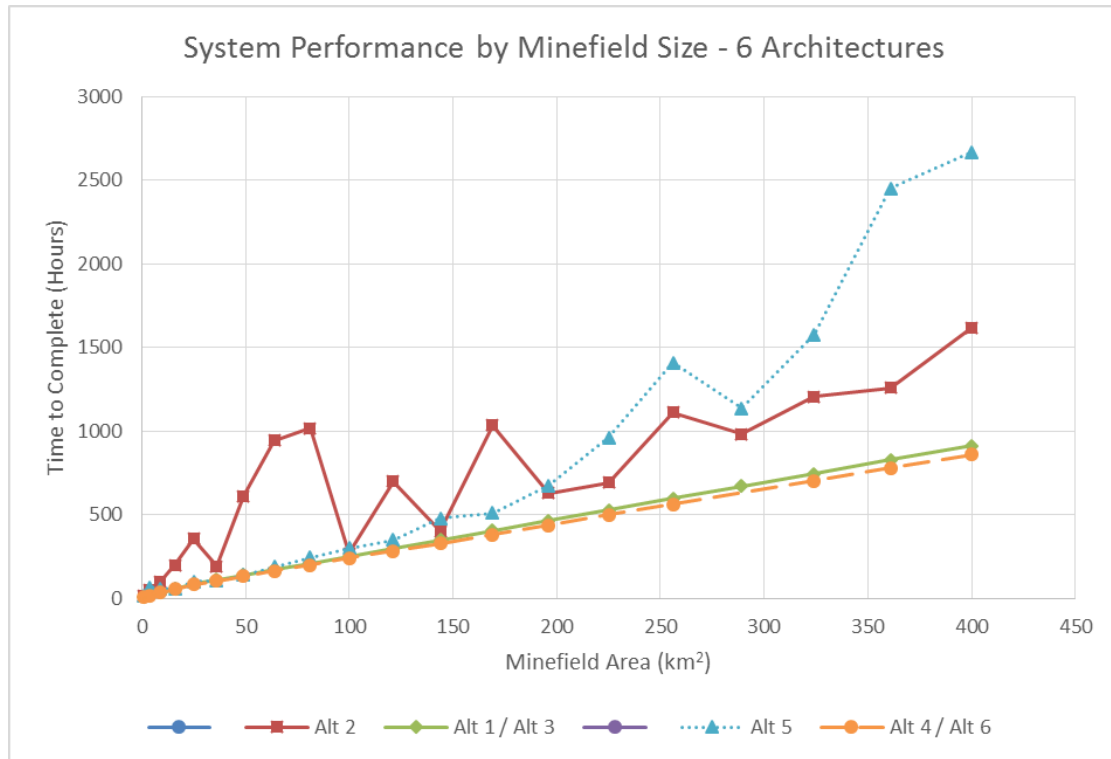


Figure 28. System Performance by Minefield Size

C. DESIGN OF EXPERIMENTS AND IMPACT OF DESIGN PARAMETERS

With a set of 18 design parameters and six proposed system architectures, we endeavored to minimize the number of simulation runs required for analysis by leveraging a set of nearly orthogonal Latin hypercubes, as described by Cioppa (2002). This structured experimental design allows each architecture alternative to be analyzed

using least squares regression with a set of just 65 simulations. The sample space is well represented, with each factor explored across its range, and design factors chosen in a nearly orthogonal manner—reducing correlation between inputs to near zero.

For each of the six alternatives, a set of 65 simulations were ran based on inputs generated with the assistance of the tools provided by NPS (Cioppa 2002). The response variables used to determine the impact of design parameters were Time to Complete (TtC) and Average Process Time (APT). We leveraged the JMP statistical analysis suite to generate least squares regressions using a step-wise analysis process based on p-value threshold selection criteria. Appendix B provides a walkthrough of the analysis methodology used to generate the figures in the following section. Following the architecture-specific discussion of the impact of design parameters, a cross-architecture impact analysis of design parameters is performed. All simulations ran to support the DOE analysis used a 10km x 10km minefield.

1. Alternative Architecture 1: No Onboard Processing with No Communications

Alternative 1 represents the baseline mission with no onboard processing and no communications. There are two distinct phases: the UUV first scans the environment to detect mines and when the UUV reaches the host platform it transfers the data for PMA.

Figure 29 shows the regression results from the DOE outputs for Alternative 1. The changes in design parameters explain 68% of changes in time to complete the mission as noted by the R^2 value. This level of correlation demonstrates a moderate descriptive value within the bounds of our design of experiments. The chart shown as part of Figure 29 shows that within the design envelope considered, the vast majority of simulated system configurations complete the mission within 1000 hours, though a small number of systems take a longer period of time. System configurations with the combination of low endurance and low speed require a substantially higher number of sorties and UUV replenishment cycles, add time to the mission.

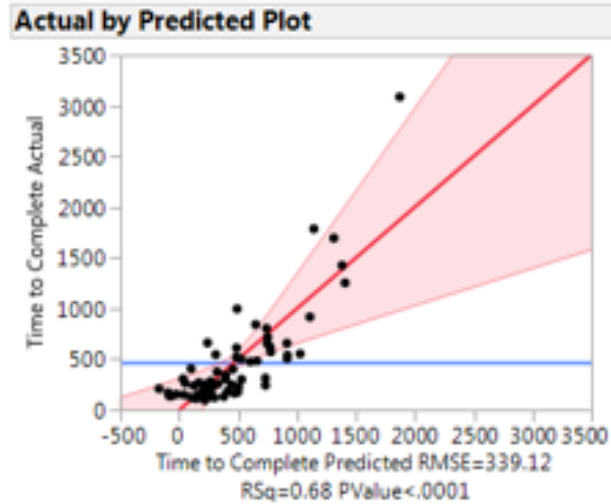
Alternative 1

No Communications
No Real Time Analysis

Sample Mean (hours)

Time to Complete: 472.0

Avg Process Time: 255.3



Parameter Estimates				
Term	Estimate	Std Error	t Ratio	Prob> t
Sensor Width	-3978.825	753.436	-5.28	<.0001*
UUV Speed	-63.68406	16.45729	-3.87	0.0004*
(Recovery Time-0.50074)*(PMA Rate-104.954)	12.625693	4.382985	2.88	0.0062*
(UUV Speed-5.56813)*(Sensor Width-0.10374)	746.12127	288.9916	2.58	0.0133*
PMA Rate	-1.883015	0.756074	-2.49	0.0167*
Intercept	764.34426	375.0039	2.04	0.0477*
Transit Time	72.629616	35.9414	2.02	0.0496*
Surface Time	2296.9127	1163.177	1.97	0.0547
Replenish Time	41.853201	24.00042	1.74	0.0883
(UUV Speed-5.56813)*(Replenish Time-5.98977)	-17.30492	10.40218	-1.66	0.1035
(UUV Speed-5.56813)*(Recovery Time-0.50074)	-224.5553	143.4282	-1.57	0.1248
(UUV Endurance-25.2198)*(UUV Speed-5.56813)	3.0842896	2.028785	1.52	0.1358
Launch Time	410.10586	288.5883	1.42	0.1625
(Launch Time-0.49854)*(Sensor Width-0.10374)	-8118.597	5730.824	-1.42	0.1638
UUV Endurance	-5.46693	4.920633	-1.11	0.2727
(Sensor Width-0.10374)*(PMA Rate-104.954)	-20.68383	19.66532	-1.05	0.2988
(UUV Endurance-25.2198)*(Replenish Time-5.98977)	-3.786909	3.904779	-0.97	0.3376
Data Collection Rate	225.44398	242.1654	0.93	0.3571
Recovery Time	-163.4331	287.4887	-0.57	0.5727
Manual Download Rate	-0.170289	0.319496	-0.53	0.5968
(UUV Endurance-25.2198)*(Surface Time-0.10356)	-27.62906	200.8716	-0.14	0.8912

Figure 29. Alternative 1's Regression Results for Time to Complete

The design parameters that have the most substantial impact on TtC are identified in Figure 29. For the purpose of this analysis, only parameters with the largest possibility of impacting TtC (p-value of 0.01 or less, or single parameters with a p-value of 0.05 or less) are discussed. Four individual parameters and one interaction were found to impact TtC for Alternative 1:

- **Sensor Width:** The width of the sensor directly impacts the number of tracks required to completely pass over the area of interest. The wider the sensor, the fewer tracks needed, which decreases the time to completely scan the area. The estimate for this variable is -3978.83, meaning for every kilometer the sensor width increases, total time decreases by 3978.83 hours. While this is a decrease, it is important to note that the range of sensor width used varied from 0.005 km to 0.2 km, meaning all other parameters constant, the time to complete can decrease by 775.87 hours when the sensor width is increased from 0.005 km to 0.2 km.
- **UUV Speed:** Second to sensor width, UUV speed also plays a large role in TtC. The faster the UUV moves along each track, the faster the total area of interest can be scanned and completed. The coefficient estimate for UUV speed is -63.68, meaning all other parameters constant, a knot increase in UUV speed decreases TtC by 63.68 hours. The simulation modeled UUV speeds from 1 to 10 knots.
- **Recovery Time*PMA Rate:** The interaction of recovery time and PMA rate impacts TtC with a coefficient of 12.63.
- **PMA Rate:** The coefficient estimate for the PMA Rate parameter is -1.88. For the simulation, the PMA Rate was varied from 10 to 100 Mbps. An increase of PMA rate by 1 Mbps is associated with a decrease in TtC of 1.88 hours.
- **Transit Time:** Transit time directly impacts TtC with an estimate of 72.63. This means for every hour transit time increases, TtC increases by 72.63 hours. Transit time ranged from 1 hour to 4 hours in the simulation, which means TtC would see an increase of 217.89 hours when the transit time was increased from 1 hour to 4 hours with all other parameters remaining constant.

2. Alternative Architecture 2: No Onboard Processing with IC

Alternative 2 represents a system architecture involving no onboard data processing, but intermittent surface communications. The concept of operations for Alternative 2 is similar to Alternative 1, with the exception that the UUV will rise to the surface and transmit data to the parent vessel after a certain amount of data is collected. This capability enables Alternative 2 to return data at an early time, but adds additional tasks during minefield operations, reducing the amount of scanning that can be performed for a given endurance.

Figure 30 shows the regression results from the DOE outputs for the intermittent communications / no onboard processing alternative, with 85% of changes in time to complete the mission explained by changes to design parameters. This level of correlation demonstrates a high descriptive value within the bounds of our design of experiments.

There are a number of design parameters with significant effects ($p < 0.05$) for Alternative 2 that are unique from those discussed for Alternative 1.

- **Intermittent Communication Data Limit:** This design parameter determines the amount of data collected, and therefore time elapsed, before the UUV rises to the surface and transmits data. This also determines the amount of data that is transmitted with each repetition of breach, transmit, and dive. This design parameter is unique in that both high and low values lead to inefficient outcomes. Too high of an IC Data Limit causes the UUV to never reach the limit and perform similar to Alternative 1, which has no communications. Too low of an IC Data Limit causes the UUV to breach and transmit too often. Since each communications process of breach, transmit, and dive means time spent not scanning the minefield, increasing the number of times spent transmitting adds additional time within operations where data is not being collected. The parameter estimates of -0.000345 are lower than other

design parameters, though the unit base of Mb means that a 1 Gb increase in IC Data limit for Alternative 2 is associated with a reduction in mission time of 0.3 hours. With the low cost and high availability of data, expanding storage is an accessible means of improving performance for Alternative 2.

- **Surface Time:** The Time to Complete a mission for Alternative 2 is affected to a greater degree by the time it takes to surface than alternatives 1, 3, 4, or 6, because the communication process associated with intermittent communications occurs repeatedly throughout each sortie and involves the UUV surfacing. This design parameter has interaction effects with other design parameters that impact endurance or increase the frequency of communication, including UUV Endurance, Recovery Time, Transit Time, and Sensor Width. As endurance decreases, the impact of increased surface time results in additional sorties needed to complete the minefield, adding significantly to expected completion time, due to the associated transit and replenish times.
- **Surface Data Transfer Rate:** This design parameter determines the bandwidth with which the UUV can transmit data during the communications portion of operations. Increased surface data transfer rate reduces the time taken to communicate a given size data set. Intermittent Communications Data Limit determines the amount of data transferred, leading to a larger impact of improvements to surface data transfer rates when the Intermittent Communications Data Limit is high, because the total amount of data transmitted for a given minefield rises with the IC Data Limit. UUV designs that include lower IC Data limit are likely to spend a smaller percentage of their elapsed mission time transmitting because of the increased time associated with surfacing and diving more times throughout the mission.

Alternative 2

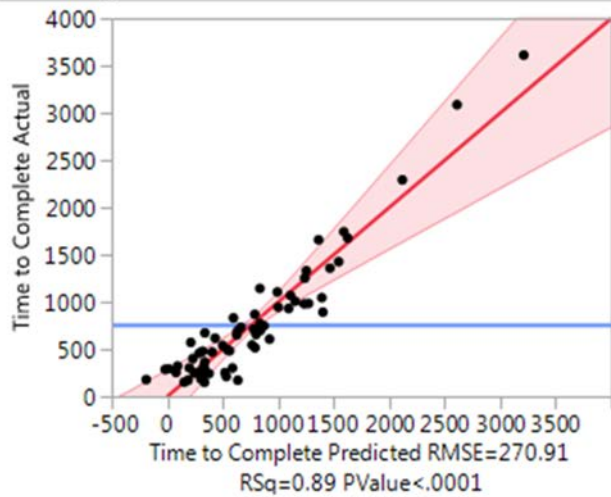
Intermittent Comms
Breach to Transmit
No Real Time Analysis

Sample Mean (hours)

Time to Complete: 472.0

Avg Process Time: 390.0

Actual by Predicted Plot



Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Sensor Width	-7344.255	601.1189	-12.22	<.0001*
UUV Speed	-91.52169	13.1832	-6.94	<.0001*
Intercept	1764.4147	299.1885	5.90	<.0001*
(Sensor Width-0.10374)*(Intermittent Communication Data Limit-1254028)	0.0104904	0.002111	4.97	<.0001*
(Surface Data Transfer Rate-13076.2)*(Intermittent Communication Data Limit-1254028)	5.1125e-8	1.062e-8	4.82	<.0001*
Intermittent Communication Data Limit	-0.000345	7.675e-5	-4.50	<.0001*
Data Collection Rate	620.74131	193.448	3.21	0.0026*
(UUV Endurance-25.2198)*(Surface Time-0.10356)	-453.1199	142.0658	-3.19	0.0028*
Replenish Time	47.480766	19.17194	2.48	0.0176*
PMA Rate	-1.452871	0.603685	-2.41	0.0208*
(Surface Time-0.10356)*(Sensor Width-0.10374)	-38315.09	17656.36	-2.17	0.0360*
(UUV Speed-5.56813)*(Intermittent Communication Data Limit-1254028)	6.1723e-5	3.24e-5	1.90	0.0640
(Surface Time-0.10356)*(Recovery Time-0.50074)	-14738.69	8055.338	-1.83	0.0748
(Surface Time-0.10356)*(Transit Time-2.00684)	-1898.503	1096.702	-1.73	0.0911
(Recovery Time-0.50074)*(PMA Rate-104.954)	7.7361485	4.659641	1.66	0.1047
(Replenish Time-5.98977)*(Intermittent Communication Data Limit-1254028)	-0.00009	5.837e-5	-1.54	0.1311
Transit Time	43.28491	28.72165	1.51	0.1397
(UUV Endurance-25.2198)*(Data Collection Rate-0.49723)	33.778573	23.25504	1.45	0.1542
Surface Time	1335.7652	928.2783	1.44	0.1579
Data Reduction Rate	-181.5456	139.8646	-1.30	0.2017
(UUV Speed-5.56813)*(Replenish Time-5.98977)	16.092675	13.43324	1.20	0.2380
UUV Endurance	4.3657555	3.935111	1.11	0.2739
Surface Data Transfer Rate	0.0018026	0.004808	0.37	0.7097
Recovery Time	18.583838	229.6541	0.08	0.9359

Figure 30. Alternative 2's Regression Results for Time to Complete

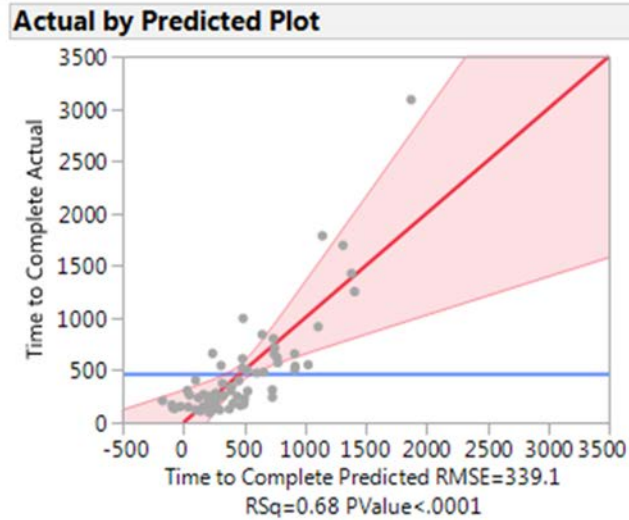
3. Alternative Architecture 3: No Onboard Processing with Constant Communications

Alternative 3 represents a system with constant subsurface communications without onboard processing. While no RTA is completed, data can be communicated throughout the mission.

Alternative 3

Constant Comms
No Real Time Analysis

Sample Mean (hours)
Time to Complete: 472
Avg Process Time: 255



Parameter Estimates				
Term	Estimate	Std Error	t Ratio	Prob> t
Sensor Width	-3978.117	753.3925	-5.28	<.0001*
UUV Speed	-63.67381	16.45634	-3.87	0.0004*
(Recovery Time-0.50074)*(PMA Rate-104.954)	12.623399	4.382732	2.88	0.0062*
(UUV Speed-5.56813)*(Sensor Width-0.10374)	745.98505	288.9749	2.58	0.0133*
PMA Rate	-1.88278	0.75603	-2.49	0.0167*
Intercept	764.08664	374.9823	2.04	0.0478*
Transit Time	72.623566	35.93933	2.02	0.0496*
Surface Time	2296.8313	1163.11	1.97	0.0547
Replenish Time	41.851903	23.99904	1.74	0.0883
(UUV Speed-5.56813)*(Replenish Time-5.98977)	-17.30498	10.40158	-1.66	0.1034
(UUV Speed-5.56813)*(Recovery Time-0.50074)	-224.5696	143.42	-1.57	0.1247
(UUV Endurance-25.2198)*(UUV Speed-5.56813)	3.0843334	2.028668	1.52	0.1357
Launch Time	410.10328	288.5716	1.42	0.1625
(Launch Time-0.49854)*(Sensor Width-0.10374)	-8118.149	5730.494	-1.42	0.1638
UUV Endurance	-5.467564	4.920349	-1.11	0.2727
(Sensor Width-0.10374)*(PMA Rate-104.954)	-20.68614	19.66419	-1.05	0.2987
(UUV Endurance-25.2198)*(Replenish Time-5.98977)	-3.786887	3.904554	-0.97	0.3375
Data Collection Rate	225.4629	242.1514	0.93	0.3570
Recovery Time	-163.368	287.4721	-0.57	0.5728
Manual Download Rate	-0.170151	0.319478	-0.53	0.5971
(UUV Endurance-25.2198)*(Surface Time-0.10356)	-27.58637	200.86	-0.14	0.8914

Figure 31. Alternative 3's Regression Results for Time to Complete

The same design parameters that greatly impact TtC for Alternative 1 are also identified for Alternative 3. Furthermore, the estimates for the coefficient of these parameters are nearly identical to the estimates for Alternative 1 as seen in Figure 31. These parameters and their role in the total time have been discussed previously. Of note for Alternative 3 is that the parameter unique to this alternative, sub-surface data transfer

rate, is not included in the effect summary. Changes to the sub-surface data transfer rate do not have a statically significant impact to the time to complete. This lack of impact results from the slow data rate inherent with acoustic communications discussed in the previous section. If the upper limit of sub-surface data transfer rates was increased substantially, an impact on results would become apparent. This level of performance is well beyond what is possible given current technology. The impact of changes to design parameters for systems with no communication and systems with constant communications are compared in Table 8.

Table 8. Comparison of Estimates for Alternative 1 and Alternative 3

Term	Alt 1		Alt 3	
	Estimate	Prob> t	Estimate	Prob> t
Sensor Width	-3978.825	<0.0001	-3978.117	<0.0001
UUV Speed	-63.68406	0.0004	-63.67381	0.0004
(Recovery Time-0.50074)*(PMA Rate-104.954)	12.625693	0.0062	12.623399	0.0062
(UUV Speed-5.56813)*(Sensor Width-0.10374)	746.12127	0.0133	745.98505	0.0133
PMA Rate	-1.883015	0.0167	-1.88278	0.0167
Intercept	764.34426	0.0477	764.08664	0.0478
Transit Time	72.629616	0.0496	72.623566	0.0496
Surface Time	2296.9127	0.0547	2296.8313	0.0547
Replenish Time	41.853201	0.0883	41.851903	0.0883
(UUV Speed-5.56813)*(Replenish Time-5.98977)	-17.30492	0.1035	-17.30498	0.1034
(UUV Speed-5.56813)*(Recovery Time-0.50074)	-224.5553	0.1248	-224.5696	0.1247
(UUV Endurance-25.2198)*(UUV Speed-5.56813)	3.0842896	0.1358	3.0843334	0.1357
Launch Time	410.10586	0.1625	410.10328	0.1625
(Launch Time-0.49854)*(Sensor Width-0.10374)	-8118.597	0.1638	-8118.149	0.1638
UUV Endurance	-5.46693	0.2727	-5.467564	0.2727
(Sensor Width-0.10374)*(PMA Rate-104.954)	-20.68383	0.2988	-20.68614	0.2987
(UUV Endurance-25.2198)*(Replenish Time-5.98977)	-3.786909	0.3376	-3.786887	0.3375
Data Collection Rate	225.44398	0.3571	225.4629	0.357
Recovery Time	-163.4331	0.5727	-163.368	0.5728
Manual Download Rate	-0.170289	0.5968	-0.170151	0.5971
(UUV Endurance-25.2198)*(Surface Time-0.10356)	-27.62906	0.8912	-27.58637	0.8914

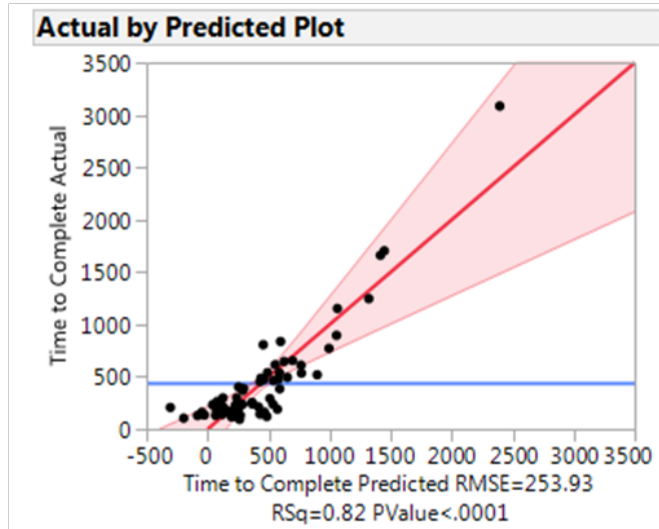
4. Alternative Architecture 4: Onboard Processing / No Communications

Alternative 4 is the first alternative to have RTA included. Similar to Alternative 1, there is no communication from the UUV during the mission. Figure 32 shows the actual by predicted plot with an R^2 value of 0.82, meaning 82% of the changes in Time to Complete are explained by the design parameters.

Alternative 4

No Comms
Real Time Analysis

Sample Mean (hours)
Time to Complete: 442
Avg Process Time: 233



Parameter Estimates				
Term	Estimate	Std Error	t Ratio	Prob> t
Sensor Width	-3752.208	563.3508	-6.66	<.0001*
(UUV Speed-5.56813)*(Sensor Width-0.10374)	1020.28	205.1231	4.97	<.0001*
UUV Speed	-60.65939	12.32659	-4.92	<.0001*
(Transit Time-2.00684)*(Real Time Analysis Rate-25.7034)	-9.078475	1.951705	-4.65	<.0001*
(Recovery Time-0.50074)*(PMA Rate-104.954)	12.80688	3.263307	3.92	0.0003*
(Manual Download Rate-275.769)*(Real Time Analysis Rate-25.7034)	-0.063897	0.016764	-3.81	0.0005*
Intercept	856.18349	287.3622	2.98	0.0048*
(UUV Speed-5.56813)*(Replenish Time-5.98977)	-23.99481	8.151244	-2.94	0.0053*
Real Time Analysis Rate	-5.517676	2.21437	-2.49	0.0168*
Surface Time	2146.6187	870.4994	2.47	0.0179*
PMA Rate	-1.39467	0.566141	-2.46	0.0180*
(Recovery Time-0.50074)*(Replenish Time-5.98977)	-348.9955	145.0427	-2.41	0.0207*
(Sensor Width-0.10374)*(PMA Rate-104.954)	-34.6732	14.58667	-2.38	0.0222*
Replenish Time	42.37836	17.95291	2.36	0.0231*
Transit Time	61.970278	26.91167	2.30	0.0264*
(Sensor Width-0.10374)*(Real Time Analysis Rate-25.7034)	80.605652	38.96934	2.07	0.0449*
(Launch Time-0.49854)*(Recovery Time-0.50074)	-3052.831	1694.595	-1.80	0.0790
Launch Time	359.16412	215.9784	1.66	0.1039
UUV Endurance	-5.894718	3.685912	-1.60	0.1174
Data Collection Rate	204.49592	181.2487	1.13	0.2658
Recovery Time	-152.7169	215.1977	-0.71	0.4819
(UUV Endurance-25.2198)*(Surface Time-0.10356)	-103.2343	148.2529	-0.70	0.4901
Manual Download Rate	-0.164676	0.239238	-0.69	0.4951

Figure 32. Alternative 4's Regression Results for Time to Complete

As shown in Figure 32, eight parameters or interactions have a significant impact on TtC with a p-value of 0.01 or less and five parameters have a significant impact on TtC with a p-value from 0.01 to 0.05. Similar to Alternatives 1 and 3, the parameters of sensor width and UUV are significant in addition to the interaction of recovery time*PMA rate. The estimates for these parameters and interactions are similar to estimates for Alternative 1 and 3. The new parameters and interactions that impact TtC for Alternative 4 are:

- UUV Speed*Sensor Width: The interaction between UUV speed and sensor width has a coefficient estimate of 1020.28. When the maximum values for either parameter are used (10 knots or 0.2 km), TtC remains the same regardless of the value of the second parameter. However, when the width is set to the minimum value of 0.005 km, and increase in UUV speed decreases TtC. The same holds true when the minimum value of UUV speed (1 knot) is used and sensor width is increased.
- Transit Time*RTA Rate: The interaction of transit time and RTA rate has a coefficient estimate of -9.08. Using the maximum RTA rate of 50 Mbps, as transit time increases, TtC decreases. The increased travel time allows for more analysis to be completed on-board instead of through PMA and the parallel operations of transiting and on-board processing save time for the whole mission because the RTA rate is maxed out. To contrast, when the minimum RTA value is used (1 Mbps), an increased transit time increases total time. With such a low RTA rate, a portion of the analysis would have to be complete post mission. If the UUV transit time is high, this means the PMA is also delayed, therefore increasing the TtC.
- Manual Download Rate*RTA Rate: The relationship of the interaction of manual download rate and RTA rate is similar to that of transit time and RTA rate. The coefficient estimate for manual download rate*RTA rate is -0.06. When either the manual download rate or the RTA rate is set to

their respective maximum values of 500 and 50 Mbps respectively, an increase in the other parameter decreases time. The opposite is true when the minimum values are used, e.g.—increasing manual download rate while RTA rate is constant at 1 Mbps increases the total time.

- **UUV Speed*Replenish Time:** The interaction between UUV Speed and Replenish time varies through the range of examined design parameters. When the UUV speed is below the midpoint, increased replenish times increase total mission time to a larger extent than when UUV speed is above the midpoint of the design envelope examined. This is due to the increased number of replenishments needed when the UUV has a low speed. When the UUV speed is high, changes to replenishment have less of an impact, because the UUV has fewer rounds of replenishment to complete the mission.
- **RTA Rate:** RTA Rate is unique to Alternatives 4–6, and its impact to TtC is expected. The faster the RTA Rate, the more data can be processed in parallel to scanning the environment, therefore reducing the TtC. The coefficient estimate for this parameter is -5.52, meaning a one-unit increase in RTA rate decreases the TtC by 5.52 hours. The RTA rate ranged from 1 to 50 Mbps.
- **Surface Time:** Surface time directly impacts the TtC as the more time spent on the surface, the longer the mission will take to complete. A one hour increase in the surface time causes TtC to increase by 2146.62 hours. There is a statistically significant impact to TtC. However, the range used for surface time in the simulation was 2.5 to 10 minutes (0.0417 to 0.1667 hours). This means if all other parameters are held constant, increasing from 2.5 minutes to 10 minutes for surface time increases the total time by 268.33 hours.

- Replenish Time: Replenish Time is a factor for Alternative 4, but not Alternatives 1 and 3 due to the increase workload of onboard processing. The UUV must be replenished more often for this Alternative, which increases TtC. The coefficient estimate for replenish time is 42.38.

5. Alternative Architecture 5: Onboard Processing with IC

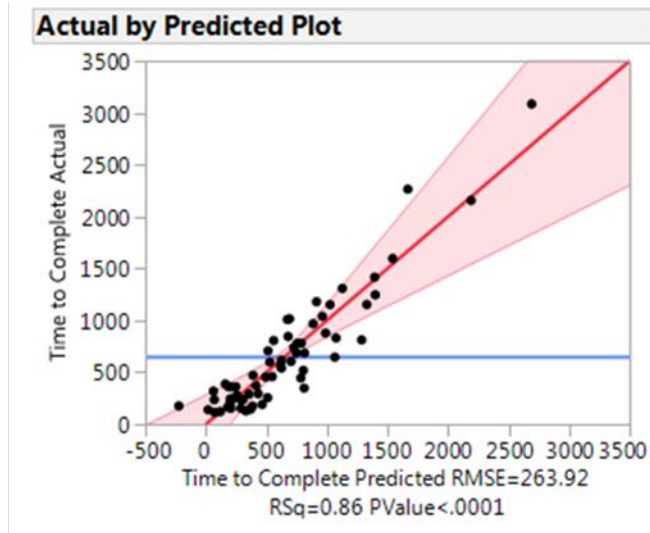
Alternative 5 represents a system architecture with the capability to perform onboard data processing, with intermittent surface communications possible. The concept of operations for Alternative 5 is identical to Alternative 2, with the exception that the UUV will process collected sensor data while scanning and preparing to surface, and transmit processed data to the parent vessel in lieu of unprocessed data, when possible. The UUV specified by Alternative 5 rises to the surface and transmits data to the parent vessel after a certain amount of data is stored—unprocessed or processed. This capability enables the UUV to return processed data at an early time, providing data earlier in the mission, and reducing the required offboard PMA time for data processed onboard. Like Alternative 2, which lacks onboard processing but shares a communications approach, the tasks associated with communications add elapsed time during minefield operations, reducing the amount of scanning that can be performed for a given endurance.

Figure 33 shows the regression results from the design of experiments outputs for UUVs with intermittent communications and onboard processing, with 86% of changes in time to complete the mission explained by changes in design parameters. This level of correlation again demonstrates a high descriptive value within the bounds of our design of experiments.

Alternative 5

Intermittent Comms
Breach to Transmit
Real Time Analysis

Sample Mean (hours)
Time to Complete: 653
Avg Process Time: 333



Parameter Estimates				
Term	Estimate	Std Error	t Ratio	Prob> t
Sensor Width	-5874.935	585.0842	-10.04	<.0001*
UUV Speed	-75.65322	12.82315	-5.90	<.0001*
Intercept	1595.5381	302.42	5.28	<.0001*
(Data Collection Rate-0.49723)*(Real Time Analysis Rate-25.7034)	48.300099	12.81119	3.77	0.0005*
Intermittent Communication Data Limit	-0.000278	7.473e-5	-3.73	0.0006*
(Sensor Width-0.10374)*(Intermittent Communication Data Limit-1254028)	0.0055635	0.001531	3.63	0.0008*
(UUV Speed-5.56813)*(Sensor Width-0.10374)	702.92688	213.6349	3.29	0.0021*
PMA Rate	-1.778016	0.588213	-3.02	0.0044*
(Recovery Time-0.50074)*(Replenish Time-5.98977)	-422.2341	150.7443	-2.80	0.0079*
Real Time Analysis Rate	-5.865338	2.301798	-2.55	0.0149*
Data Collection Rate	469.53076	188.3202	2.49	0.0170*
(Recovery Time-0.50074)*(PMA Rate-104.954)	9.6298331	3.910176	2.46	0.0183*
Data Reduction Rate	-333.852	135.927	-2.46	0.0186*
Replenish Time	39.27261	18.6525	2.11	0.0417*
(Surface Data Transfer Rate-13076.2)*(PMA Rate-104.954)	-0.000149	7.88e-5	-1.89	0.0668
(Transit Time-2.00684)*(Intermittent Communication Data Limit-1254028)	-0.000145	7.911e-5	-1.84	0.0737
Transit Time	38.492085	27.97658	1.38	0.1767
Recovery Time	276.85174	223.6824	1.24	0.2232
Launch Time	243.48243	224.4727	1.08	0.2847
Surface Time	981.66679	905.2717	1.08	0.2849
(Data Collection Rate-0.49723)*(Data Reduction Rate-0.51836)	902.15228	939.38	0.96	0.3428
(Recovery Time-0.50074)*(Transit Time-2.00684)	166.6776	191.0245	0.87	0.3883
(Real Time Analysis Rate-25.7034)*(PMA Rate-104.954)	-0.042404	0.053158	-0.80	0.4299
Surface Data Transfer Rate	0.0034945	0.004682	0.75	0.4599
(Surface Time-0.10356)*(Intermittent Communication Data Limit-1254028)	-0.001156	0.002719	-0.42	0.6732

Figure 33. Alternative 5's Regression Results for Time to Complete

The impact of the design parameters Sensor Width, UUV Speed, IC Data Limit, and PMA Rate affects Alternative 5 similar to Alternative 2. The concept of operations and reliance on intermittent communications are similar for both alternatives. The RTA Rate of Alternative 5 is similar to Alternative 4, where RTA reduces the reliance on PMA. By processing data concurrently with the collection of data while in the minefield,

systems with the capability to perform RTA save processing time that would occur after they have completed scanning the minefield, reducing the time to complete. No new parameters were introduced in the analysis of Alternative 5.

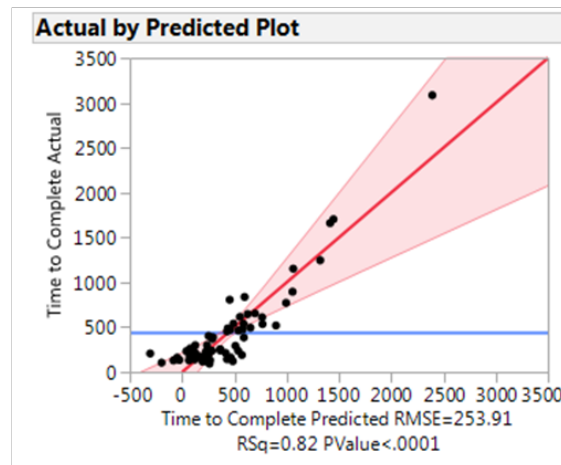
6. Alternative Architecture 6: Onboard Processing and Constant Communications

Alternative 6 represents systems with constant subsurface communications with onboard processing. The actual by predicted plot shown in Figure 34 demonstrates a high descriptive value within the bounds of our design of experiments with an R^2 value of 0.82.

Alternative 6

Constant Comms
Real Time Analysis

Sample Mean (hours)
Time to Complete: 442
Avg Process Time: 233



Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Sensor Width	-58.74935	585.0842	-10.04	<.0001*
UUV Speed	-75.65322	12.82315	-5.90	<.0001*
Intercept	1595.5381	302.42	5.28	<.0001*
(Data Collection Rate-0.49723)*(Real Time Analysis Rate-25.7034)	48.300099	12.81119	3.77	0.0005*
Intermittent Communication Data Limit	-0.000278	7.473e-5	-3.73	0.0006*
(Sensor Width-0.10374)*(Intermittent Communication Data Limit-1254028)	0.0055635	0.001531	3.63	0.0008*
(UUV Speed-5.56813)*(Sensor Width-0.10374)	702.92688	213.6349	3.29	0.0021*
PMA Rate	-1.778016	0.588213	-3.02	0.0044*
(Recovery Time-0.50074)*(Replenish Time-5.98977)	-422.2341	150.7443	-2.80	0.0079*
Real Time Analysis Rate	-5.865338	2.301798	-2.55	0.0149*
Data Collection Rate	469.53076	188.3202	2.49	0.0170*
(Recovery Time-0.50074)*(PMA Rate-104.954)	9.6298331	3.910176	2.46	0.0183*
Data Reduction Rate	-333.852	135.927	-2.46	0.0186*
Replenish Time	39.27261	18.6525	2.11	0.0417*
(Surface Data Transfer Rate-13076.2)*(PMA Rate-104.954)	-0.000149	7.88e-5	-1.89	0.0668
(Transit Time-2.00684)*(Intermittent Communication Data Limit-1254028)	-0.000145	7.911e-5	-1.84	0.0737
Transit Time	38.492085	27.97658	1.38	0.1767
Recovery Time	276.85174	223.6824	1.24	0.2232
Launch Time	243.48243	224.4727	1.08	0.2847
Surface Time	981.66679	905.2717	1.08	0.2849
(Data Collection Rate-0.49723)*(Data Reduction Rate-0.51836)	902.15228	939.38	0.96	0.3428
(Recovery Time-0.50074)*(Transit Time-2.00684)	166.6776	191.0245	0.87	0.3883
(Real Time Analysis Rate-25.7034)*(PMA Rate-104.954)	-0.042404	0.053158	-0.80	0.4299
Surface Data Transfer Rate	0.0034945	0.004682	0.75	0.4599
(Surface Time-0.10356)*(Intermittent Communication Data Limit-1254028)	-0.001156	0.002719	-0.42	0.6732

Figure 34. Alternative 6's Regression Results for Time to Complete

The same design parameters that impact TtC for Alternative 4 are also identified for Alternative 6, see Table 9. Furthermore, the estimates for the coefficient of these parameters are nearly identical to the estimates for Alternative 4. These parameters and their role in the total time have been discussed previously. Similar to the results of Alternative 4, sub-surface data transfer rate is not identified as significantly impacting the time to complete. As discussed previously, this lack of impact results from the slow data rate inherent with acoustic communications.

Table 9. Comparison of Estimates for Alternative 4 and Alternative 6

Term	Alt 4		Alt 6	
	Estimate	Prob> t	Estimate	Prob> t
UUV Speed	-60.65939	<0.0001	-60.65903	<0.0001
Sensor Width	-3752.208	<0.0001	-3751.046	<0.0001
(UUV Speed-5.56813)*(Sensor Width-0.10374)	1020.28	<0.0001	1020.3973	<0.0001
(Transit Time-2.00684)*(Real Time Analysis Rate-25.7034)	-9.078475	<0.0001	-9.080372	<0.0001
(Recovery Time-0.50074)*(PMA Rate-104.954)	12.80688	0.0003	12.802928	0.0003
(Manual Download Rate-275.769)*(Real Time Analysis Rate-25.7034)	-0.063897	0.0005	-0.063871	0.0005
Intercept	856.18349	0.0048	855.86458	0.0048
(UUV Speed-5.56813)*(Replenish Time-5.98977)	-23.99481	0.0053	-23.99074	0.0053
Real Time Analysis Rate	-5.517676	0.0168	-5.520905	0.0168
Surface Time	2146.6187	0.0179	2146.7111	0.0179
PMA Rate	-1.39467	0.018	-1.395254	0.018
(Recovery Time-0.50074)*(Replenish Time-5.98977)	-348.9955	0.0207	-348.9427	0.0207
(Sensor Width-0.10374)*(PMA Rate-104.954)	-34.6732	0.0222	-34.64438	0.0223
Replenish Time	42.37836	0.0231	42.388091	0.0231
Transit Time	61.970278	0.0264	61.939065	0.0265
(Sensor Width-0.10374)*(Real Time Analysis Rate-25.7034)	80.605652	0.0449	80.670887	0.0448
(Launch Time-0.49854)*(Recovery Time-0.50074)	-3052.831	0.079	-3053.784	0.0789
Launch Time	359.16412	0.1039	359.19427	0.1039
UUV Endurance	-5.894718	0.1174	-5.889919	0.1177
Data Collection Rate	204.49592	0.2658	204.78941	0.2651
Recovery Time	-152.7169	0.4819	-152.928	0.4813
(UUV Endurance-25.2198)*(Surface Time-0.10356)	-103.2343	0.4901	-103.2767	0.4899
Manual Download Rate	-0.164676	0.4951	-0.16436	0.4959

The proposed alternative architecture for the MCM UUV share a number of design parameters that drive modeled performance. If the USN determines to continue development of mine hunting UUVs performing the “detect and classify” mission, the proposed system architecture will likely resemble one of these architectures. The anticipated mission profile may establish one alternative approach to communications or RTA, allowing the preceding analysis to prescribe direction for investment in specific system performance characteristics. Until the next generation approach to mine hunting using an MCM UUV is identified, there are a number of system parameters that can provide improvements to MCM UUV performance regardless of which architecture is chosen. Table 10 provides the top five design parameters, ranked by the statistical significance of their impact on UUV TtC a 10km x 10km minefield mission. Across all six proposed system solutions, sensor width has the greatest impact on time to complete. Increases in sensor width reduce the number of tracks required to scan the entire minefield, reducing the time required to scan the minefield and collect raw sensor data. UUV speed has a similar impact, though the benefit occurs in both the scanning portion of the mission and the transit portions to and from the minefield. Beyond UUV speed and sensor width, the rank of design parameter impact is dependent upon which architecture alternative is of interest. For systems with intermittent communications, the IC data limit is the third ranked design parameter. For alternatives without intermittent communications, those with the capability to perform RTA see the RTA rate as the third highest ranked design parameter, while those without RTA see the PMA rate as third highest ranked design parameter. The design parameters that have an impact on all examined architecture alternatives offer a set of investment options for the USN that are most likely to benefit MCM UUV effectiveness.

Table 10. Design Parameters Ranked by Impact

Design Parameter	Architecture Alternative					
	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6
Sensor Width	1	1	1	1	1	1
UUV Speed	2	2	2	2	2	2
PMA Rate	3		3	5	4	5
RTA Rate				3	5	3
IC Data Limit		3			3	
Surface Time	4		4	4		4
Data Collection Rate		4				
Transit Time	5		5			
Replenish Time		5				

The design parameters that our analysis did not identify as having significant impacts on system performance offer insights as valuable as those identified do. Communications rates for CC and IC, launch time, and recovery time are all found to have no statistically significant impact on the time to complete a mission in our examined range of inputs. The absence of significance for launch and recovery time is due to the relatively small initial values, which offer little room for improvement. For constant communications, the range of examined transfer rates is beyond the likely technological capability over the next decade and still does not reach the required transfer rates to positively impact MCM UUV performance. The rate of data collection remains over 1000 times larger than data transmission using underwater acoustic modems. Interest in these technologies, and the resources invested by the USN, should not be driven based on anticipated benefits to MCM UUVs.

VI. CONCLUSIONS AND RECOMMENDATIONS

Our capstone team followed a methodology informed by the systems engineering discipline from project inception through the development of our final recommendations. The systems engineering toolset, particularly MBSE and modeling and simulation, supported our development of a structured understanding of the problem space, and helped us to generate proposed solutions and a methodology for assessing the anticipated effectiveness of these solutions. This capstone allowed us to generate recommendations for Department of the Navy leadership.

A. SUMMARY

Our project started with the review of past research related to the use of UUVs in performing the mine countermeasures mission and examined the current state of MCM assets. Chapter II outlined the problem space of interest, and bounded the scope of our project to the “detect and classify” portion of the minehunting mission. This information was used to outline a range of potential approaches to performing the “detect and classify” portion of the UUV minehunting mission. The six identified approaches and the associated system architecture utilize a combination of three different communications approaches (no communication, intermittent communications, and constant communications) and two processing locations (onboard RTA and offboard processing).

Chapter III defined the system functions required to complete the mission for each of the identified approaches and associated architectures, as well as detailing the design parameters that impact the time elapsed while performing each function. Functional flow block diagrams (FFBDs) and a functional hierarchy were developed to ensure our proposed concept of operations offered a logically consistent approach to performing the mission. The FFBDs were used to develop a discrete event simulation that represented UUV operations for all proposed architecture alternatives, across a range of environmental and system characteristics. For each simulation, inputs were based on a DOE methodology developed at the Naval Postgraduate School which was applied to the

design parameter boundaries to identify design parameter inputs for each run of the simulation.

We identified measures of effectiveness for the “detect and classify” mission in Chapter V, and analyzed the results of multiple simulation runs using these measures of effectiveness. The results of the simulation elucidated the impact of improvements to individual design parameters on the performance of MCM UUVs. The analysis of these results showed that the primary drivers of the time to complete a mission were UUV speed and sensor width.

B. CONCLUSIONS

The goal behind performing analysis into the impact of improvements to system characteristics on system performance is to aid investment decisions regarding future research and improvements related to MCM UUVs. Our results predict the estimated benefit of improvements to system design characteristics, and can be combined with cost estimates to perform a cost/benefit analysis (CBA) of proposed UUV system improvements. In an environment of constrained resources, detailed understanding of the likely value of investment decisions enables decision makers to better recognize the best course of action when committing resources. In the absence of cost estimates, this research informs the UUV community of the system characteristics with the greatest impact on system performance.

Regardless of which proposed architecture best represents the UUV design that the DoN decides to pursue to fill the role of performing the “detect and classify” mission, UUV speed and sensor width are expected to drive system performance more than any other design parameter researched. The largest portion of time elapsed while performing the MCM UUV mission is associated with physically traversing and scanning the minefield. Increasing UUV speed or sensor width reduces not just the time spent in the minefield, but also the time spent transiting to and from the minefield and replenishing the UUV by reducing the total number of sorties required. Increases to UUV speed leads to this by increasing the number of tracks scanned per UUV sortie, which decreases the

number of sorties required to scan the minefield, while increases to sensor width reduce the number of tracks in the minefield, also reducing the number of sorties required to scan the minefield. However, care should be taken in regards to altering UUV speed to ensure other system performance criteria are not affected. For example, an increase in UUV speed may negatively affect the sensor's ability to collect and process data since the sensor typically requires a nominal speed from the host UUV. While these conclusions may not be surprising within the MCM community, they offer additional support for investments towards improvement of these system characteristics, and a defense against the belief that changes to communications and onboard processing offer a comparatively more effective approach to clearing minefields.

The design parameters that our analysis did not identify as having significant impacts on system performance offer insights as valuable as those that were identified. Communications rates for constant communication and intermittent communications, launch time, and recovery time are all found to have no statistically significant impact on the time to complete a mission in our examined range of inputs. The absence of significance for launch and recovery time is due to the relatively small initial values, which offer little room for improvement. For constant communications, the range of examined transfer rates is beyond likely technological capabilities over the next decade and still does not reach the required transfer rates to positively impact MCM UUV performance. The rate of data collection remains over 1000 times larger than data transmission using underwater acoustic modems, making the impact of communications while the UUV is underwater negligible.

Improvements to data processing do not have a significant impact on the total time to clear a minefield. This is due to the parallel nature between processing and data collection that is created by the multiple sorties required to scan the entire minefield. While the UUV is performing all sorties after the first completed trip, data processing can occur onboard the parent vessel for data collected in previous sorties. The current rate of data processing that can be performed on the parent vessel is suitably fast to keep pace with the data generated by the UUV. Though improved processing speed may not have

significant impact on the time to complete the collection and processing of data for the entire minefield, there was an incremental improvement for the time taken to process data for each individual area of the minefield. Depending upon the reacquisition and neutralization approach used, and the size of the minefield, this could offer improved SoS performance for the overall MCM mission.

While changes to the concept of operations for MCM UUVs offers an intuitive improvement to performance, our results suggest that available technologies limit the potential benefits of a revolution in how we approach minehunting using UUVs. Changes to the concept of operations, including the addition of communication with the parent vessel and onboard processing, did not offer substantial performance improvements relative to the current approach of operating without communications or onboard processing. Beyond our examined scope of 10 years, communications technology may grow to the point that transmission of collected data is feasible and offers superior performance, but the threshold system characteristics for realizing the proposed benefits of communications are beyond what will realistically be obtainable in the next decade. The benefits of real time analysis, performed onboard the UUV during operations, are limited due to the speed at which the UUV can traverse the minefield and collect data, and the multiple replenishments required to complete a scan of an entire minefield. Interest in these technologies, and the resources invested by the USN, should not be driven based on anticipated benefits to MCM UUVs.

C. SUGGESTIONS FOR FUTURE RESEARCH

The development of functional flows and a discrete event simulation performed in this capstone report offered a data-rich investigation of the impacts of MCM UUV system design decisions on MCM UUV system performance. The level of detail used for this analysis laid somewhere between operational modelling and physical modelling, and opportunities exist for additional research in both of these directions. Operational modeling based upon the foundations outlined in this report could connect changes to system design to overall MCM SoS performance. By including neutralization systems

and command processes, a better understanding of the entire mine hunting process could be gained, whereas this capstone maintained a focus on the “detect and classify” portion of the MCM mission. Additional analysis could be performed to maximize the capability of system architectures with intermittent communications capabilities. Our proposed system followed a static transmission cadence, which may not be optimal as mission conditions change.

Physical modeling could be used to better identify the realistic boundaries of the design parameters used in this study. Our inputs were based on rough orders of magnitude estimates of technological development over the next 10 years. Research into the physical constraints on system performance could offer a better foundation for these design parameter boundaries. If a method of maintaining constant communications without being limited to the transmission rates of underwater acoustic modems was identified, systems involving constant communication would be immediately more valuable. One potential physical solution is a tethered communication buoy.

Additional system concepts of operations could be added to the developed discrete event simulation and used to support modeling and decision making for MCM UUVs across a longer timeframe. We created the discrete event simulation with the intention to support swarms of MCM UUVs, but this was deemed out of scope due to the 10-year timeframe that we were interested in. Swarms of UUVs with some level of system to system communication could potentially reduce reacquisition timelines, and is worthy of additional research.

Finally, the outcomes of this report could be combined with the larger MCM body of knowledge to compare performance and cost of using different asset combinations for the MCM mission. Satellites, aircraft, surface vessels and UUVs offer myriad combinations of meeting the warfighters’ requirement to clear minefields.

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APPENDIX A. OPERATIONAL SIMULATION

A. REPRESENTATION OF FFBD IN THE OPERATIONAL SIMULATION

Appendix A shows one example of how the functional flow block diagram created within Innoslate is depicted in the operational simulation created within ExtendSim. While the goal was to mirror the two, it was not always possible as will be shown. Figure 35 decomposes Function 0.1 Choose MCM System into all the options for both communication type and location of data processing.

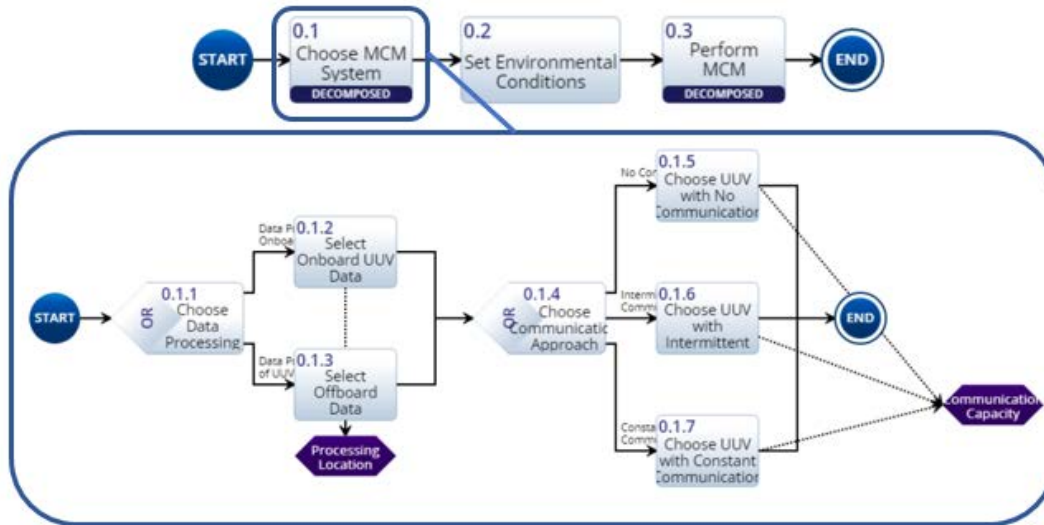


Figure 35. Choose MCM System Decomposed

Within the model, the selection of options for the six alternatives is not as clearly shown. Within what is called the “Onboard Data Tracking” hierarchy block shown in Figure 36, the “Calculate Data Transfer Times” (circled in orange within Figure 36) block utilizes two internal parameters, “RTAFlag” and “CommsFlag,” to dictate capabilities associated with the alternative currently being simulated by a particular run.

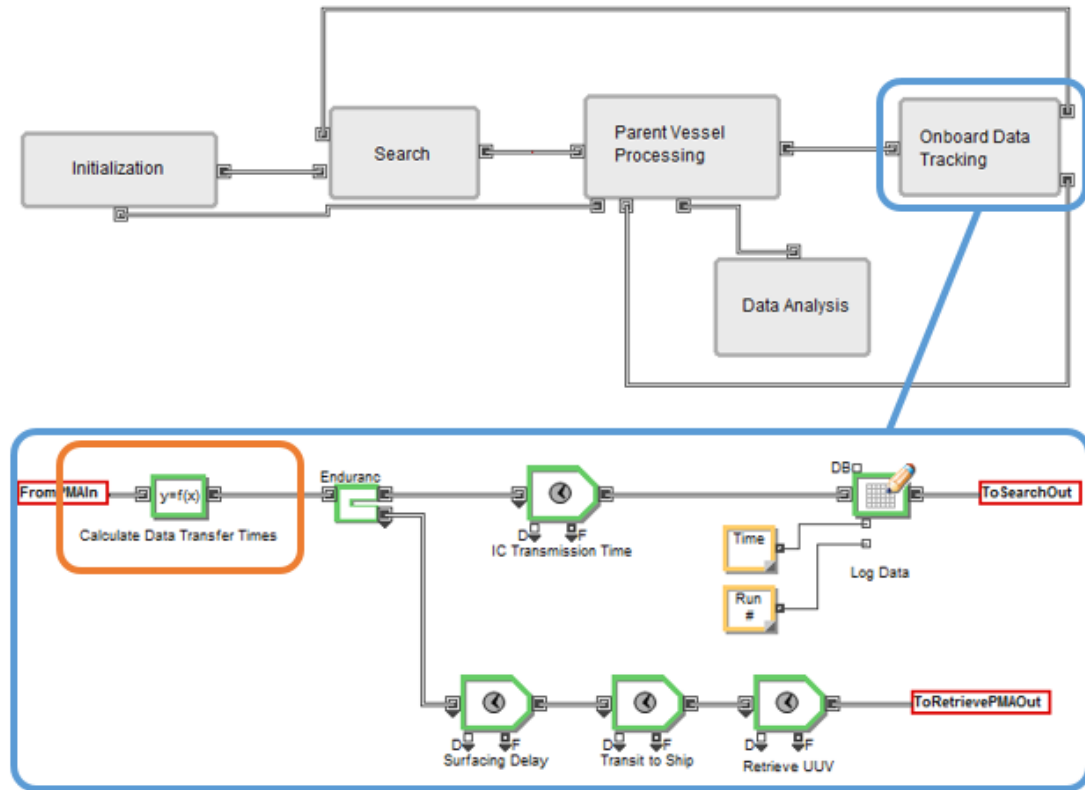


Figure 36. Decomposed “Onboard Data Tracking”

These two internal parameters, among many others, reside within the “Read Input Variables” (circled in orange within Figure 36) database block that is part of the “Initialization” hierarchy block of the top-level model, shown in Figure 37.

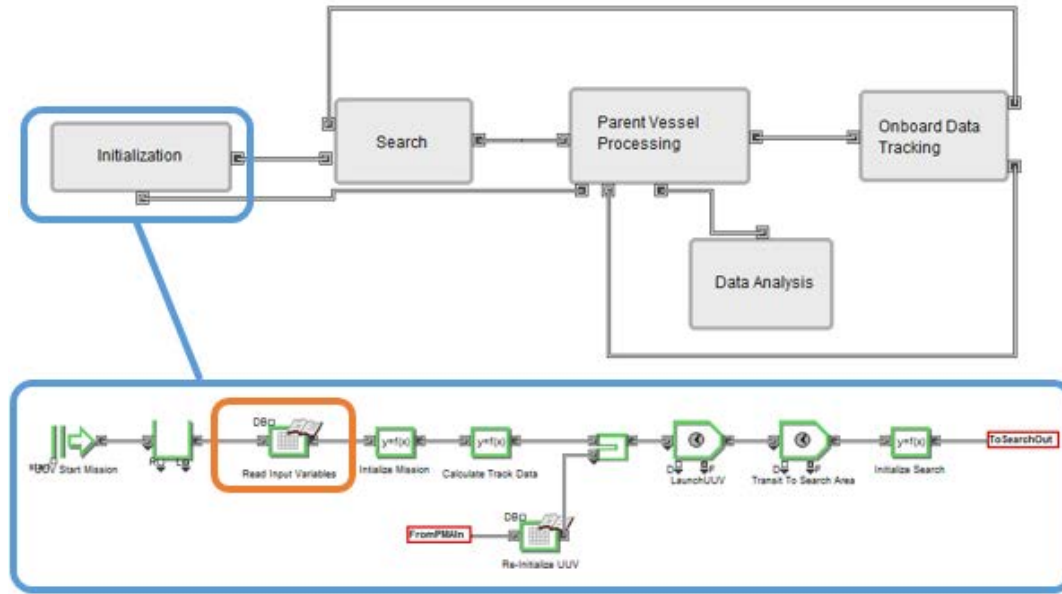


Figure 37. “Initialization” Block Decomposed

The database block contains the results of the DOE including all the parameters that are varied and the internal variables dictating the alternative that is chosen. While the functionality is maintained, the clarity and method of achieving that functionality is not always preserved when moving from the functional flow block diagram to the operational simulation. This example shows just one of the many similarities and differences between the Innoslate functional flow block diagram and the ExtendSim Model.

Within the model, the selection of options for the six alternatives is not as clearly shown. Within what is called the “Pre-PMA” hierarchy block shown in Figure 38, the “Calculate Data Transfer Times” block utilizes two internal parameters, “RTAFlag” and “CommsFlag,” to dictate capabilities associated with the alternative currently being simulated by a particular run.

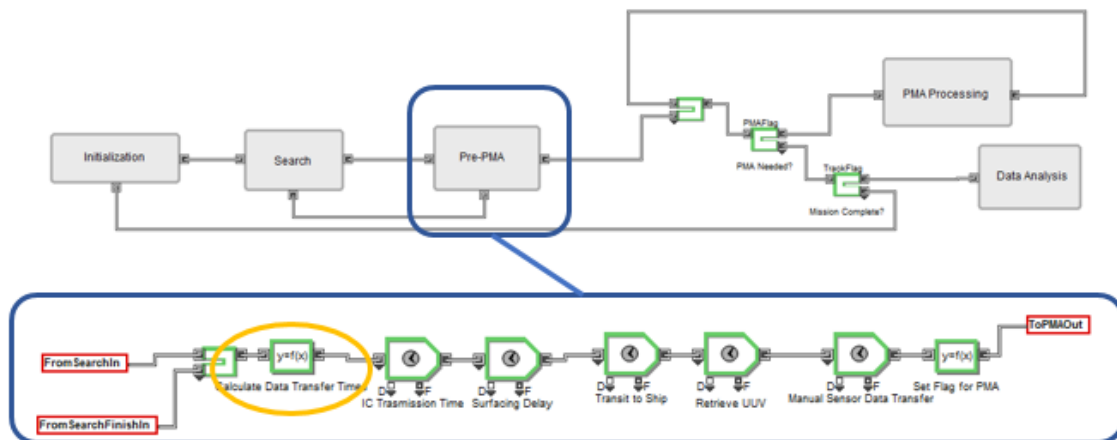


Figure 38. Pre-PMA Decomposed for the Operational Simulation

These internal parameters reside within the “Read Input Variables” database block that is part of the “Initialization” hierarchy block of the top-level model, shown in Figure 39.

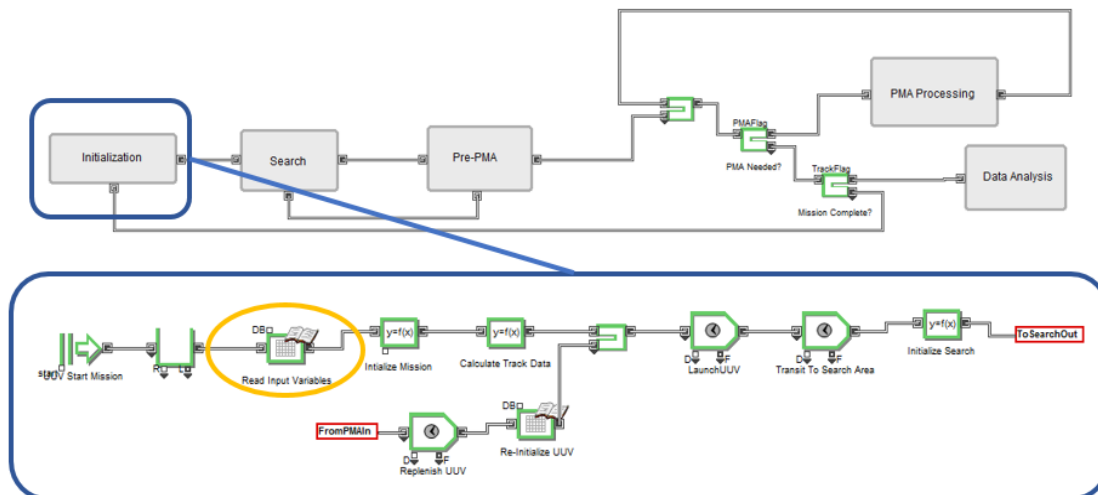


Figure 39. Initialization Decomposed

The input database contains the results of the DOE including all the parameters that are varied and the internal variables dictating the alternative that is chosen. This example shows just one of the differences between the Innoslate functional flow block

diagram and the ExtendSim Model. The next section discusses in further detail how the model is constructed and how it operates.

B. MODEL OVERVIEW

This section presents a detailed review of the ExtendSim simulation highlighting the major functions, Figure 40, of each hierarchy block. It also includes a breakdown of each hierarchy block to show the inner artifacts making up the simulation.

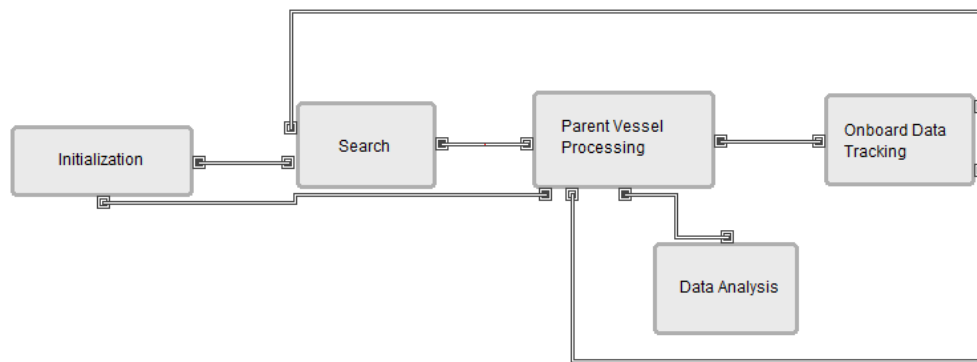


Figure 40. Top Level ExtendSim Model

The six system alternatives represented by the functional architecture were combined into a single model using a simulation program called ExtendSim. A list of these alternatives can be seen in Chapter III, Table 2. The team chose a discrete-event simulation to model the operational simulation of the UUV. The simulation follows a single item, the UUV, through the simulation while tracking the time it takes to move through each activity. As a Discrete-Event Simulation, the time between the activities can be considered to be zero and the only time that will be added to the mission will be that of each activity the UUV performs. Time is the major output of the simulation tracking both the time the UUV spent searching for MILCOs and the time the PMA team spent analyzing the data collected. The simulation (and UUV mission) will only be considered

complete once the UUV has completed searching all its required tracks, as well as the PMA team completing its analysis.

The first hierarchical block in the simulation is Initialization. The Initialization breakdown can be seen in Figure 41.

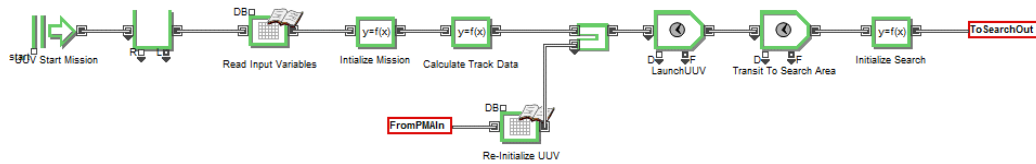


Figure 41. Initialization

This block starts with the creation of the UUV “item” which is what the ExtendSim tracks throughout the simulation. The UUV then reads in the input parameters from the database and converts these parameters into “attributes” which assign the database values to the UUV item for the remainder of the simulation. The values of the input parameters were created from a DOE that were discussed earlier in this paper. The specific UUV alternative is assigned during this step. A full list of the database parameters and mapped attributes can be seen in this Appendix. The two parameters used to indicate which configuration is being run are the “CommsFlag” and “RTAFlag” with integer values of 0, 1, and 2, and 0 and 1, respectively. The block then continues initializing the mission by creating and assigning local variables, parameters that are not from the database, that need to be used for future calculations and then calculating the Area of Interest (AoI) parameters, such as how many tracks will be necessary to search the given area. Once these initial calculations are complete, the rest of the block is used to track the time it takes for the UUV to leave the staging base and prepare for its search. After the UUV has completed a sortie, it will return to the initialization block to reset some of its parameters and track the time to retrieve, replenish, and return to the mission area.

Leaving the Initialization block, the UUV enters the Search hierarchy block, Figure 42, which handles the majority of the actual mission performed by the UUV.

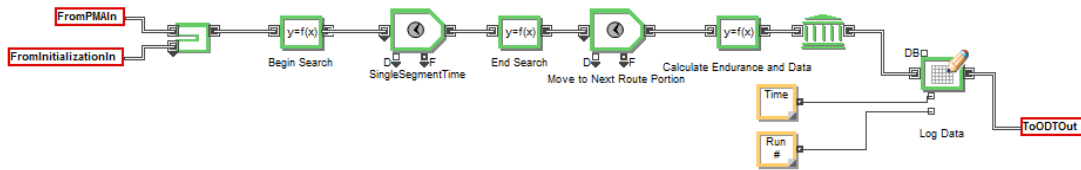


Figure 42. Search

This block represents a single segment of the track run by the UUV. The tracks can be split into specified sized segments so data can be tracked at multiple points along each UUV track. This gives a more flexible output which will help draw a more dynamic conclusion when comparing each alternative. The Search block calculates how many segments the UUV has completed during this sortie and its current position inside the search area. Knowing its position allows the UUV to determine when it should turn or how long it will take to return to the staging base. Using this information, the Search block checks if the UUV can continue to search based on its current endurance level and passes this information to the next block, Parent Vessel Processing. All UUV configurations perform the same search function during this hierarchy block.

The Parent Vessel Processing block, Figure 43, is the next step for the UUV and contains the data calculations based upon the UUV's specific alternative during the sortie.

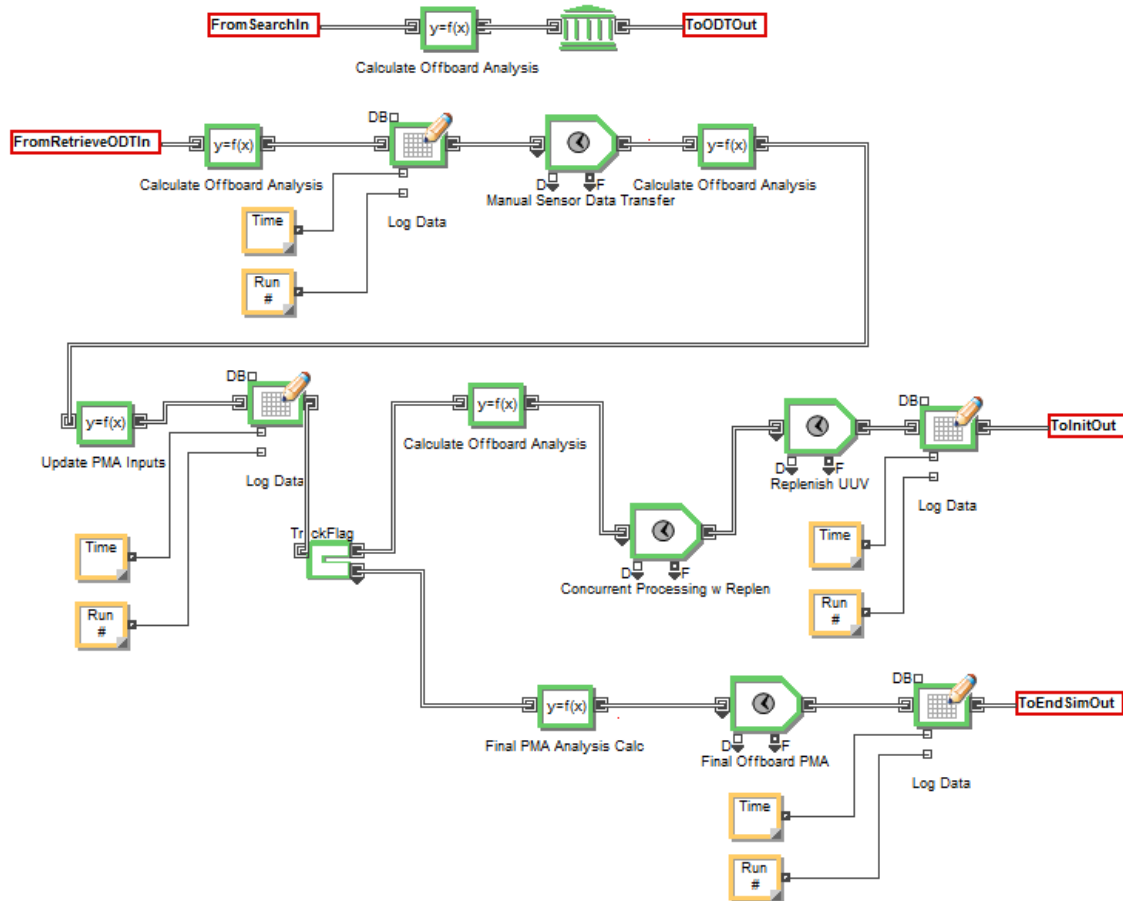


Figure 43. Parent Vessel Processing

The equation blocks utilize the input parameters of the specific mission and the mission times calculated from the Search block to compute most of the data manipulation including data collected, processed, and transmitted with the associated time it took to complete these tasks. Depending on the UUV alternative, terrestrial transmission time or acoustic transmission time will be utilized to transmit some of the processed data to perform PMA in parallel with the mission before the UUV returns to the staging base. These calculations are then sent to the Onboard Data Tracking block where they can be used to finalize the times necessary to transfer and process the remaining data on the UUV. Once the UUV no longer has endurance to continue the sortie, it will take a different path through this block which will add the processing and transfer times performed on the staging vessel to the total mission time using the data collected from

each segment. If there are still tracks to be completed in the mission, the UUV will return to the Initialization block to replenish and continue its mission. If all the tracks have been completed by the UUV, this block will route the UUV to the Data Analysis block to finalize any remaining calculations and complete the mission.

The UUV moves into the Onboard Data Tracking hierarchy block, Figure 44, to complete any data processing and transfer calculations that happen on the UUV itself.

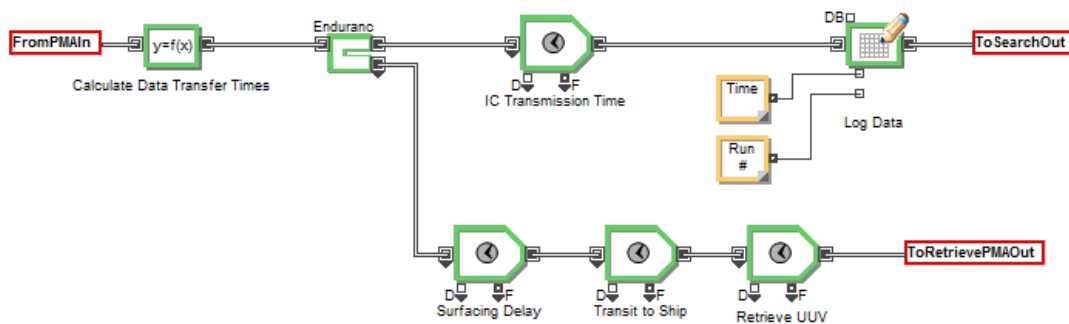


Figure 44. Onboard Data Tracking

If the UUV alternative is using intermittent communications, this is the block that will track the time taken to surface, transmit data, and dive back down to continue the mission. Depending on the UUV alternative, all or some of unprocessed and unanalyzed data may remain on the UUV. The UUV will then be routed to perform another search segment of its sortie. If the endurance of the UUV, calculated in the previous Search block, is not enough to continue the mission, it will be routed through the Parent Vessel Processing block to finalize sortie calculations. This block will also add the logistic times of transiting and retrieving the UUV back at the staging base and add these times to the mission. The final block of the simulation is the Data Analysis hierarchy block, Figure 45.

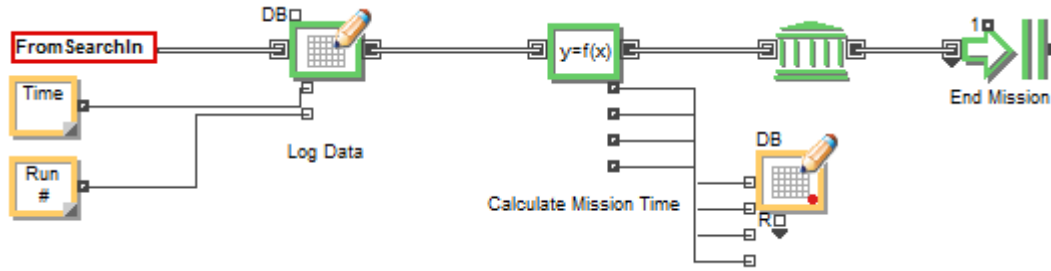


Figure 45. Data Analysis

This block collects the final sortie and mission times completed by the UUV and combines them into total sortie time, total PMA time, and total mission time. This data is then written to the output database for each run of the UUV for export and analysis. The data collected at this block and throughout the simulation will be used to analyze the benefits of each UUV alternative. The variable inputs created by the DOE should give a dynamic view of the advantages and disadvantages of each alternative given multiple mission and UUV parameters.

C. SIMULATION MODEL INPUTS AND OUTPUTS

Table 11 shows the complete matrix of global and local input variables, as well as the output variables. For each variable, the matrix also describes each, shows which alternative they pertain to and ranges for the ones that vary.

Table 11. Global and Local Input Variables

Variable Name	Description	Type	Models						Unit	Min	Max
			1	2	3	4	5	6			
CommsFlag	Used to signal UUV communication capability	Global	X	X	X	X	X	X	N/A	0	2
CompletedSegs	Number of completed segments the UUV has completed	Local	X	X	X	X	X	X	N/A	N/A	N/A
CompletedTracks	Amount of tracks the UUV has successfully completed	Local	X	X	X	X	X	X	N/A	N/A	N/A
CompressedData	Amount of data compressed before it is given to the PMA team.	Local	X	X	X	X	X	X	Mb	N/A	N/A
DataCollected	Total amount of data collected during each search mission.	Local	X	X	X	X	X	X	Mb	N/A	N/A
DataCollectionRate	Tate at which the UUV senors are collecting data while searching	Global	X	X	X	X	X	X	Mbps	10	200
EnduranceFlag	Flag used to reroute the UUV to the command ship when it does not have enough endurance to perfrom another track	Local	X	X	X	X	X	X	N/A	N/A	N/A
ICDataLimit	Amount of data collected for the intermittent communications before the UUV comes up to transmit data	Global		X			X		Mb	100000	500000
LaunchTime	Amount of time necessary to launch the UUV into the water	Global	X	X	X	X	X	X	Minutes	15	45
ManualDLTime	Amount of time needed to manually download collect data	Local	X			X			Hours	N/A	N/A
ManualDownloadRate	Rate the UUV can physically	Global	X			X			Mbps	50	5000

Variable Name	Description	Type	Models						Unit	Min	Max
			1	2	3	4	5	6			
	transfer data to the PMA subsystem										
MissionEnd	Time the UUV finished its mission	Local/Output	X	X	X	X	X	X	Hours	N/A	N/A
MissionStart	Time the UUV started the mission	Local	X	X	X	X	X	X	Hours	N/A	N/A
NumberOfTracks	Number of tracks needed to be completed	Local	X	X	X	X	X	X	N/A	N/A	N/A
OffbrdCompData	Amount of data compressed offboard the UUV	Local	X	X	X	X	X	X	Mb	N/A	N/A
PMADataTime	Amount of time needed to complete PMA on the data received	Local	X	X	X	X	X	X	Hours	N/A	N/A
PMARate	Rate at which the PMA team can analyze the data	Global	X			X			Mbps	10	100
PositionFlag	Flag used to determine if the UUV is on a odd or even track	Local	X	X	X	X	X	X	Binary	N/A	N/A
ProcessedData	Amount of data the has been processed by the UUV or PMA system	Local	X	X	X	X	X	X	Mb	N/A	N/A
ProcessPercent	Amount of data processed by the UUV before transfer to the PMA subsystem	Local		X	X		X	X	N/A	N/A	N/A
ProcessTime	Time required for the UUV to process data offboard the UUV	Local	X	X	X	X	X	X	Hours	N/A	N/A
RecoveryTime	Time required to remove the UUV from the water to the command ship	Global	X	X	X	X	X	X	Minutes	15	45
ReductionRatio	Ratio of data reduction applied to the data collected for processed	Global	X	X	X	X	X	X	N/A	0.1	0.95

Variable Name	Description	Type	Models						Unit	Min	Max
			1	2	3	4	5	6			
	data										
ReplenishTime	Time required to recharge the UUV	Global	X	X	X	X	X	X	Hours	3	9
ReturnTime	Time required for the UUV to return to the command ship	Local	X	X	X	X	X	X	Hours	N/A	N/A
RTAFlag	Flag used to track whether the UUV will be performing RTA	Global				X	X	X	N/A	0	1
RTARate	UUV data processing rate	Global				X	X	X	Mbps	10	200
SearchAreaLength	Length of AOR to be searched for mission	Global	X	X	X	X	X	X	NM	5	20
SearchAreaWidth	Width of AOR to be searched for mission	Global	X	X	X	X	X	X	NM	5	20
SearchTime	Amount of time the UUV has been actively searching	Local	X	X	X	X	X	X	Hours	N/A	N/A
SegmentLength	Length of each UUV track segment	Local	X	X	X	X	X	X	km	N/A	N/A
SegmentsPerTrack	Number of sections that make up one track of the UUV's route	Local	X	X	X	X	X	X	N/A	N/A	N/A
SensorWidth	Width of the UUV's sonar swath.	Global	X	X	X	X	X	X	km	0.005	0.2
SingleLaneTime	Amount of time to complete a track.	Local	X	X	X	X	X	X	Minutes	N/A	N/A
SingleSegTime	Amount of time necessary to complete each segment of the UUV's track	Local	X	X	X	X	X	X	Hours	N/A	N/A
Sub-SurfaceDataTransferRate	Rate at which the UUV can transmit data while underwater	Global			X			X	kbps	5	35
SurfaceDataTransferRate	Rate at which the UUV can transmit data while on the surfaced	Global		X			X		Mbps	1	25
SurfacePerSort	Amount of times the UUV surfaces	Local		X		X			N/A	N/A	N/A

Variable Name	Description	Type	Models						Unit	Min	Max
			1	2	3	4	5	6			
	for each sortie										
SurfaceTime	Amount of time necessary for the UUV to surface and establish communications with the staging base	Global		X			X		Minutes	2.5	10
Total_Data_Reaching_PMA	Amonut of data collected and Processed during UUV mission	Output	X	X	X	X	X	X	Mb	N/A	N/A
TotalPMATime	Amount of time the taken to complete PMA throughout the mission	Local/Output	X	X	X	X	X	X	Hours	N/A	N/A
TotalTime	Amount of time elapsed for the entire mission, including PMA	Local/Output	X	X	X	X	X	X	Hours	N/A	N/A
TrackBuffer	Distance the UUV must travel past each track to have time and realign with the next track	Local	X	X	X	X	X	X	km	N/A	N/A
TrackFlag	Flag use to reroute the UUV when it has completed all its tracks for the mission	Local	X	X	X	X	X	X	N/A	N/A	N/A
TrackPerSurface	Number of tracks the UUV with intermittent communications can complete before coming up to transmit data	Local		X		X			N/A	N/A	N/A
TracksInSortie	Number of tracks completed in the current sortie	Local	X	X	X	X	X	X	N/A	N/A	N/A
TransitTime	Time required for the UUV to move between areas	Global	X	X	X	X	X	X	Hours	0	4
TransmittedData	Amount of data transmitted to the command ship	Local		X	X		X	X	Mb	N/A	N/A

Variable Name	Description	Type	Models						Unit	Min	Max
			1	2	3	4	5	6			
TransmitTime	Time required for the UUV with IC to transmit data	Local		X		X			Hours	N/A	N/A
UnprocessedData	Data unprocessed when the data reaches the PMA team.	Local	X	X	X	X	X	X	Mb	N/A	N/A
UUVEndurance	Time the UUV can operate before its energy is depleted	Global	X	X	X	X	X	X	Hours	10	40
UUVProcessTime	Amount of time necessary for the UUV to process data	Local				X	X	X	Hours	N/A	N/A
UUVSpeed	Propulsion speed of the UUV while on tracks	Global	X	X	X	X	X	X	Knots	1	10
Xposition	Position of the UUV on the X axis	Local	X	X	X	X	X	X	km	N/A	N/A
Yposition	Position of the UUV on the Y axis	Local	X	X	X	X	X	X	km	N/A	N/A

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APPENDIX B. JMP REGRESSION OUTPUT

The outputs from the ExtendSim simulation were imported into the JMP statistical analysis suite. A stepwise model was created for each alternative and each metric (Time to Complete and Average Process Time) by selecting the “Fit Model” option in the Analyze menu. All parameters were entered as Effects, either TtC or APT was selected as the Y variable, and the alternative number was used in the “By” variable to allow for filtering for each alternative. The “Factorial to Degree” was used with two degrees. The probability to enter p-value was set to 0.25 and the probability to leave p-value was set to 0.05. Next, the output of the stepwise model was used to make the least square regression model. To complete this, the “Make Model” button was selected and standard least squares was chosen as the personality before running the model. The output of the standard least square model is shown in Chapter V and this appendix.

A. TIME TO COMPLETE INTERACTION PLOTS

The interaction plots for the time to complete metric for each alternative are shown in Figures 46 to 51. The significant interactions with a p-value of 0.05 or less are noted below each figure.

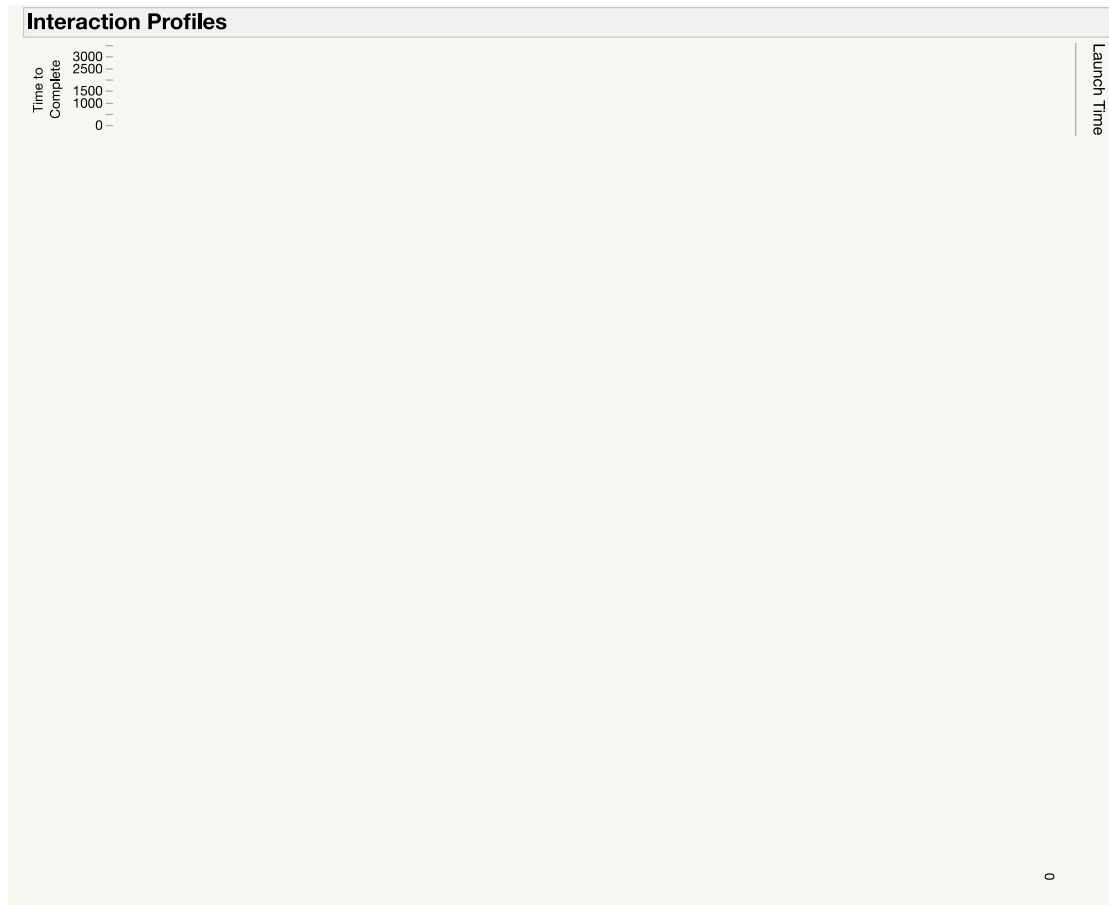


Figure 46. Alternative 1 – Time to Complete Interaction Plot

Significant interactions:

- Recovery Time*PMA Rate
- UUV Speed*Sensor Width

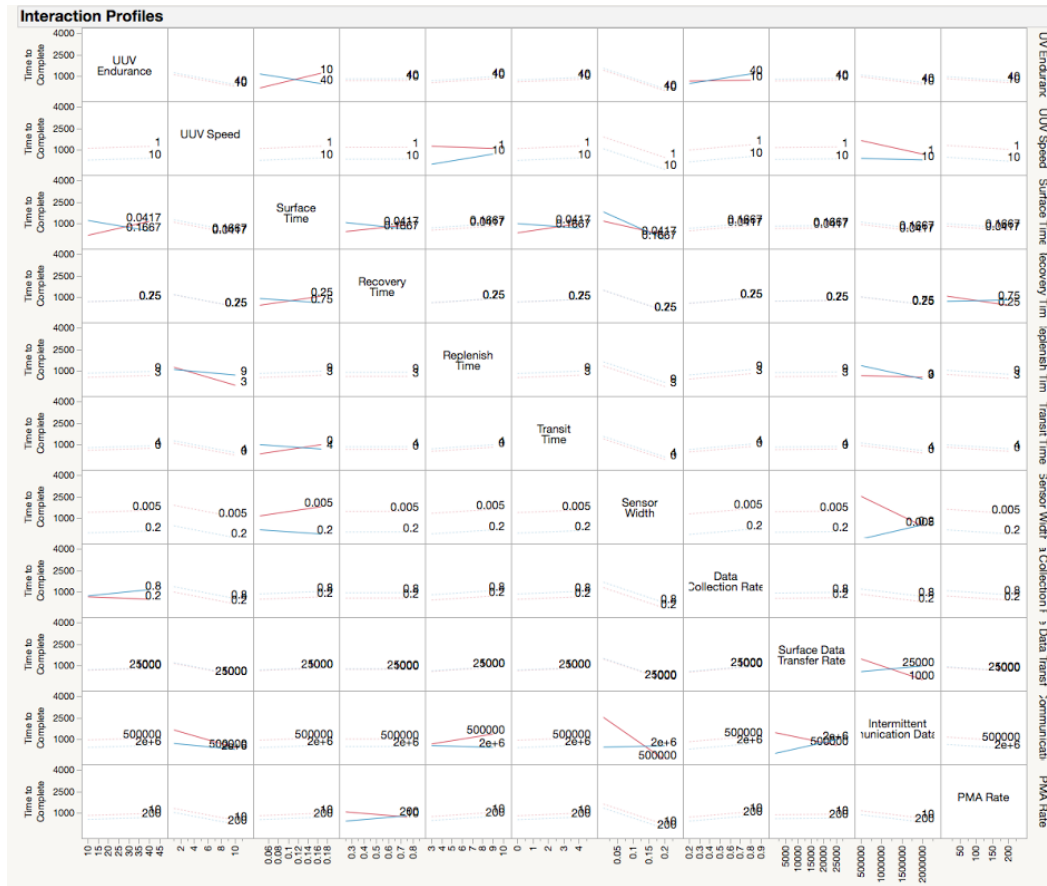


Figure 47. Alternative 2 – Interaction Plot Time to Complete

Significant interactions:

- Sensor Width*IC Data Limit
- Surface Data Transfer Rate*IC Data Limit
- UUV Endurance*Surface Time
- Surface Time*Sensor Width

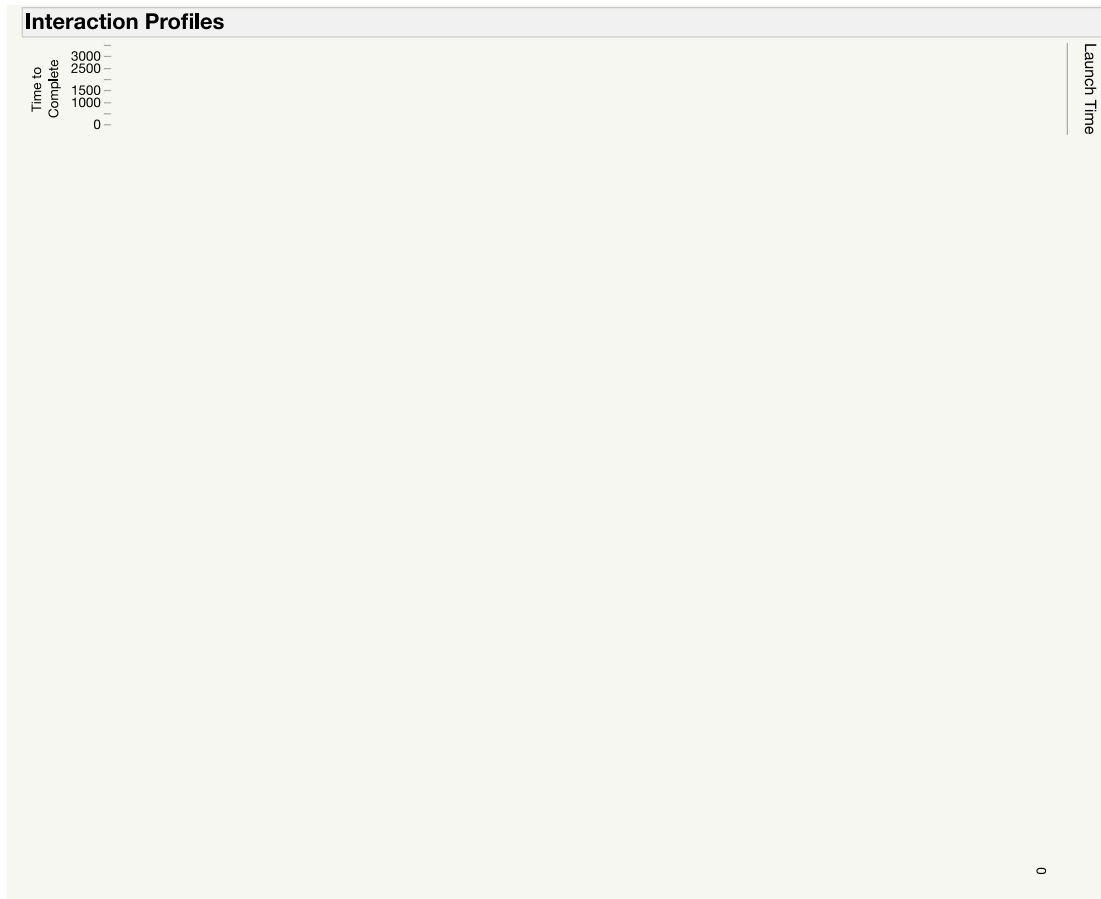


Figure 48. Alternative 3 – Time to Complete Interaction Plot

Significant interactions:

- Recovery Time*PMA Rate
- UUV Speed*Sensor Width

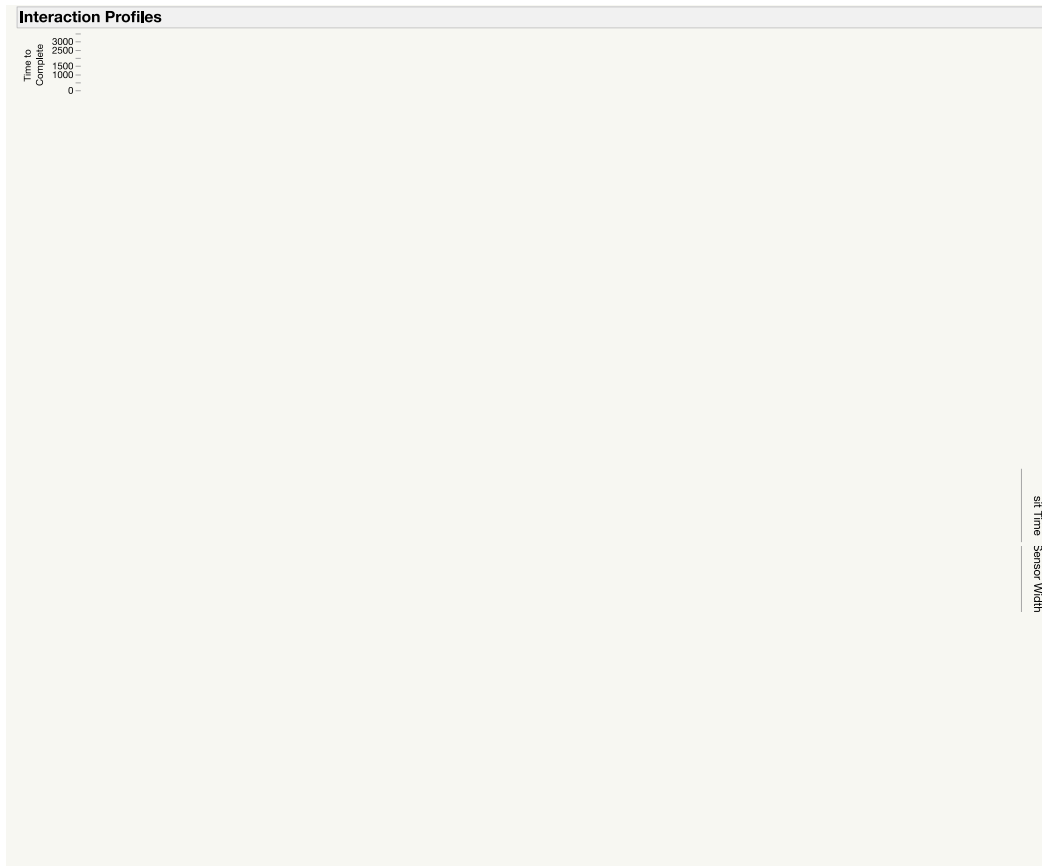


Figure 49. Alternative 4 – Time to Complete Interaction Plot

Significant interactions:

- UUV Speed*Sensor Width
- Transit Time*RTA Rate
- Recovery Time*PMA Rate
- Manual Download Rate*RTA Rate
- UUV Speed*Replenish Time
- Recovery Time*Replenish Time
- Sensor Width*PMA Rate
- Sensor Width*RTA Rate

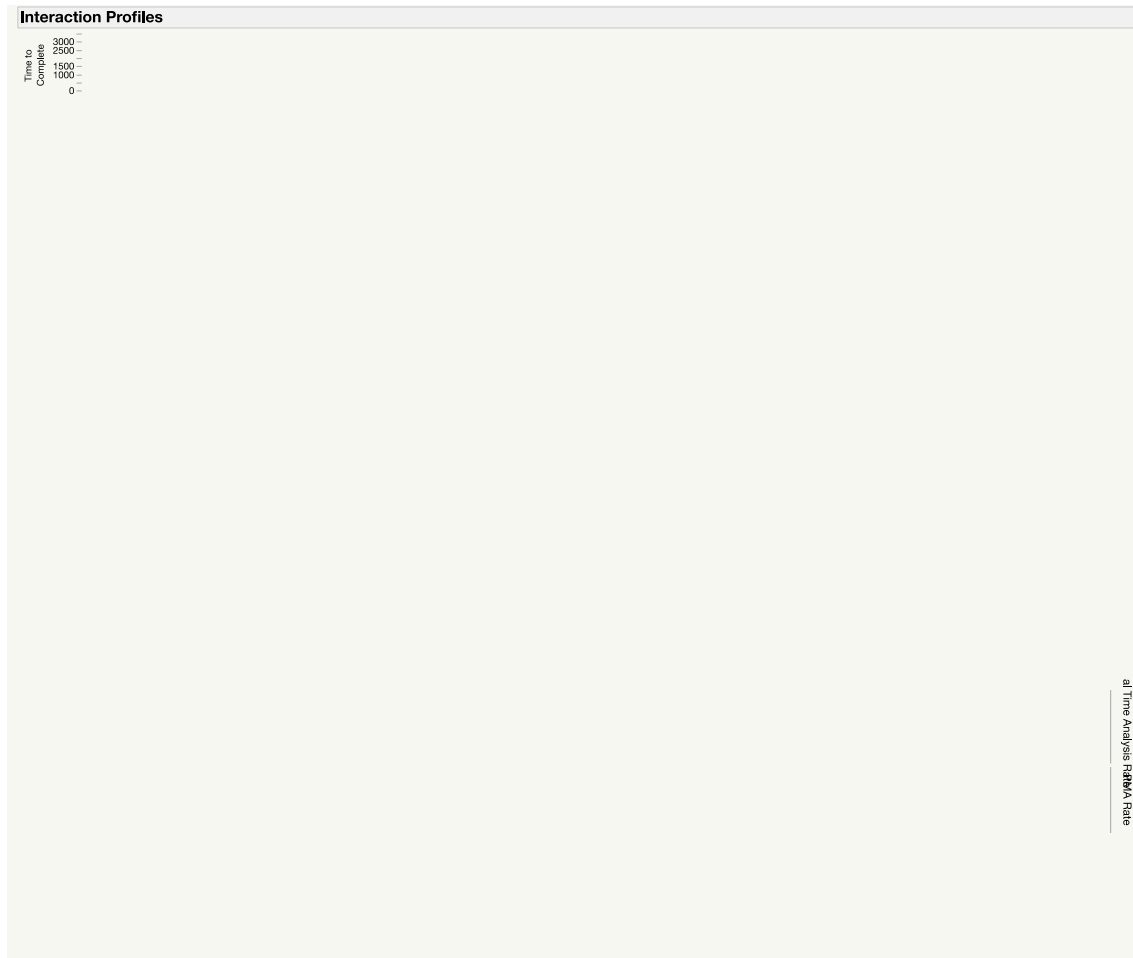


Figure 50. Alternative 5 – Time to Complete Interaction Plot

Significant interactions:

- Data Collection Rate*RTA Rate
- Sensor Width*IC Data Limit
- UUV Speed*Sensor Width
- Recovery Time*Replenish Time
- Recovery Time*PMA Rate

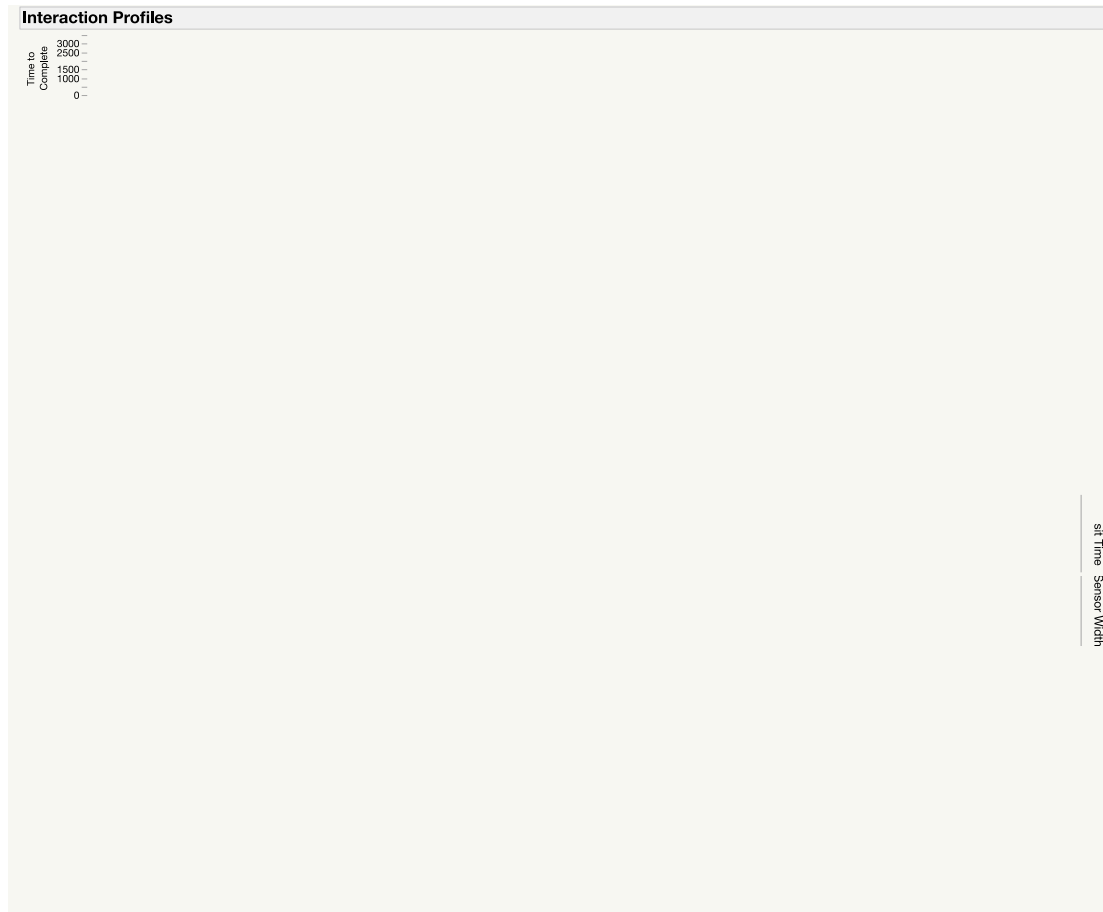


Figure 51. Alternative 6 – Time to Complete Interaction Plot

Significant interactions:

- UUV Speed*Sensor Width
- Transit Time*RTA Rate
- Recovery Time*PMA Rate
- Manual Download Rate*RTA Rate
- UUV Speed*Replenish Time
- Recovery Time*Replenish Time
- Sensor Width*PMA Rate
- Sensor Width*RTA Rate

B. AVERAGE PROCESS TIME PREDICTED PLOTS, PARAMETER ESTIMATES, AND INTERACTION PLOTS

Figure 52 through Figure 69 show the predicted plots, parameter estimates, and interactions plots for the average process time metric for each alternative.

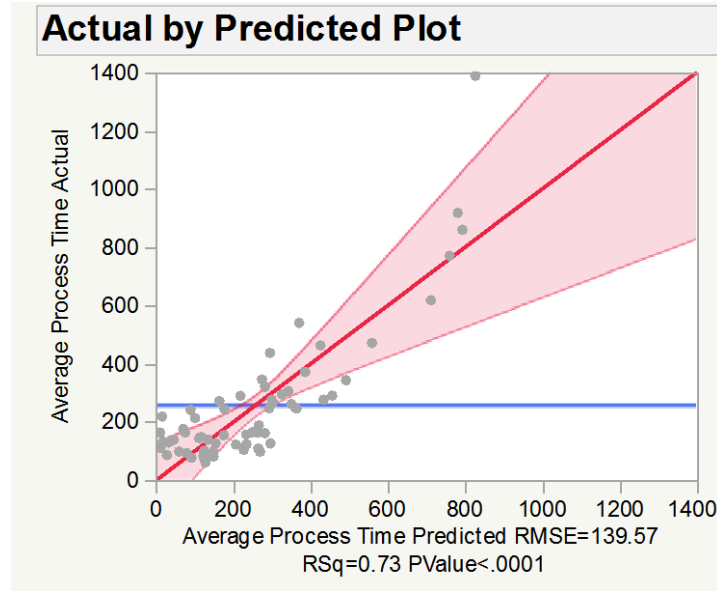


Figure 52. Alternative 1 – Average Process Time Regression Results

Parameter Estimates				
Term				
Sensor Width	-1794.799	308.6797	-5.81	<.0001*
(Data Collection Rate-0.49723)*(PMA Rate-104.954)	-7.04684	1.793296	-3.93	0.0003*
UUV Speed	-26.38854	6.74618	-3.91	0.0003*
(Recovery Time-0.50074)*(PMA Rate-104.954)	6.8707839	1.894994	3.63	0.0007*
(UUV Speed-5.56813)*(Sensor Width-0.10374)	355.12217	115.5288	3.07	0.0035*
PMA Rate	-0.944872	0.310997	-3.04	0.0039*
Surface Time	1075.893	477.8188	2.25	0.0292*
Transit Time	32.654227	14.78919	2.21	0.0323*
Intercept	307.04393	146.0023	2.10	0.0410*
Replenish Time	20.572819	9.860341	2.09	0.0425*
(Launch Time-0.49854)*(Sensor Width-0.10374)	-4195.449	2057.079	-2.04	0.0472*
(Transit Time-2.00684)*(Manual Download Rate-275.769)	0.193418	0.098906	1.96	0.0566
(Surface Time-0.10356)*(Sensor Width-0.10374)	-15884.25	8718.621	-1.82	0.0750
Launch Time	187.01757	118.6364	1.58	0.1218
Data Collection Rate	149.81851	99.46187	1.51	0.1388
Manual Download Rate	-0.164196	0.13147	-1.25	0.2180
(Surface Time-0.10356)*(Data Collection Rate-0.49723)	-4463.882	3701.777	-1.21	0.2340
Recovery Time	-75.8583	118.25	-0.64	0.5244

Figure 53. Alternative 1 – Average Process Time Parameter Estimates



Figure 54. Alternative 1 – Average Process Time Interaction Plot

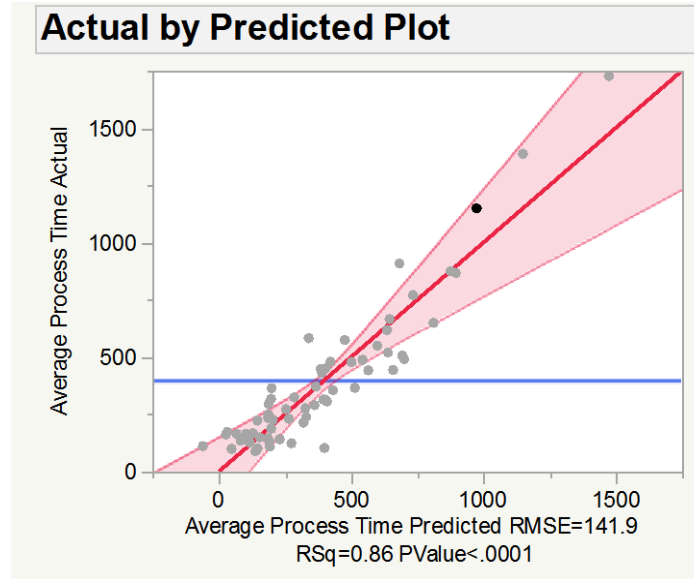


Figure 55. Alternative 2 – Average Process Time Regression Results

Parameter Estimates				
Term				
Sensor Width	-3516.642	314.8256	-11.17	<.0001*
UUV Speed	-42.80702	6.907136	-6.20	<.0001*
Intercept	840.04518	156.6435	5.36	<.0001*
(Sensor Width-0.10374)*(Intermittent Communication Data Limit-1254028)	0.003824	0.000735	5.20	<.0001*
(Surface Data Transfer Rate-13076.2)*(Intermittent Communication Data Limit-1254028)	2.7308e-8	5.349e-9	5.10	<.0001*
Intermittent Communication Data Limit	-0.000155	4.019e-5	-3.85	0.0004*
(UUV Endurance-25.2198)*(Surface Time-0.10356)	-303.5536	82.08609	-3.70	0.0006*
Data Collection Rate	344.67487	101.3188	3.40	0.0015*
PMA Rate	-0.797303	0.316379	-2.52	0.0156*
(Surface Time-0.10356)*(Sensor Width-0.10374)	-21453.7	9209.834	-2.33	0.0247*
Replenish Time	18.746784	10.03052	1.87	0.0686
(Recovery Time-0.50074)*(PMA Rate-104.954)	4.3208698	2.377826	1.82	0.0763
UUV Endurance	3.4961393	2.060435	1.70	0.0971
(Recovery Time-0.50074)*(Surface Data Transfer Rate-13076.2)	-0.024737	0.015919	-1.55	0.1277
(UUV Endurance-25.2198)*(Data Collection Rate-0.49723)	17.515292	12.15698	1.44	0.1571
Surface Time	681.78442	486.1406	1.40	0.1681
Transit Time	18.369724	15.04111	1.22	0.2288
(Sensor Width-0.10374)*(PMA Rate-104.954)	9.4987628	8.110916	1.17	0.2482
Data Reduction Rate	-80.36418	73.2535	-1.10	0.2789
(Replenish Time-5.98977)*(Data Collection Rate-0.49723)	78.436076	73.08729	1.07	0.2893
Surface Data Transfer Rate	0.0002247	0.002518	0.09	0.9293
Recovery Time	-9.025726	120.2659	-0.08	0.9405

Figure 56. Alternative 2 – Average Process Time Parameter Estimates



Figure 57. Alternative 2 – Average Process Time Interaction Plot

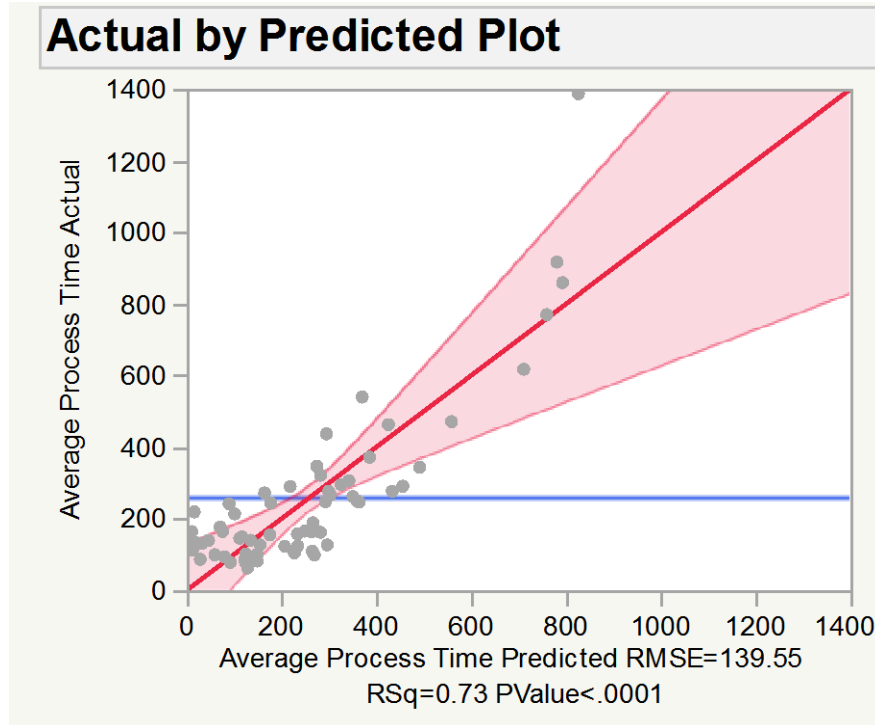


Figure 58. Alternative 3 – Average Process Time Regression Results

Parameter Estimates				
Term				
Sensor Width	-1794.225	308.6385	-5.81	<.0001*
(Data Collection Rate-0.49723)*(PMA Rate-104.954)	-7.046007	1.793057	-3.93	0.0003*
UUV Speed	-26.38166	6.74528	-3.91	0.0003*
(Recovery Time-0.50074)*(PMA Rate-104.954)	6.8691479	1.894741	3.63	0.0007*
(UUV Speed-5.56813)*(Sensor Width-0.10374)	355.02331	115.5134	3.07	0.0036*
PMA Rate	-0.944637	0.310955	-3.04	0.0039*
Surface Time	1075.7477	477.7551	2.25	0.0292*
Transit Time	32.649781	14.78722	2.21	0.0323*
Intercept	306.81392	145.9829	2.10	0.0411*
Replenish Time	20.572749	9.859026	2.09	0.0425*
(Launch Time-0.49854)*(Sensor Width-0.10374)	-4195.555	2056.805	-2.04	0.0471*
(Transit Time-2.00684)*(Manual Download Rate-275.769)	0.1934196	0.098893	1.96	0.0566
(Surface Time-0.10356)*(Sensor Width-0.10374)	-15883.46	8717.458	-1.82	0.0750
Launch Time	187.01483	118.6206	1.58	0.1217
Data Collection Rate	149.84162	99.44861	1.51	0.1387
Manual Download Rate	-0.164082	0.131453	-1.25	0.2183
(Surface Time-0.10356)*(Data Collection Rate-0.49723)	-4464.004	3701.284	-1.21	0.2340
Recovery Time	-75.80597	118.2342	-0.64	0.5246

Figure 59. Alternative 3 – Average Process Time Parameter Estimates



Figure 60. Alternative 3 – Average Process Time Interaction Plot

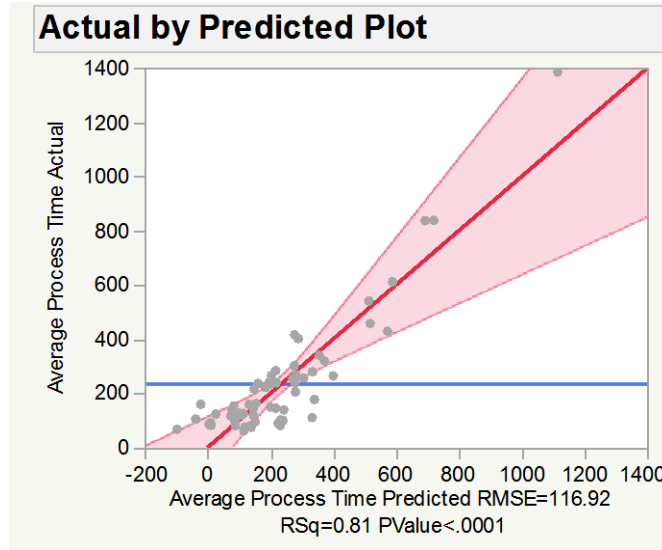


Figure 61. Alternative 4 – Average Process Time Regression Results

Parameter Estimates

Term				
Sensor Width	-1666.642	258.5456	-6.45	<.0001*
(Transit Time-2.00684)*(Real Time Analysis Rate-25.7034)	-4.429396	0.921635	-4.81	<.0001*
(UUV Speed-5.56813)*(Sensor Width-0.10374)	424.09607	93.65506	4.53	<.0001*
UUV Speed	-24.31056	5.643768	-4.31	0.0001*
(Manual Download Rate-275.769)*(Real Time Analysis Rate-25.7034)	-0.035749	0.0086	-4.16	0.0002*
(Recovery Time-0.50074)*(PMA Rate-104.954)	5.5350622	1.48881	3.72	0.0006*
(Sensor Width-0.10374)*(PMA Rate-104.954)	-16.85273	5.933405	-2.84	0.0070*
(Replenish Time-5.98977)*(PMA Rate-104.954)	0.7314861	0.260672	2.81	0.0076*
Intercept	345.36589	125.1787	2.76	0.0086*
Real Time Analysis Rate	-2.708668	1.018029	-2.66	0.0111*
Replenish Time	19.806837	8.262424	2.40	0.0212*
PMA Rate	-0.621647	0.260622	-2.39	0.0218*
Surface Time	941.29616	400.3292	2.35	0.0236*
Transit Time	26.559634	12.39265	2.14	0.0381*
(UUV Speed-5.56813)*(Replenish Time-5.98977)	-7.25147	3.780734	-1.92	0.0621
(Launch Time-0.49854)*(Data Collection Rate-0.49723)	-1400.425	808.1099	-1.73	0.0906
(Launch Time-0.49854)*(Transit Time-2.00684)	-219.0286	139.891	-1.57	0.1251
Data Collection Rate	126.67867	83.29581	1.52	0.1360
Launch Time	149.15728	99.36052	1.50	0.1410
(Surface Time-0.10356)*(Manual Download Rate-275.769)	-4.962774	3.464284	-1.43	0.1596
Manual Download Rate	-0.139049	0.110156	-1.26	0.2140
(Surface Time-0.10356)*(Transit Time-2.00684)	-342.537	410.3245	-0.83	0.4087
Recovery Time	-71.46962	99.0572	-0.72	0.4747

Figure 62. Alternative 4 – Average Process Time Parameter Estimates

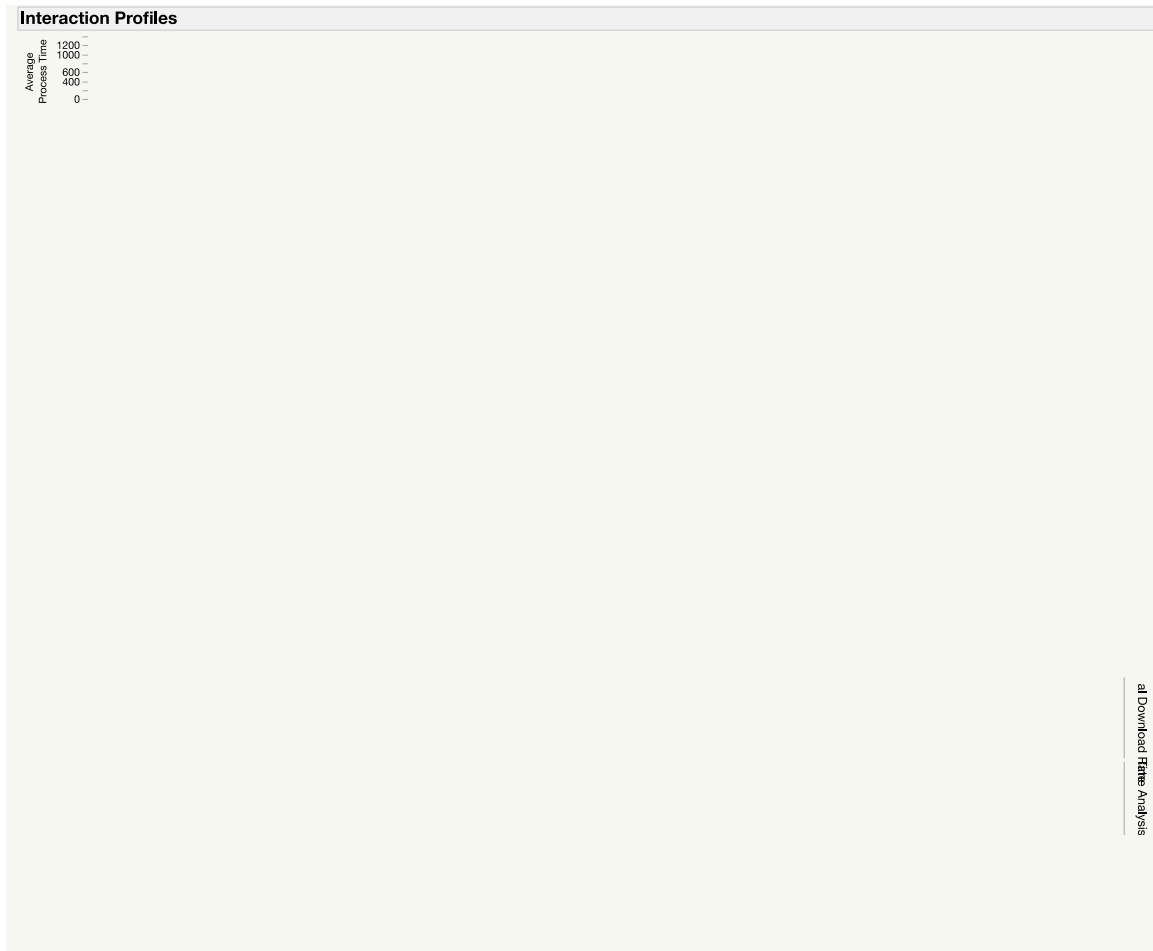


Figure 63. Alternative 4 – Average Process Time Interaction Plot

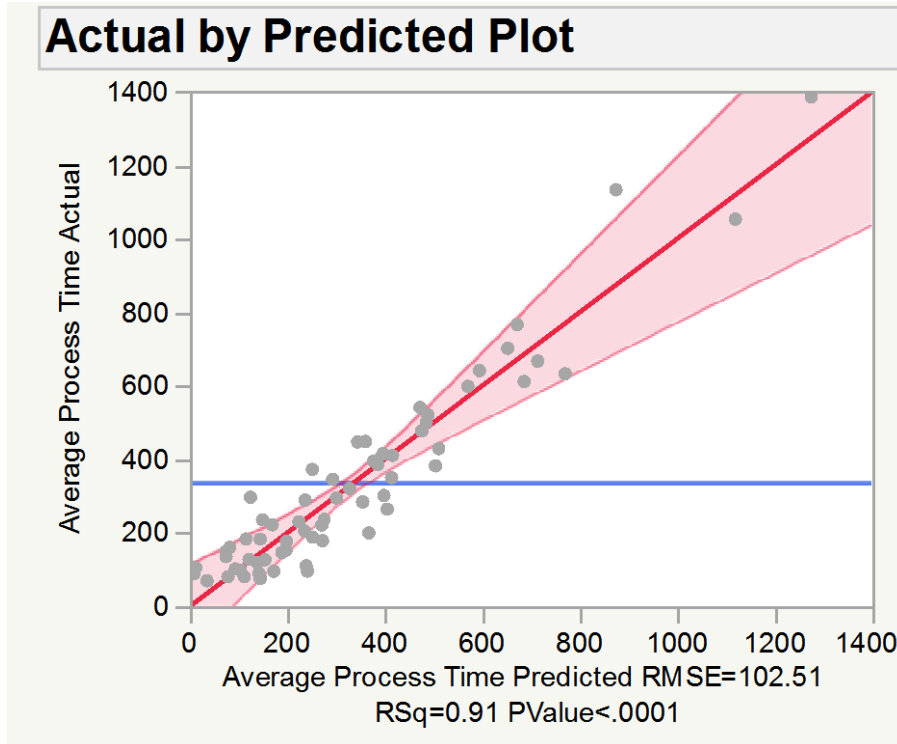


Figure 64. Alternative 5 – Average Process Time Regression Results

Parameter Estimates

Term				
Sensor Width	-2814.415	227.7279	-12.36	<.0001*
Intercept	921.29888	103.9311	8.86	<.0001*
UUV Speed	-37.56669	4.997384	-7.52	<.0001*
(Data Collection Rate-0.49723)*(PMA Rate-104.954)	-9.948171	1.798933	-5.53	<.0001*
(Surface Data Transfer Rate-13076.2)*(Real Time Analysis Rate-25.7034)	0.0006023	0.000131	4.61	<.0001*
Intermittent Communication Data Limit	-0.000131	0.000029	-4.52	<.0001*
(Recovery Time-0.50074)*(PMA Rate-104.954)	5.3109525	1.393655	3.81	0.0005*
PMA Rate	-0.843949	0.228456	-3.69	0.0007*
(UUV Speed-5.56813)*(Sensor Width-0.10374)	301.98186	83.34093	3.62	0.0008*
Real Time Analysis Rate	-3.183829	0.894697	-3.56	0.0010*
Data Collection Rate	254.92298	73.11376	3.49	0.0012*
(Sensor Width-0.10374)*(Data Collection Rate-0.49723)	-5844.39	1697.277	-3.44	0.0014*
(Replenish Time-5.98977)*(Sensor Width-0.10374)	-380.4301	131.9981	-2.88	0.0064*
Data Reduction Rate	-151.5342	53.05297	-2.86	0.0068*
(Recovery Time-0.50074)*(Transit Time-2.00684)	228.78614	83.91356	2.73	0.0095*
(Data Collection Rate-0.49723)*(Intermittent Communication Data Limit-1254028)	-0.00042	0.000182	-2.31	0.0265*
Replenish Time	15.421601	7.248837	2.13	0.0398*
(Data Collection Rate-0.49723)*(Real Time Analysis Rate-25.7034)	10.34493	5.188548	1.99	0.0532
(Replenish Time-5.98977)*(PMA Rate-104.954)	0.3290842	0.17175	1.92	0.0627
(Recovery Time-0.50074)*(Replenish Time-5.98977)	-105.9755	58.23687	-1.82	0.0765
Recovery Time	145.52513	86.89211	1.67	0.1020
(Data Collection Rate-0.49723)*(Data Reduction Rate-0.51836)	464.94709	330.2767	1.41	0.1671
(UUV Speed-5.56813)*(Data Collection Rate-0.49723)	34.559303	30.53078	1.13	0.2646
Transit Time	12.264159	10.86711	1.13	0.2660
Surface Data Transfer Rate	0.0010802	0.001819	0.59	0.5561

Figure 65. Alternative 5 – Average Process Time Parameter Estimates

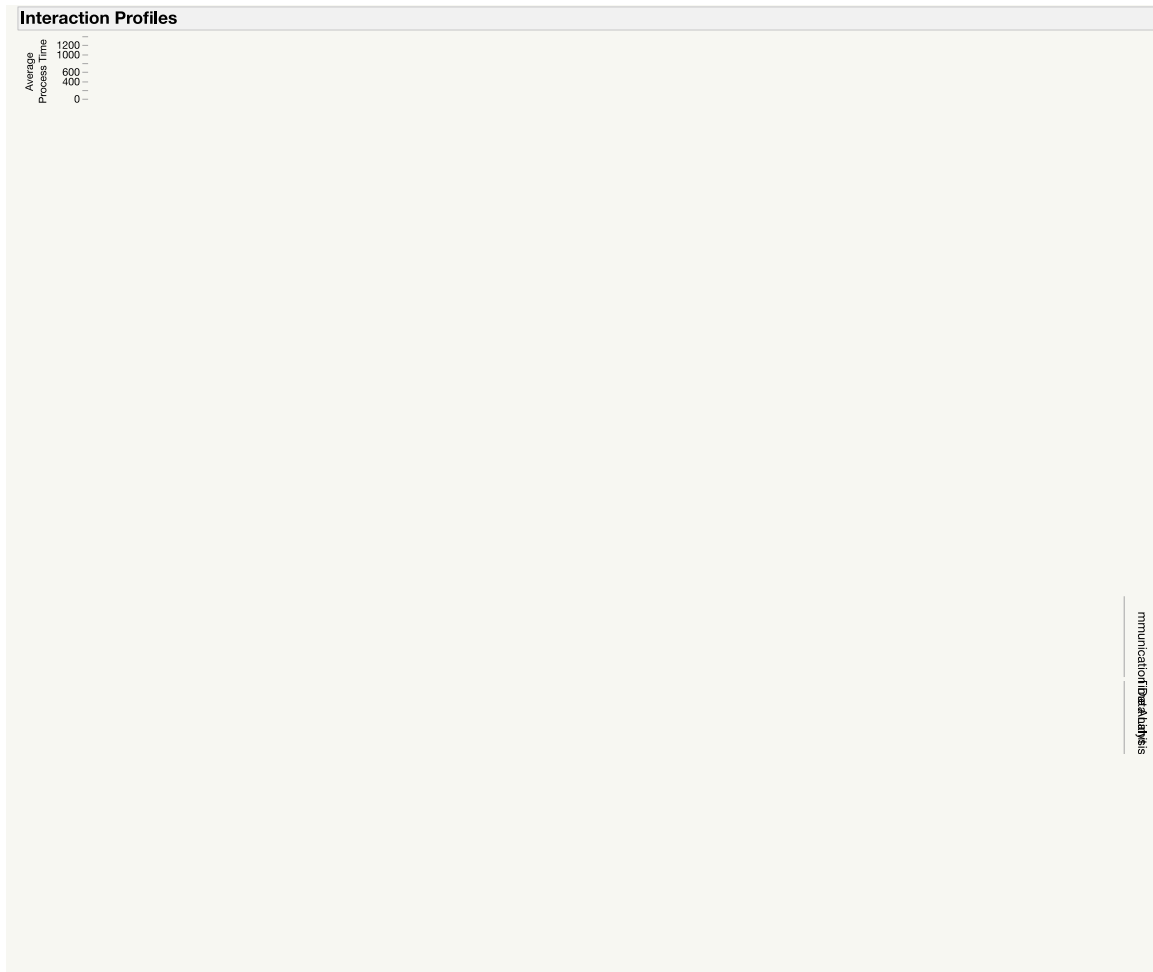


Figure 66. Alternative 5 – Average Process Time Interaction Plot

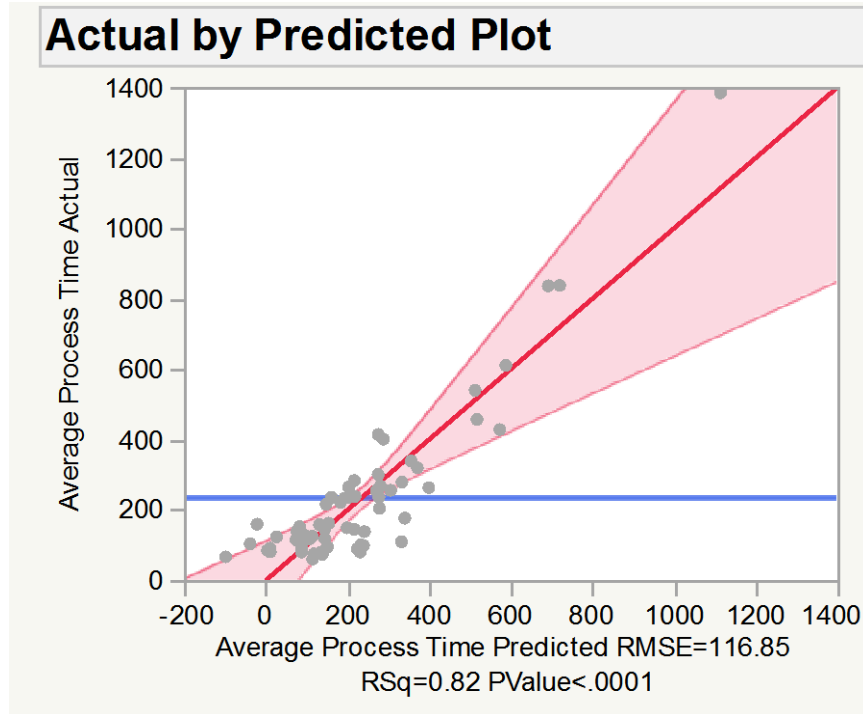


Figure 67. Alternative 6 – Average Process Time Regression Results

Parameter Estimates				
Term				
Sensor Width	-1663.937	258.3836	-6.44	<.0001*
(Transit Time-2.00684)*(Real Time Analysis Rate-25.7034)	-4.443402	0.921057	-4.82	<.0001*
(UUV Speed-5.56813)*(Sensor Width-0.10374)	424.79988	93.59638	4.54	<.0001*
UUV Speed	-24.33494	5.640232	-4.31	<.0001*
(Manual Download Rate-275.769)*(Real Time Analysis Rate-25.7034)	-0.035645	0.008594	-4.15	0.0002*
(Recovery Time-0.50074)*(PMA Rate-104.954)	5.5227924	1.487877	3.71	0.0006*
(Sensor Width-0.10374)*(PMA Rate-104.954)	-16.76344	5.929687	-2.83	0.0072*
(Replenish Time-5.98977)*(PMA Rate-104.954)	0.7336955	0.260509	2.82	0.0074*
Intercept	345.1671	125.1003	2.76	0.0086*
Real Time Analysis Rate	-2.719564	1.017391	-2.67	0.0107*
Replenish Time	19.84441	8.257247	2.40	0.0209*
PMA Rate	-0.6238	0.260459	-2.40	0.0213*
Surface Time	941.88264	400.0784	2.35	0.0234*
Transit Time	26.450575	12.38488	2.14	0.0387*
(UUV Speed-5.56813)*(Replenish Time-5.98977)	-7.237095	3.778365	-1.92	0.0624
(Launch Time-0.49854)*(Data Collection Rate-0.49723)	-1402.901	807.6035	-1.74	0.0899
(Launch Time-0.49854)*(Transit Time-2.00684)	-219.0102	139.8034	-1.57	0.1249
Data Collection Rate	127.55072	83.24362	1.53	0.1331
Launch Time	149.25627	99.29826	1.50	0.1405
(Surface Time-0.10356)*(Manual Download Rate-275.769)	-4.989335	3.462113	-1.44	0.1571
Manual Download Rate	-0.138122	0.110087	-1.25	0.2167
(Surface Time-0.10356)*(Transit Time-2.00684)	-340.3739	410.0674	-0.83	0.4113
Recovery Time	-72.27623	98.99514	-0.73	0.4695

Figure 68. Alternative 6 – Average Process Time Parameter Estimates

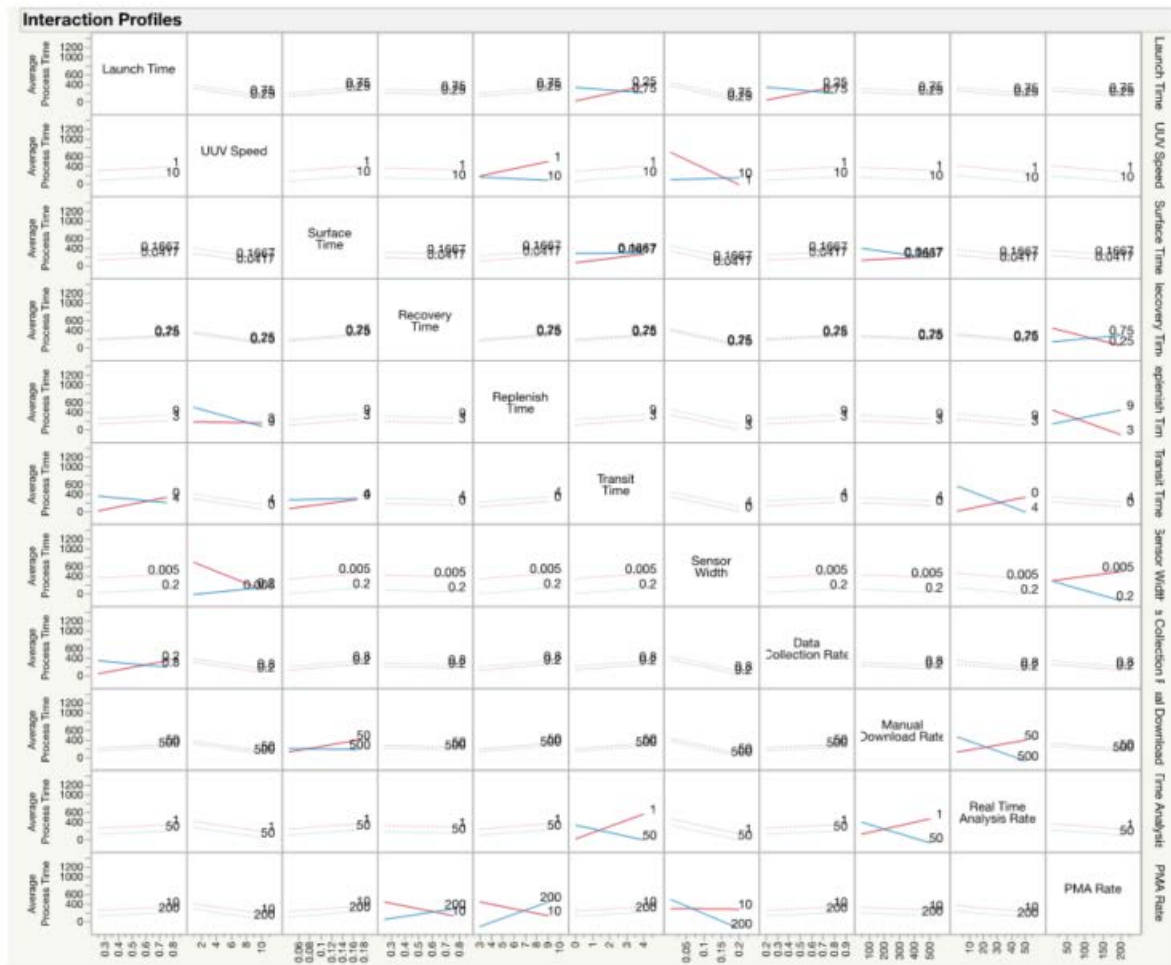


Figure 69. Alternative 6 – Average Process Time Interaction Plot

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