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SYSTEM ARCHITECTURE AND OPERATIONAL ANALYSIS OF MEDIUM DISPLACEMENT UNMANNED SURFACE VEHICLE SEA HUNTER AS A SURFACE WARFARE COMPONENT OF DISTRIBUTED LETHALITY

by

Kristjan J. Casola

June 2017

Thesis Advisor:	Eugene Paulo
Co-Advisor:	Paul Beery
Second Reader:	Fotis Papoulias

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Kristjan J. Casola
Lieutenant, United States Navy
B.S., University of Maryland, 2008

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Approved by: Eugene Paulo, Ph.D.
Thesis Advisor

Paul Beery, Ph.D.
Co-Advisor

Fotis Papoulias, Ph.D.
Second Reader

Ronald E. Giachetti, Ph.D.
Chair, Department of Systems Engineering

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This thesis analyzes the vessel's potential contribution to distributed lethality as a surface warfare (SuW) platform. The author first attempts to establish traceability, requirements and capabilities while determining the architecture framework in accordance with the Department of Defense Architectural Framework (DODAF). Then, using an experimental approach with a basic operational analysis, this thesis demonstrates, through the use of model-based systems engineering (MBSE) and simulation tools, the effectiveness of an anti-surface warfare (ASUW) version of the Anti-Submarine Warfare Continuous Trail Unmanned Vessel (ACTUV) in supporting distributed lethality. Analysis is built on ACTUV simulation data already available as well as results from the author's simulations.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACTUV	Anti-submarine Warfare Continuous Trail Unmanned Vessel
AFP	adaptive force package
AHP	analytical hierarchy process
ASCM	anti-ship cruise missile
ASUW	Anti-surface Warfare
ASW	antisubmarine warfare
C2	command and control
CONOPS	concept of operations
DDG	guided missile destroyer
DODAF	Department of Defense Architectural Framework
EFFBD	enhanced functional flow block diagram
EMCON	emissions condition
IAMD	integrated air and missile defense
ISR	intelligence, surveillance, reconnaissance
LCS	littoral combat ship
LWC	light-weight canister
MBSE	model based systems engineering
MDUSV	medium displacement unmanned surface vehicle
ONR	Office of Naval Research
RAM	reliability, availability, maintainability
RAS	replenishment at sea
RCS	radar cross section
ROE	rules of engagement
SAG	surface action group
SE	systems engineering
SOP	standard operating procedure
SRBOC	super rapid bloom offboard countermeasures
SUWC	surface warfare commander
TTP	tactics, techniques, and procedures
VLS	vertical launching system

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EXECUTIVE SUMMARY

The U.S. Navy is in the process of implementing a new operational strategy for Surface Warfare (SuW). This model, called Distributed Lethality (DL), is centered around the premise of employing combatant units in an offensive manner that forces the adversary to disperse his forces (Fanta et al. 2015). To be effective, DL requires a given quantity and quality of platforms. For the surface navy, this means having enough warships to form multiple offensive "hunter killer" surface action groups to take the fight to the enemy in his own backyard. It also means these warships must possess a lethality that warrants attention from the adversary and presents a threat. The needs to effectively implement DL are clear and obvious. How to meet those needs in a cost-effective manner is not as obvious. The U.S. Navy has released plans to increase the fleet's size to 355 ships (Cavas 2017). In order to accomplish that goal while remaining fiscally responsible, it is vital to consider what types of ships will provide the most benefit while remaining affordable.

One possible solution to consider is the use of unmanned surface ships. The U.S. Navy is currently testing such a ship. *Sea Hunter,* an autonomous surface ship displacing 145 long tons, was designed and built to hunt submarines. *Sea Hunter* is also known by its system name of Anti-Submarine Warfare Continuous Trail Unmanned Vessel (ACTUV). With a range of up to 17,000 nautical miles, and the ability to operate in environmental conditions up to sea state 7, it signifies a leap forward in autonomous maritime capability and could represent the next phase of naval surface operations (Stella 2016). When evaluated aside from its original anti-submarine roles, the vessel appears to have significant potential to perform a myriad of other missions, such as surface warfare. With its two separate mission support areas on the main deck, the author envisions the vessel as a mobile anti-ship cruise missile-launching platform. The vessel's unmanned nature, coupled with a relatively affordable procurement cost of $23 million, could indicate a low risk system capable of both supporting DL and meeting the goal of a 355-ship Navy.

In order to assess the system's potential as an effective addition to the surface fleet, the author incorporates traditional systems engineering (SE) practices and methodology. The traditional "Vee" model serves as the SE tool of choice for analyzing the system for the purpose of conducting SuW within DL. The methodology progresses from an initial concept exploration to establishing system requirements and developing a concept of operations. A functional and physical architecture is developed in order to establish a high-level design and partial detailed design. Finally, computer modeling and simulation offers some insight on how to equip and employ *Sea Hunter* as an effective warship in a combat scenario.

The DL high level needs for conducting SuW with *Sea Hunter* are determined to be ease of integration, logistics, system size and scalability, command and control and lethality. These needs are further delineated into requirements to be met by specific functions. A physical architecture traces the functions to allocated physical components. Diagrams depicting functional and physical hierarchy, as well as functional flow diagrams, provide visual aids to understand the established architecture.

Scenarios for the computer-based simulations are loosely based on previous wargames conducted by an Operational Analysis class at the Naval Postgraduate School. The wargames featured several Medium Displacement Unmanned Surface Vehicles (MDUSVs) that were used as picket boats to conduct reconnaissance and gather intelligence one the adversary surface force. An MDUSV is the same platform as *Sea Hunter* without the ASW-specific role and equipment. The simulations in this report extend the MDUSVs' role to that of an offensive platform by simulating their launching of anti-ship cruise missiles (ASCMs). Two separate set of simulations provide both predictive and comparative analysis of salvo exchanges.

Comparative analysis of salvo exchange results is performed through the use equations originating from Captain (Ret.) Wayne Hughes' Salvo Model. Spreadsheet calculations provide analysis of force-on-force engagements. Inputs include number of vessels, number of missiles launched per vessel, number of incoming missiles each vessel can shoot down, and number of missile hits required to take a vessel out of action. Results of two opposing forces of equal capabilities demonstrate the need for a significant force size advantage if casualties are to be minimized. Tables provided the minimum number of MDSUVs and ASCMs per vessel for a given opposing force size.

Predictive analysis of engagements' is provided by the Imagine That Inc. modeling program, ExtendSim. ExtendSim allows for more dynamic and complex simulations by providing the option of variable inputs. The results of the Salvo Model simulations indicate the need for a more robust missile defense. The first two scenarios simulate the effects of utilizing a defense ship version of the MDUSV. This defense ship provides a short-range integrated air and missile defense (IAMD) by employing the SeaRAM system. Each SeaRAM system provides an integrated search and tracking radar and fire control system along with eleven RIM-116 missiles. Simulation results indicate significant decreases in the number of MDUSVs lost in an engagement.

A final scenario proposes the use of a MDUSV defense ship as a "missile sponge" by increasing its probability of being targeting by an incoming ASCM. In reality, an increase in radar cross section could accomplish the same result. To counteract the increase in hostile targeting, the defense ships were simulated to employ countermeasures, such as chaff. Unsurprisingly, this configuration resulted in the fewest friendly MDUSV casualties, whether defense ships or ASCM-launching ships.

This report establishes an architecture that provides traceability from high-level needs to functions and components. A proposed concept of operations provides a realistic and feasible model of how MDUSVs could operate as part of an adaptive force package in conjunction with DL operational objectives. Simulations of MDUSVs with specific weapon systems demonstrate a theoretical ability to pose a significant threat. The findings of this thesis lend the author to emphatically recommend further investigation on utilizing the MDUSV platform for SuW.

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I. INTRODUCTION

Over the last two years, two events occurred that this author believes could have a significant effect on the U.S. Navy (USN) and how it operates in the near future. First, on April 7, 2016, Defense Advanced Research Projects Agency (DARPA) christened an autonomous and unmanned surface vessel, named *Sea Hunter* (DARPA 2016). This autonomous vessel, whose platform type is called an Anti-Submarine Warfare Continuous Trail Unmanned Vessel (ACTUV), is the result of a project to develop an unmanned surface vehicle capable of countering the growing diesel-electric submarine threat posed by the U.S. Navy's adversaries. *Sea Hunter,* shown in Figure 1, is the largest unmanned ship to date and reflects a shift in naval warfare to the increased dedication and focus on developing unmanned and autonomous systems. DARPA is currently conducting joint testing of the vessel with the Office of Naval Research (ONR) and expects to eventually hand the *Sea Hunter* over to the Navy in 2018 (DARPA 2016).

Second, in 2015, Vice Admiral (VADM) Thomas Rowden co-authored an article with Rear Admiral Peter Fanta and Rear Admiral Peter Gumataotao in the journal *Proceedings,* entitled "Distributed Lethality" (Fanta et al. 2015). In it, the authors claim that some of the U.S. Navy's adversaries have made noteworthy strides in their surface warfare (SuW) capabilities, particularly with anti-ship cruise missiles (ASCMs). As a result, the USN is no longer unchallenged in the sea control domain. The authors then precede to layout a new strategy to counter this new challenge—a model they call Distributed Lethality (DL). While there are many facets to DL with several potential modes of implementation and areas of application, one idea that seems to take root with several Naval leaders is the need for offensive surface vessels that can be deployed in such a way as to disperse the adversary's forces while posing a significant threat (Rowden 2014). To be in line with the current fiscal environment, this platform must be cost-effective, from both a procurement and operating perspective. Finally, if this platform is to be a viable and effective offensive weapon, task commanders must be willing to accept the risk of losing it as a result of sending it into harm's way.

Figure 1. ACTUV during Initial Testing. Source: Jontz (2016).

A. PURPOSE

This thesis is a response to a general study topic request from the Naval Research Program to identify and conceptualize other warfare roles for the ACTUV. SuW is the chosen warfare area for this thesis. In particular, though, this thesis focuses on the SuW element of Distributed Lethality and seeks to determine what SuW role, if any, the ACTUV platform could have in DL. Building on work completed by Naval Postgraduate School (NPS) students in a war-gaming class, and working in tandem with a NPS distance learning class that is analyzing the Command and Control (C2) component of DL, this author will present the methods for integrating the ACTUV into the SuW component of DL.

Current information indicates that the ACTUV is a promising platform with potential to excel in multiple warfare roles. According to a DARPA press release from October 24, 2016, *Sea Hunter* has performed admirably in its autonomous abilities and has already served as a testbed for other systems. It successfully demonstrated the ability to deploy the Towed Airborne Lift of Naval Systems (TALONS), further showcasing its ability to conduct a “wide variety of missions” (DARPA 2016). If one considers the

ACTUV platform as a truck with the ability to carry various types of loads in its cargo bed, it is easy to see the many possible ways to utilize the ACTUV. The current two-year test plan currently only calls for ASW and Mine Warfare (MW) testing (Littlefield 2017). It may be highly advantageous to extend the testing to other areas, such as SuW.

DL is also quickly gaining traction as an accepted course change in how the USN should approach projecting power. While DL can involve many, if not all, of the warfare areas, the surface ship application is one of the most obvious due to the inherent endurance and visual deterrence of warships. Since its formal introduction in the *Proceedings* article, DL has been the subject of many journal articles, conferences and academic projects, including war-gaming efforts. In fact, in June 2015, VADM Rowden stood up the Distributed Lethality Task Force (DLTF) to spearhead and coordinate the efforts to implement this new strategy (Truver 2016). This thesis represents another effort to determine how to best implement DL by examining the ACTUV's potential role in DL and the benefits to be gained.

B. RESEARCH QUESTIONS

- Does the ACTUV have potential to be an effective SuW system for DL?
- How can the ACTUV be integrated into an Adaptive Force Package to support SuW, especially within DL?
- How should the ACTUV be used, in terms of system configuration and tactics, as a SuW component in DL?

C. BENEFITS OF STUDY

Now that a Medium Displacement Unmanned Surface Vehicle (MDUSV) prototype exists and is well into its testing phase, with what have so far been promising results, the question on many Navy leaders' minds is, "What else can we do with ACTUV?" This study attempts to provide at least one answer. Prudence dictates that, if the ACTUV platform is as useful as it appears, the Navy should seek to capitalize on the investments made within the ACTUV program and determine what other roles it could play. From a defense acquisition perspective, the ACTUV could represent a technological opportunity. It is possible that the ACTUV represents not just a cost-effective answer to the goals of Distributed Lethality, but perhaps one that offers game-changing SuW capabilities and performance too.

This study seeks to determine what those capabilities are and how to best utilize them. It will attempt to provide realistic solutions on how to use the MDUSV based on realistic assessments of its capabilities. Additionally, it will attempt to determine what additional resources are needed in order for the MDUSV to be an effective SUW tool.

A note on nomenclature: the terms *Sea Hunter*, *ACTUV* and *MDUSV* are used throughout this report and are easy to misconstrue. Although they essentially refer to the same thing, it is the opinion of this author that they should not be used interchangeably. As such, specific definitions are presented in order to avoid confusion.

- *ACTUV*: The original platform with an anti-submarine warfare mission set. Does not refer to a specific vessel per se, but the platform itself.
- *Sea Hunter:* The specific vessel that was built by Leidos and is currently undergoing testing. *Sea Hunter* is the name given the vessel at its christening.
- *MDUSV*: The non-warfare specific platform that *Sea Hunter* is based on. It refers to the system that is the ACTUV without the ASW components. Since this thesis focuses on SuW, MDUSV is the term used most often in this report. When referring to a SuW variant of the ACTUV, MDUSV is the term used most often in this report.

D. SCOPE AND METHODOLOGY

The main objective of this thesis is to utilize the tenets of systems engineering (SE) to analyze the use of the MDUSV platform as an offensive, over-the-horizon, SuW tool that supports DL. While there are many facets of systems engineering, this thesis places an emphasis on defining architecture and utilizing model-based system engineering.

For the purpose of this thesis, a specific system (the MDUSV) is presented as a solution. As such, there will not be the typical analysis of alternatives. However, the analysis and evaluation of the MDUSV as a DL SuW system is in accordance with basic SE principles. Starting with determining the top-level system requirements, the system architecture is developed in an attempt to establish traceability from top-level needs to specific functions and the components that perform them.

With the SuW operational setting as a reference, this report will establish the high-level functional requirements needed for the MDUSV to perform SuW in a DL capacity. This is followed by a more detailed functional analysis, laying out the specific criteria involved to meet the goal. Finally, a physical architecture will trace the functions to the components performing the functions, as well as document the interfaces involved.

One of the more commonly utilized SE models is the "Vee" model, shown in Figure 2 (Blanchard and Fabrycky 2011, 37). The SE methods in this report follow the left side of the model—the "Decomposition and Definition" portion, starting with a concept exploration and ending the analysis with a high-level design.

The top left of the "Vee" model, circled in red in Figure 2, is a natural beginning as this thesis could generally be considered as a feasibility study. The methodology utilized in this thesis progresses through the Concept of Operations with the development of a functional architecture, which allows for the determination of the needs and requirements. This is followed by examining the existing MDUSV physical architecture and supplementing that architecture with SuW-specific physical components. The revised physical architecture helps bridge the gap between requirements and capability by presenting the components that will perform the functions. This emphasis on traceability is what allows the definition needed to reach a high-level and even detailed design. Low-fidelity modeling and simulation offers some analysis of the proposed system.

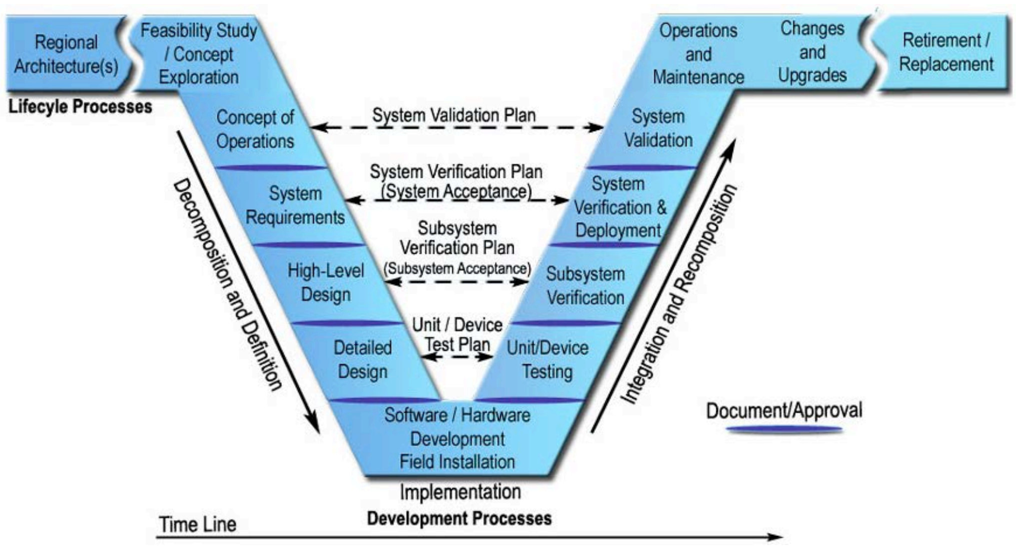

Figure 2. Systems Engineering "Vee" Model. Source: U.S. Department of Transportation, Office of Operations (2017).

II. BACKGROUND

A. THE EVOLUTION OF MODERN SURFACE WARFARE

After emerging from World War II with the most powerful surface fleet in the world, the U.S. Navy did not consider sea-area access an issue—it was an assumption. According to VADM Rowden, that assumption caused the Department of Defense (DOD) and the Navy to focus on projecting power ashore while allowing its sea-control proficiency to dwindle (Rowden 2014). As carrier-based air operations became the mainstay of offensive capability, the rest of the surface combatants (cruisers, destroyers and frigates) were gradually relegated to defending the high value units (aircraft carriers and amphibious assault ships). Surface-combatant capabilities became increasing focused on carrier defense and anti-submarine warfare (ASW). Surface warfare continued to be a role for the surface combatants, but also one that was supplemented, if not exceeded, by the embarked air wing. Arguably, the main offensive role of modern USN surface combatants had been launching Tomahawk cruise missiles for tactical strike missions against land targets (Rowden 2014).

VADM Rowden (2014) suggests that while the USN has focused on continually improving its ability to project power ashore, its adversaries have been improving their ability to deny the USN unrestricted sea access. Potential adversaries such as China have steadily fielded both land-based anti-surface warfare systems and their own lethal surface combatants (Osborn 2016). Such capabilities do not just present a challenge to sea access for the USN. The cascading effect of limited sea access, depending on the extent, is the inability of the USN from projecting power ashore. In essence, these potential capabilities could deny the USN's surface fleet the ability to operate under the premise and strategy it has been dedicated to and centered on for decades—uncontested power projection.

As a response, Fanta et al. (2015) argue that unlimited sea control is not necessarily a must-have in order to conduct effective warfighting. Rather, they suggest that simply securing the needed areas and maintaining vital sea lanes is sufficient to conduct power projection ashore. As a means to accomplish this, they provide an example of a surface action group (SAG) consisting of three different platforms that go on the offensive to support a Marine Corps detachment on an island. This SAG will take the fight to the enemy, force the enemy to disperse his assets, and then conduct offensive, over-the-horizon engagements. As VADM Rowden points out, this long-range offensive SuW capability is a crucial part of DL when air-wing support is not available.

B. DISTRIBUTED LETHALITY AS A WAY TO CONDUCT SuW

DL, at its heart, is the ability to "cause the adversary to shift his own defenses to counter our thrusts" (Rowden 2014). In terms of Surface Warfare, this means providing the quantity and quality of combat platforms necessary to provide a credible threat. Currently, there exist challenges in meeting those goals. According to a 2016 report from the Heritage Foundation, in 2015 the U.S. Navy had a 35-vessel shortfall in terms of inventory vs required ships in the small surface combatant (LCS and frigates) category (Heritage Foundation 2017). The downward trend in small surface combatant inventory restrains the U.S. Navy's ability to adequately "disperse" an adversary, depending on the size of that adversary's fleet. Fewer surface combatants mean fewer, or less capable, "hunter-killer surface action groups." In terms of quality, as ADM Rowden points out in his Distributed Lethality article, the ships we do have are not as exceptional in their Surface Warfare capabilities as they once were. Arleigh Burke destroyers and Ticonderoga cruisers equipped with the standard four Harpoon missiles do not benefit from any advantage over near peers in range or warhead size.

In order to achieve the desired effects of DL, the goals are simple: increase the number of available platforms and make those platforms deadly. More specifically, there needs to be enough platforms to adequately "disperse" the adversary. Then, ideally, those platforms would employ weapons more lethal than those employed by the adversary. Some, such as Rear Admiral Peter Fanta, have proposed arming everything "that floats" (Freedberg 2015).

In his online journal, *Center for International Maritime Security* article, *Surface Warfare: Taking the Offensive*, Vice Admiral Rowden advocates shifting from relying on carrier air groups to provide the strike capability to utilizing the surface fleet for over the horizon engagements. Because of the declining size of the fleet, Vice Admiral Rowden emphasizes the need for a networked fleet "equipped with the weapons and sensors to enable this offensive shift" (Rowden 2014)."

C. THE ROLE OF THE MDUSV IN SuW

DL represents a break from the surface warfare tradition of late that seeks to minimize the risks to our surface ships by relegating them to primarily defensive roles and leaving the offensive engagements to less-susceptible aircraft. Even so, the desire to reduce risk remains, especially for the expensive, "high-mix" surface combatants such as the multi-billion dollar destroyers and cruisers. The answer, according to McCabe (2015) lies in the addition of robust small surface combatants (SSCs). As McCabe states, "In a 1962 Proceedings article, then-Captain Zumwalt argued for a mix of 'complex' and 'simplified' mainstream surface combatant designs." McCabe goes on to state that, for various reasons, today's surface navy consists of mainly "high-end" ships. As a result, today's complex and highly-capable warships are taxed with relatively simple tasks, such as anti-piracy and drug interdiction. Smaller, cheaper SSCs are much more suited to these tasks than guided missile cruisers and destroyers and would allow those capital ships to perform the more complex tasks those ships were designed for originally. However, as McCabe points out, SSCs have a role in the offensive nature of Distributed Lethality as well. At the very least, they pose less of a risk since their damage or loss would be relatively less devastating. As a result, commanders would have a viable option for missions posing too much risk for capital ships. McCabe suggests Patrol Coastal ships (PCs) and Littoral Combat Ships (LCS) as viable alternatives. However, unmanned vessels, such as the ACTUV completely remove the human risk factor while also lowering the financial risk.

Leidos, the ACTUV's manufacturer, suggests that the vessel has the ability to serve in various other capacities besides ASW (Kable 2016, 10:18). While Leidos does not specifically list Surface Warfare, a general analysis of the ACTUV reveals its potential to effectively provide these capabilities. The ACTUV's potential as a SSC capable of supporting Distributed Lethality is based on observations and inferences gained from an article and video from an online magazine that attended the ACTUV's christening (Stella 2016). As with any system under review for DOD acquisition, there are two main aspects to consider: performance and cost.

In terms of performance, the ACTUV looks promising initially. It passed its autonomous navigation tests with flying colors, tracking a surrogate vessel while complying with the rules of the road (Stella 2016). Additionally, its range and ability to operate in rough seas suggest a robust platform with far-reaching and ocean-crossing endurance. The ACTUV's significant payload ability, which, right now, is configured for ASW and carries the applicable hardware, translates into a myriad of other potential mission roles. Further analysis will reveal the possibility and practicality of modifying the ACTUV into a ship-killer by switching the ASW-related components for anti-ship missiles.

Finally, the ACTUV's cost is approximately $23 million—significantly less than the best-case-scenario $480 million price tag attached to an LCS (Congressional Research Service 2017). This is vital; as Rowden (2014) points out, the fiscal environment will substantially impact the realization of Distributed Lethality. Daily operating costs are estimated at $15,000 per day—significantly less than an Arleigh Burke-class destroyer (Housel 2017).

The affordable cost coupled with the low risk associated with an unmanned vessel seem to indicate that the ACTUV could be an ideal platform to add to Distributed Lethality's arsenal. The ACTUV is a platform that commanders could send into harm's way with very little risk. If properly equipped for SuW roles, the ACTUV could effectively establish and maintain sea access for carriers, allowing the Navy to continue to perform one of its primary objectives—projecting power ashore.

D. EXAMPLE SCENARIO

Before initiating the system architecture development, some background on the concept of operation is needed, as shown in the top left corner of the "Vee" model in Figure 2. An understanding of what the system performing its mission looks like allows for the decomposition of its functions. Since the topic of this thesis is how the MDUSV fits into the DL SuW role, the concept of operations (CONOPS) are specific to the MDUSV application.

In June 2016, a NPS Operational Analysis class (OA4604 "Wargaming Applications") introduced a war-game scenario involving the use of MDUSVs (Ersoz et al. 2016). The scenario featured two opposing task forces (Red Force and Blue Force) in the Eastern Mediterranean. The purpose of the scenario was to "provide an assessment of Distributed Lethality's capabilities and limitations during phase 0 (shaping operations) and phase 1 (deterrence operations)." That scenario serves as the model CONOPS for both this thesis and the simultaneously-developed capstone project.

The NPS Systems Engineering department's distance learning capstone project class, Class 311–154O, expanding on the war game scenario by examining the unique C2 needs for an AFP operating within the context of DL. The team developed an architectural model to suite the requirements for information flow in a "decentralized and distributed" AFP (Corbett et al. 2017). While the AFP used in their development did not include a MDUSV, their C2 architecture still applies, and is utilized in this report.

This report picks up the scenario where the Operational Analysis class left off, advancing to phase 2 (seize initiative) and phase 3 (dominate). The force-on-force scenario features task force compositions shown in Table 1.

Table 1. Scenario Task Force Composition

Red Force	**Blue Force**
1 x Cruiser 1 x Destroyer 2 x Frigate 2 x Corvette 2 x Maritime Patrol Craft 1 x Squadron Bomber 72 x Land-launched ASCMs	2 x Auxiliary 3 x Frigate 1 x LHA (w/ 1 x squadron F-35) 1 x Destroyer 4 x MDUSV

In the OA 4604 class scenario, Blue Force distributes its forces, causing Red Force to respond by dispersing its forces to maintain coverage. Blue Force effectively used its MDUSVs in phase 0 and phase 1 as pickets, increasing their maritime picture and "saturating the battle space with noise." At this point, tensions are high and an exchange of fire is imminent. The next phases of the scenario are demonstrated through the modeling and simulation results in Chapter IV.

III. SYSTEM ARCHITECTURE

This chapter initiates the more methodical and detailed SE analysis of the MDUSV as a SuW system for DL. The focus is on developing the architecture, starting with the functional requirements and transitioning to physical components. With a firm architecture in place, the Decomposition and Definition process can move towards the high-level and detailed design.

A. FUNCTIONAL HIERARCHY

The Concept of Operations, provided in the previous chapter, allows for the progression into the Systems Requirement portion of the "Vee" model shown in Figure 2. This starts with the general, high-level stakeholder needs and requirements. The System Requirements is what allows for the formal documentation of what the system needs to do to be successful, as determined by the stakeholders' needs. In this case, the system (SuW variant MDUSV) needs to be capable of conducting SuW in a DL capacity. The functional architecture development will walk through exactly what that means and looks like.

Utilizing diagraming software, such as Vitech's Core program for detailed architecture-based relationships, and Lucid's online diagram software, Lucidchart for more general hierarchy-type representations, this section delineates the requirements, starting at the top, high-level functions and gradually increasing in level of detail. Eventually, all the functions for SuW will be addressed and then accounted for with corresponding physical components.

1. High-Level Needs

With the operational picture provided in the previous section as a reference, the architecture development process can begin. The CONOPS for the situation described in the previous section is not very different from a typical SuW scenario, with a few exceptions. The decentralized aspect of DL increases the complexity and challenges associated with certain SuW-supported operations, such as C2 and logistics, as supported by Harlow's (2016) thesis and Class 311-154O's capstone project. In any case, the high-level needs and general requirements are categorized in the following list.

a. Integration Needs

The MDUSV solution to DL SuW needs to be affordable and easy to integrate into existing tactics, techniques and procedures (TTP). SuW operators are trained to fight in a specific way. Utilizing tactics and lessons learned from centuries of naval warfare, they are precise in how they fight, both in individual efforts and in coordinated group efforts. Any MDUSV-unique advantages withstanding, incorporating SuW variants MDUSVs should not require major changes to the standard operating procedure (SOP) of SuW.

b. Logistics

Just as the employment of SuW variant MDUSVs should not require radical changes, the sustainment of them should also utilize the logistics model already in place. DL has inherent challenges associated with logistics. In his thesis, Travis Harlow proposes an architectural framework that addresses those challenges. The SuW variant MDUSV should incorporate the same model. Sustainability issues, such as refueling, rearming and maintenance, should be addresses in such a way to support the SuW mission by allowing the MDUSVs to stay close to the fight for as long as possible.

c. System Size/Scalability

The SuW variant MDUSV model should not depend on the number of vessels. The theatre commander should be able to utilize the same TTPs regardless of how many MDUSVs are available. While specific engagement scenarios may require an adjustment in tactics based on the number of MDUSVs, the SOP should be the same regardless.

d. Command and Control (C2)

The C2 aspect concerns not just the combat element, but the overall employment of MDUSVs as platforms that provide a maritime picture and serve as a deterrent. With the proposed robust sensor suite, the MDUSV is a capable intelligence, surveillance and reconnaissance (ISR) platform. With the addition of TALONS, it becomes even more of an ISR asset. The MDUSV needs to be capable of dispersing that information to other assets on a common network. Conversely, the MDUSV needs to be capable of receiving the same type of information from other assets, and utilizing it appropriately. It also needs to reliably receive commands and input from the human supervisors, whether locally or remotely.

e. Lethality

In order to be successful at dispersing the adversary, the system must present enough of a threat to warrant attention from the adversary. This is accomplished through lethality. In the modern naval age, the most lethal systems are those with the most capable ASCMs coupled with adequate anti-ASCM defense. In other words, installing a medium or even large caliber gun will not deter the enemy. The system must be capable of inflicting enough damage that the adversary is forced to counter with allocated resources.

2. Functional Analysis

Now that the high-level needs and requirements have been laid out, the next step is to determine the functional needs that will accomplish said needs and requirements, as applied to the MDUSV. Functional analysis allows for the "identification of the resources necessary for the system to accomplish its tasks" (Blanchard and Fabrycky 2011, 100). In this case, the needs of a surface warfare commander (SUWC) in an AFP are presented in a formal order with the intent of determining the details associated with performing SuW.

a. Functional Hierarchy

The functional hierarchy in Figure 3 allows for a top-down decomposition of the functions required to meet the high-level needs and requirements in the previous section. These functions are exclusive to the MDUSV which is conducting SuW. It is important to note there are two components, or users, performing the functions: Autonomous Operations functions and Human Supervisor Operations. While the MDUSV autonomously performs most of the functions, a human operator remotely performs the functions associated with targeting, arming and launching of the ASCMs.

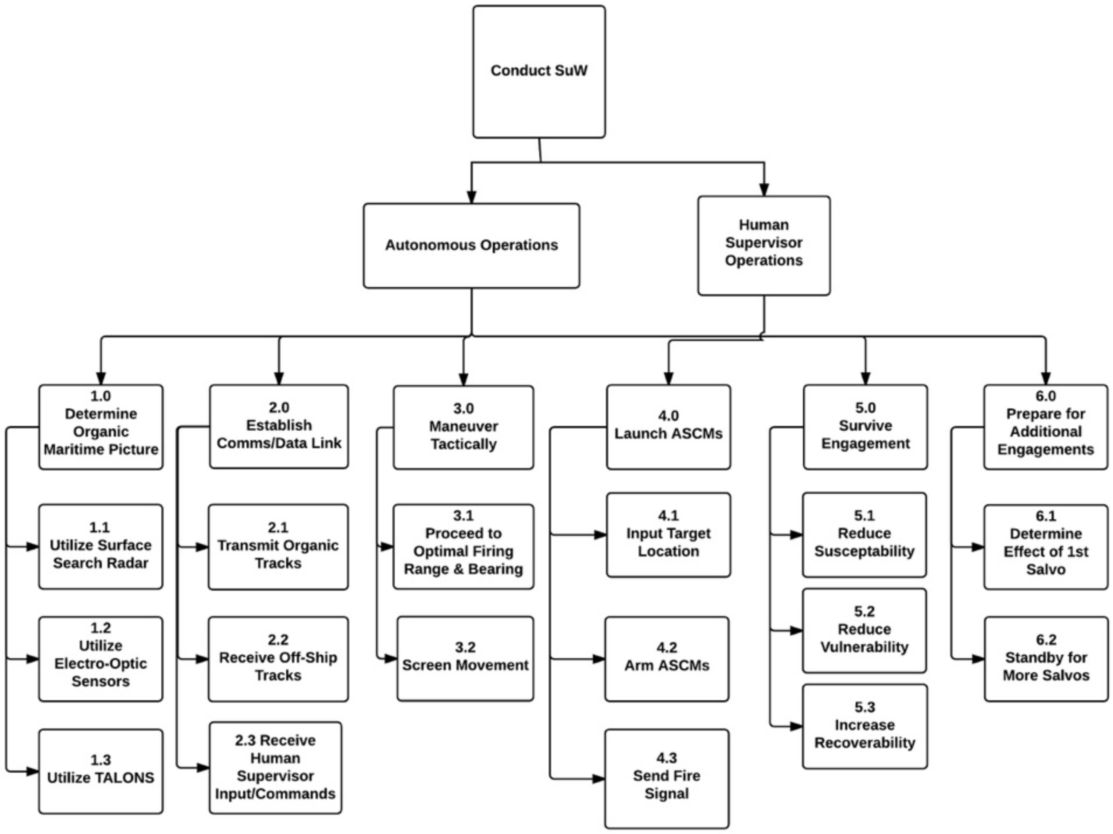

Figure 3. Functional Hierarchy of Surface Warfare for a MDUSV

b. Function Descriptions

This section describes in more detail the functions shown in Figure 3. A better understanding of what each function is and what it entails will aid the process of tracing functional requirements to their allocated components. Though the function titles could be considered sufficient to give an idea of their purpose, the descriptions here are intended to provide traceability to the high-level operational needs and requirements specific to the MDUVS in SuW, as explained in the previous section.

1.0 **Determine Organic Maritime Picture:** The system must have situational awareness and an accurate understanding of what vessels are in the area and where. This is crucial not just for safe maneuvering, but also to identify and distinguish between friendly and hostile vessels.

1.1 **Utilize Surface Search Radar:** The system shall energize its radar to detect any and all vessels within range. However, the system should consider a form of emissions control to avoid detection from hostile forces. Turning off or alternating radar emissions might prove tactically advantageous.

1.2 **Utilize Electro-Optic Sensors:** The electro-optic sensors consist of the forward and rear-facing cameras, infrared and laser range-finders. These sensors serve as a backup to the radar systems in maintaining situational awareness and determining the maritime picture. Weather and visibility permitting, they may serve as the primary detection method when in an elevated emissions condition (EMCON).

1.3 **Utilize TALONS:** When operating at maximum altitude, TALONS extends the range of its payload (in this case a surface radar and radio transmitter) by three times its normal value. This capability enhances the detection ability of the MDUSV, possibly providing an element of tactical surprise.

2.0 **Establish Comms/Data Link:** The common picture tool meant to share tracks and increase situational awareness amongst all friendly platforms (surface and air) is vital for the C2 aspect of DL. A secure and reliable network is of utmost importance since the MDUSV cannot launch weapons without it.

2.1 **Transmit Organic Tracks:** The system shall transmit all tracks acquired by the MDUSVs sensors.

2.2 **Receive Off-Ship Tracks:** The system shall receive tracks acquired by other platforms via the Comms/Data Link to supplement its maritime picture.

2.3 **Receive Human Supervisor Input/Commands:** The system shall be constantly capable of receiving inputs and commands from the supervisory operators via primary and secondary communication links. These inputs could be requests for system status or commands such as waypoints.

3.0 **Maneuver Tactically:** As an autonomous system, the MDUSV must be programmed on how to maneuver in a combat scenario. It must consider range and target bearing relative to adversary vessels as well as concealment objectives while maneuvering.

3.1 **Proceed to Optimal Firing Range & Bearing:** Although the human supervisor can provide this location to the MDUSV, the system be capable of determining the ideal location from which to launch missiles, considering the maritime picture and intelligence regarding the adversary's capabilities.

3.2 **Screen Movement:** The system should attempt to conceal its location and intentions in regards to maneuvering to the fullest extent possible. Waypoints to a location should factor the adversary vessels location, course and speed.

4.0 **Launch ASCMs:** The system shall be capable of launching ASCMs from the MDUSV. The ASCM launching function is performed by the human supervisor and is separate from the MDUSV's autonomous functions. For safety precautions and cyber security purposes, the ASCM fire control system shall be separate from the MDUSV's autonomous control system. It shall have no data connection between the ASCM's fire control system and the MDUSV's operating system.

4.1 **Input Target Location:** The system shall provide the ASCM fire control system targeting information. The designated human supervisor shall input the data via the C2 network.

4.2 **Send Fire Signal:** The system shall send a weapons release fire command to the ASCM fire control system for each missile. The designated human supervisor shall provide the signal via the C2 network.

5.0 **Survive the Engagement:** The system shall incorporate survivability enhancement features so as to withstand the effects of operating in a hostile environment and maintain a reasonable level of availability.

5.1 **Reduce Susceptibility:** The system shall contain both passive and active methods of avoiding damage from hostile fire. The system shall detect incoming ASCMs and employ some type of defeat system, whether countermeasures or ballistic projectiles. It shall take advantage of any means to reduce its signature and employ maneuvering techniques that reduce its susceptibility. If feasible, the system shall employ a threat suppression system.

5.2 **Reduce Vulnerability:** The system shall be capable of withstanding a certain degree of damage and, if possible, maintaining operations. Component isolation, redundancy and effective separation should be applied.

5.3 **Increase Recoverability:** The system shall be capable of containing and controlling damage so as to prevent cascading damage and loss of the system. In addition, it should be capable of restoring normal operations when system redundancy permits.

6.0 **Prepare for Additional Engagements:** The system shall be capable of multiple engagements, depending on adversary force size and defensive capabilities in the initial engagement. With regards to fuel and armament, it shall be capable of matching the mission readiness of conventional ships so as to maintain availability.

6.1 **Determine Effect of 1st Salvo:** The system shall be capable of monitor the effect of organic ASCMs launched in salvo. It shall be capable of performing a battle damage assessment on individual adversary vessels.

6.2 **Standby for More Salvos:** The system shall be capable of detecting additional threats and executing follow-on engagements. It shall determine the minimum number of ASCMs necessary to minimize friendly losses while defeating the adversary in each engagement so as to retain a maximum number of ASCMs at any given time.

c. Functional Flow Block Diagram

The hierarchy presented in the previous section offers an overall description of what the system needs to do. A functional flow block diagram, as shown in Figure 4 and Figure 5 demonstrates the sequential flow of the functions. The example in Figure 4 and Figure 5 depicts a typical, generic SuW engagement and the sequence of events that transpire from detect to engage. While some of the terminology may differ from what is used in the functional hierarchy shown in Figure 3, the concepts are the same. One of the unique aspects of the CORE software is the use of a “Trigger,” depicted in the green oval captions. The triggers indicate when a particular function, or functions, occur as a direct result of a previously-occurring function or functions.

The events shown in Figure 4 and Figure 5, when combined, provide the complete functional flow block diagram and are described as follows:

The Blue Force AFP is operating in a contested area. Red Force detects Blue Force’s presence in the area and transits to the area. The Blue Force SUWC, in determining the maritime picture, detects Red Force vessels in the area and orders *Sea Hunter* to set up a screen. *Sea Hunter* initiates SUW operations and closes distance to the Red Force. As *Sea Hunter* detects the Red Force vessels via its own sensors, it transmits that data to Blue Force SUWC. Red Force maneuvers to a firing position and proceeds to acquire a firing solution. Red Force then fires ASCMs at conventional Blue Force ships. *Sea Hunter* detects ASCMs inbound for the Blue Force ships and relays the information to Blue Force SUWC. After determining Red Forces hostile intent, Blue Force SUWC authorizes weapon release and sends a firing solution to *Sea Hunter*’s Harpoon missile system. Red Force vessels detect inbound Harpoons and initiate evasive maneuvers. Harpoons hit Red Force vessels. *Sea Hunter* observes hit through electro-optical sensors and continues to monitor Red Force vessels to assess battle damage. Eventually, Red Forces withdrawal due to damage. *Sea Hunter* shadows vessels until they are safe distance from Blue Force AFP.

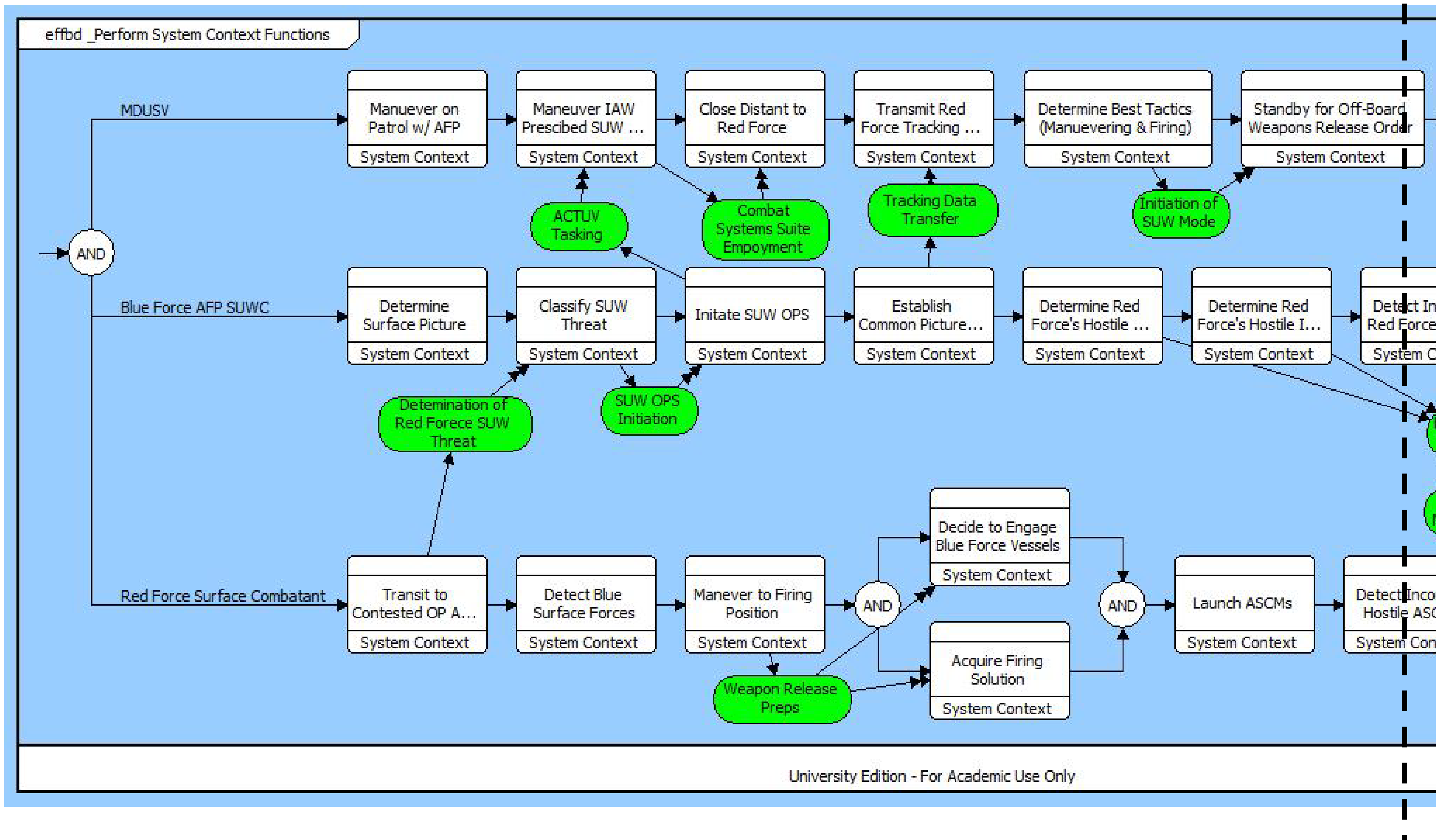

Figure 4. Left Side of Functional Flow Block Diagram of SuW with MDUSV

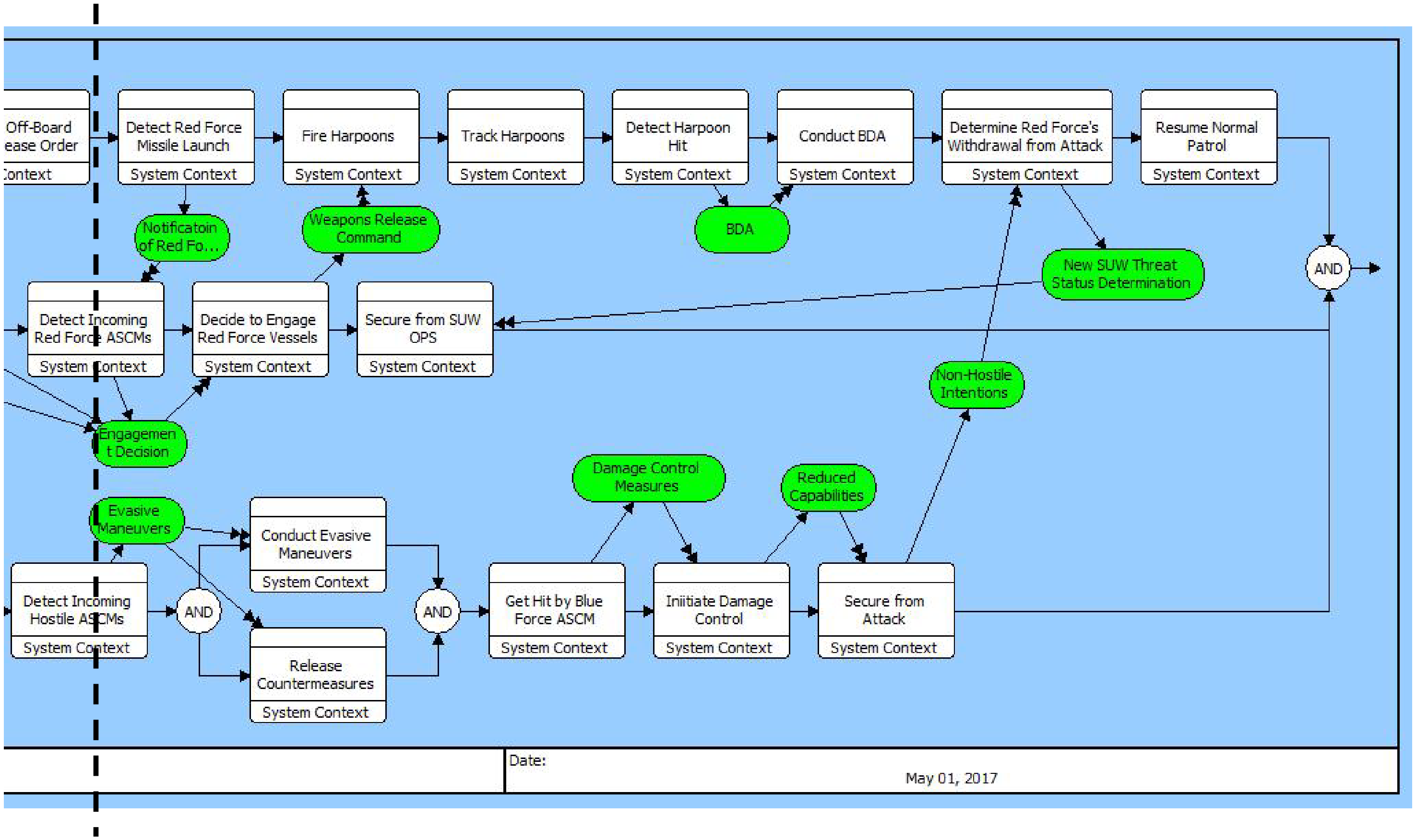

Figure 5. Continuation of Functional Flow Block Diagram of SuW with MDUSV

B. PHYSICAL ARCHITECTURE

This section provides the details that bridge the gap between what the system needs to do (functions) and how it will do it by providing physical components or design aspects that will accommodate and perform the functions. According to the "Vee" model, the analysis now transitions from the System Requirements to the High-Level Design (Blanchard and Fabrycky 2011, 37). As with the functional architecture, the physical architecture will start at the high level and proceed into more detailed criteria. The high-level physical component hierarchy is shown in Figure 6.

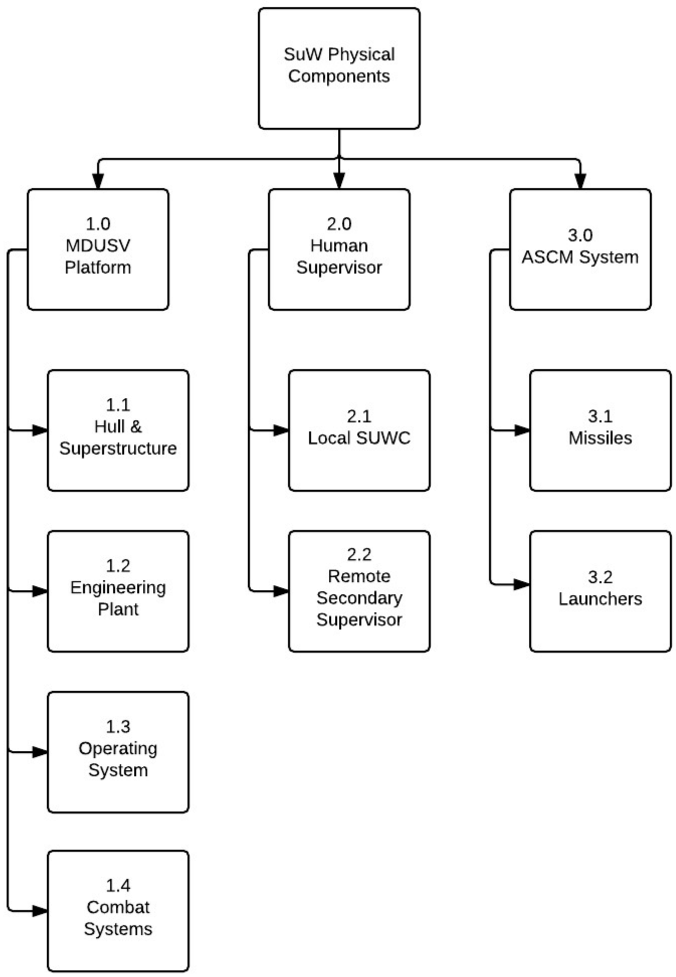

Figure 6. Physical Hierarchy of SuW Components Specific to MDUSV

1. Component Description

This section describes what each component in Figure 6 is and what it performs.

1.0 **MDUSV Platform:** Refers to the vessel itself and the main, but not sole, component of the SuW variant MDUSV system. This includes all the various subsystems of the MDUSV that allow for autonomous operation and maritime operation in general.

1.1 **Hull and Superstructure:** Refers to the main hull, the two side hulls (amas) and deckhouse. The main hull includes the two mission decks that support the external payload. The main deckhouse serves as the mounting point for the various sensors and masts, which contain the antennae for various communication systems.

1.2 **Engineering Plant:** Refers to the electrical and mechanical components and subsystems that provide propulsion, electrical power and auxiliary services.

1.3 **Operating System:** Refers to the computer software program and associated hardware that enable autonomous operation. The operating system is interfaced via a data flow and communication network with every system onboard the vessel, except the ASCM system.

1.4 **Combat Systems:** Refers to the sensors and communication equipment that enable both maneuvering and conducting SuW.

2.0 **Human Supervisor:** Refers to the human operator on the watch team that supervises the MDUSV operation. Operator receives data provided from the MDUSV and provides specific tasking to the MDUSV. Operator is also able to override the MDUSV's autonomous operating system and take remote control of the vessel.

2.1 **Local SUWC:** Refers to the SUWC of the AFP that the MDUSV is operating with. Relays tasking to the MDUSV via a watch team member. Serves as the primary supervisor of the MDUSV.

2.2 **Remote Secondary Supervisor:** Refers to the auxiliary human supervisor, which is part of the watch team that monitors remotely on a shore-based command center.

3.0 **ASCM System:** Refers to the missile system onboard the MDUSV. The ASCM system is separate from the other MDUSV systems and is not connected to the autonomous operating system.

3.1 **Missiles:** Refers to the canisterized missiles on the mission deck.

3.2 **Launchers:** Refers to the canisters and fire control system. The fire control system is directly connected via SATCOM to the Human Supervisor and receives the weapon fire command to launch missiles.

The allocation of DL SuW functions and requirements is accomplished through both diagrams listing the physical components, as shown in Figure 6. and through an explanation of the CONOPS. Before proceeding to lower level physical architecture details allocation, a discussion on how the system could operate is presented to give context to the physical component allocation.

2. A MDUSV-Configured AFP/SAG

Integration of a SuW variant MDUSV into an AFP is one of the main tasks in this report. There are a variety of theoretical AFP configurations that could include an MDUSV, including the configuration in the OA 4604 Wargaming Applications class scenario. In that scenario, the four MDUSVs served in a supplemental role, seeking out and shadowing the adversary. As a SuW variant, however, the MDUSV could perhaps replace some of the conventional vessels.

The conventional AFP example given in VADM Rowden's DL article was a three-ship SAG consisting of an LCS with an ASW module, a Flight III Arleigh Burke-class destroyer and a Zumwalt-class destroyer. Between those three ships, the AFP is able to perform several different mission sets, including SuW and Maritime Interdiction Operations (Zumwalt), ASW (LCS with ASW module) and Integrated Air and Missile Defense (Arleigh Burke). However, since the current procurement plan calls for only three Zumwalt-class ships, the limited availability of said ship type points to the need of a replacement (Majumdar 2015). A SuW-variant of the MDUSV could fill the SuW role left by the absence of the Zumwalt-class ship.

The AFP's SuW commander (SUWC), whether onboard the DDG or LCS, would oversee the MDUSV's operation and provide it with tactical inputs. Given the fact that the MDUSV has a procurement and operating cost that is a fraction of the Zumwalt's, it is possible that the AFP could include multiple SuW-variant MDUSVs. If one or more of the MDUSVs were to employ the TALONS system, the AFP could employ those MDUSVs in a such a way to maximize the maritime surveillance.

Given the autonomous nature of the MDUSV, the AFP would operate much the same as a traditional AFP. The SUWC would provide tasking to the MDUSV, just as the SUWC would with a manned ship. Theoretically, the Rules of Engagement (ROE) would not need to change in order to accommodate the MDUSV. Besides providing the direct order to fire ASCMs, the only additional tasking on the SUWC is to ensure acknowledgement and distribution of the MDUSV's sensor input that contributes to the maritime picture and providing sufficient oversight and supervision of the MDUSV's operation. It is estimated that a two-person watchteam could supervise operations for up to six MDUSVs.

3. A SuW-Variant MDUSV

With a proposed concept of operations, this report can now establish what exactly a SUW-variant MDUSV entails. Rather simply, it the Leidos-built ACTUV platform with one or more ASCM launchers installed on the main deck, as shown in Figure 7. For the dual purpose of modeling and providing realistic and readily-applicable analysis, a specific ASCM was chosen in order to establish specific performance parameters. These parameters, such as speed and range, were obtained using unclassified sources and serve as input for the wargame simulations in Chapter IV.

a. ASCM Selection

There are a variety of ASCMs available that serve as candidates for the SuW-variant MDUSV. The MDUSV's hull is not deep enough for a VLS, which restricted the candidates to canister-launched types and eliminated proven missiles such as the anti-ship versions of the Tomahawk and SM-6. In an attempt to appease both the acquisition corps and the warfighter, candidates were evaluated based on the following parameters:

- Range
- Speed
- Cost
- Weight

With these performance aspects in mind, the author used an analytical hierarchy process (AHP) to determine which missile meets the requirements best. The spreadsheet used for the calculations are located in the appendix. The AHP yielded the Harpoon Block II Extended Range (ER) as the best missile for the SUW-variant MDUSV. The AHP results, coupled with the fact that Harpoon is already a program of record with the desired reliability, availability and maintainability (RAM) metrics, confirmed the Harpoon as the best option. The Long Range Anti-Ship Missile (LRASM) is another potential weapon system with even greater performance than the Harpoon Block II ER. However, given that the LRASM is still under development, it was excluded from the selection process.

b. ASCM Launcher Configuration

In order to add value to this report's analysis, the physical feasibility of installing ASCMs and the accompanying launchers on the MDUSV was considered. *Sea Hunter* has two payload areas on its main deck, aft of its temporary deckhouse, as shown in Figure 7. Both of these so-called mission support areas are 20 ft long and 11 ft wide. Considering the Mk 140 light-weight canister (LWC) launcher dimensions, each mission support area would allow space for up to two launchers, each capable of carrying four missiles each, to be installed in each mission deck (Jane's IHS Markit 2017c). Based on available deck area dimensions alone, *Sea Hunter* could carry up to four launchers for a total of 16 ASCMs. However, *Sea Hunter*'s current design limits maximum payload to 20,000 lbs with a center of gravity four feet above the main deck in order to maintain stability for desired operating ranges (up to sea state 5 for normal operation, up to sea state 7 for survivability) (Littlefield 2017). Since a single Mk 140 launcher with four

LWCs and four Harpoon Block II missiles weighs 8,532 lbs, the limit would be three launchers for a total of 12 ASCMs.

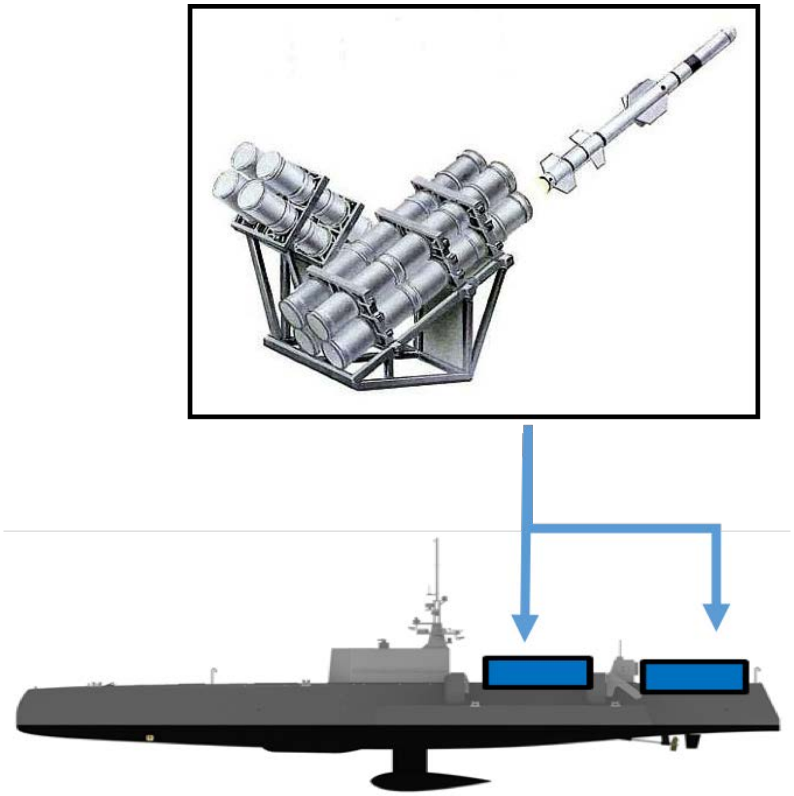

Figure 7. Proposed Location of ASCM Launchers on *Sea Hunter*. Source: Littlefield (2017).

4. Logistics Model

With an idea of what a MDUSV-inclusive SAG or AFP could look like, and what a SuW-variant MDUSV could be, the next logical step is to determine how to operate SuW variant MDUSVs, from a maintainability perspective. In order to provide a more complete analysis, it is important to develop a logistics model and operating procedures. In other words, how to deploy the MDUSV and how to employ it in combat. As every combat operator knows, logistics is a significant, possibly the most significant, and often challenging aspect of operations. Logistics for DL presents even more challenges. This report builds on the DL logistics architecture built by Howard (2016) in his thesis, but focuses specifically on the logistical needs of MDUSVs.

a. MDUSV Deployment

Sea Hunter was designed to function similarly to a conventional ship in that it would operate out of a homeport. The homeport would serve as the major logistical and maintenance hub. Leidos accounted for the transit distance between homeport and likely operating areas by giving *Sea Hunter* a range of up to 17,000 nm, depending on transit speed (Leidos 2016). This range is crucial for a ship that is incapable of conducting a replenishment at sea (RAS)—a tricky feat for an autonomous vehicle. The type of logistical support—whether the vessel can conduct a RAS or has to return to port for refueling and resupply—is important because it can significantly affect performance aspects of the design, such as range and mission turn-around time, that are closely related to the concept of operations. Additionally, as Harlow (2016) pointed out in his thesis, the logistics for DL can become challenging quickly due to the need for support spread throughout an operating area. However, the autonomous nature of *Sea Hunter* allows for possible deviations from the logistical norm.

b. Forward Deployed

Forward deployed in this case means the use of shore-based facilities to conduct resupply and minor repair of MDUSVs. These shore-based facilities could be at bases already in use, such as Navy Region Center Singapore, which services LCS and other USN vessels, or simply any shore-based facility in friendly locations.

The main advantage of a forward-deployed operation with shore-based logistical support is that there is already an existing infrastructure in places close to where SUW-variant MDUSVs are envisioned to operate (the aforementioned Singapore facility, Japan and the Philippine Islands in the Pacific; Bahrain in the Persian Gulf) and the fact that *Sea Hunter* is fully capable of making those transits. However, the transiting-between-homeport-and-operational-areas model fails to capitalize on *Sea Hunter*'s unmanned aspect. Because there is no need consider crew rest or even a crew swap, ideally *Sea Hunter* should operate with as quick a turn-around time as possible. This concept is similar to the idea that production machinery in a manufacturing plant should be kept running as often as possible. Additionally, there are the added constraints that long transits place on the design of the vessel. With less fuel required for long transits, perhaps *Sea Hunter*'s payload could be increased.

c. Support Ship

The support ship model addresses the desire to keep MDUSVs on station longer by minimizing the need to transit to homeport. There are two variations of the support ship model: a tender that would service MDUSVs alongside, and a mothership, capable of carrying MDUSVs onboard. Barring major repairs or overhauls, the support ship in this model would supply all needed maintenance and minor repair work as well as logistics, including refueling and missile reloads. One of the assumptions for this model is that at-sea missile on-loads are possible. This is based on the relative ease of canister launcher installation compared to VLS missile onloads (Harlow 2016).

(1) Tender

The use of a tender is a familiar concept to the submarine fleet. In this model, a dedicated tender would remain in the vicinity of the MDUSVs and transit to each operational area with the vessels. Using a tender would eliminate the need for frequent transits to homeport but still implies that the MDUSVs would remain at sea and transit to operational areas on their own power. Towing the MDUSVs may not be ideal for normal operation due to added vulnerability to both the tender and MDUSVs. However, if one or more MDUSV suffers a loss of propulsion, a dedicated tender in close proximity could quickly reach the vessel and tow it back to homeport.

The main advantage of a tender is the ease of implementation from a logistical operation. A tender ship class already exists, though any type of re-supply ship could serve as a tender, assuming at-sea refueling is possible. Additionally, depending on how far the MDUSVs are from the main fleet force, they may not need a dedicated tender to remain in same vicinity at all times. The main disadvantage of a tender is the resources incurred by having a dedicated support ship. It also does not fully minimize the transits inherent with operation, thus maintaining the need for significant fuel storage.

(2) Mothership

Another option is to utilize a heavy-lift type of ship, such as the Navy's Expeditionary Transport Dock (also known as the Mobile Landing Platform), shown in Figure 8. This model is similar to the tender ship concept in that the vessels would remain deployed longer. However, in this model the MDUSVs are carried on the mothership. Expeditionary Transport Dock (ESD) ships have the capability to ballast down and submerge their mission deck in up to 5m of water—more than enough draft for *Sea Hunter*. Additionally, the mission decks dimensions are 154 m long and 50 m wide (White et al. 2016). With the vessels parked perpendicular to the ESD ship's keel, at least 9 MDUSVs could be loaded on the mission deck with plenty of room between the vessels for access.

Figure 8. LCAC Docking with ESD's Mission Deck. Source: General Dynamics NASSCO (2017).

This main advantage of this model is that it significantly reduces the required transits and thus has the greatest effect on minimizing required fuel. Since mothership carries the MDUSVs to each operational area and the vessels only deploy prior to a mission, the fuel requirement is significantly less than what was originally designed. This could allow for an increased payload, depending on location within the vessel. Additionally, the ESD ship has the ability to carry multiple squadrons' worth of MDUSVs. Depending on the total number of MDUSVs required for a mission, it is possible that just one ESD ship could fulfill the MDUSV transport requirements for an entire theater. This is noteworthy, as the disadvantage of the ESD is similar to tender ships in that it requires a dedicated ship from an even smaller pool of candidate support ships.

5. Survivability Assessment

An in-depth analysis of a potential combatant unit would not be complete without at least a general investigation into the survivability of the system. Even at the relatively affordable procurement cost of the MDUSV, the system loses substantial effectiveness if it suffers from the availability issues inherent with a high combat-loss rate. The concept of operations presented here proposes sending these vessels directly into harm's way, with the most risk acceptable in modern U.S. naval operations. As such, it is worth some effort to examine the systems attribute that affect its vulnerability and susceptibility.

This survivability assessment will be limited in scope to the expected environment the MDUSV would operate in during a SUW mission. As such, threats assessments will comprise those typically found in such an environment. Additionally, the level of detail will not exceed that which would violate the proprietary information status of the system.

a. Susceptibility

According to Robert E. Ball (2003, 445), susceptibility "refers to the inability of the aircraft *or ship* [emphasis added] to avoid being hit by one or more damage mechanisms in the pursuit of its mission." Susceptibility reduction measures can exist in the form of system features as well as tactics. In the case of susceptibility reduction tactics, the most obvious method is to stay outside of the adversary's weapon range. In order to complete the mission, the MDUSV would need a ASCM with a range that significantly exceeded that of an adversary's. Since targeting information would come from a third party, the assumption is that the MDUSV does not need to have a fire control radar that could satisfy the safe stand-off range. Equipping the MDUSV with a long range ASCM, such as the Harpoon Block II Extended Range or the highly anticipated Long Range Anti-Ship Missile (LRASM), offers the best chance of employing this tactic.

As for susceptibility-reduction features inherent with *Sea Hunter*'s current design, the system is somewhat lacking and stands to gain the most survivability improvement in this area. The most glaring discrepancy is the omission of any type of countermeasures, electronic or canister-launched. The additional lack of a gun-based close-in weapon system means the MDUSV has no defense against an incoming-missile. This is likely due to the platform's original focus on ASW coupled with the likely assumption that it would operate with the support of friendly combatants in its vicinity. In order to provide any value for SUW, the MDUSV needs to include a missile defense system. Even when equipped with ASCMs that far exceed the range of adversary's ASCMs, the threat of hostile submarine, land or air-launched ASCMs necessitates the need for at least a passive missile defense.

The missile defense issue is compounded by the lack of an air search radar. One of the more simple but effective solutions would be the installation of Mk 36 Super Rapid Bloom Offboard Countermeasures Chaff and Decoy Launching System (SRBOC). The canisters are small and lightweight, minimizing the effect on the MDUSV's performance while leaving enough deck space for ASCM canisters. However, the Mk 36 system is not stand-alone and requires some sort of missile detection method, such as the SLQ-32 electronic warfare suite. Such a system would require dual cabinets installed on the exterior of the ship in order to provide 360-degree coverage. With the limited space available on the narrow main hull, a SLQ-32 variant electronic countermeasure system is not an easy to implement solution.

An alternative solution is a stand-alone option such as the Phalanx CIWS or SeaRAM system, both of which contain a missile detection systems and a way to shoot down incoming missiles (a six-barreled, 20 mm Gatling gun and eleven RIM-116 missiles, respectively). Neither of these options are relatively cheap, and both carry significant weights that would severely limit the ASCM payload. However, both systems would be easy to implement given that all they need is electrical power and a SATCOM feed so the human supervisor could arm the system and set the doctrine. Between the two systems, the CIWS is cheaper to procure and operate. However, the need to reload after the expenditure of the first 1550 rounds could be problematic (J. Given a magazine capacity of 1550 rounds, and an average successful CIWS engagement requirement of 200 rounds, the maximum number of engagements a CIWS could make before needing human-provided reloading is 7.75. SeaRAM, shown in Figure 9, has a maximum of eleven RIM-116 missiles and suffers from the same inability to reload after expending all the missiles (Jane’s IHS Markit 2017d). SeaRAM is better performing in terms of ability to successfully engage incoming ASCMs, and is able to engage multiple missiles simultaneously. However, it is also heavier and more expensive.

Figure 9. Mk 15 Mod 31 SeaRAM with Eleven-Cell RIM-116 Missile Launcher System. Source: Jane’s IHS Markit (2017d).

A third possible option could be the use of an aircraft-based missile detection system, such as the ALQ-156. Such systems are compact, light-weight and have the ability to provide input to a countermeasure launching system.

In any case, the need for a missile defense system is a vital upgrade needed for a SUW variant MDUSV. In a salvo exchange with adversaries utilizing ASCMs with equivalent ranges, the ability to defend against missiles is vital, as will be shown in the salvo equations presented in Chapter V. Despite the low price tag and low risk associated with unmanned vessels, it would not make financial sense to consider MDUSVs expendable.

Finally, a SUW variant of the MDUSV equipped with only ASCMs could present itself as a target for attack or boarding from smaller vessels. If said vessel is expected to operate without close support from gunned ships, a remote-controlled small or medium caliber gun system would help deter threats. The Mk 15 CIWS gun is capable of providing both air and surface defense. Its surface mode ability provides a threat suppression method against small craft attacks and boarding attempts.

b. Vulnerability

As a sea-going surface vessel, *Sea Hunter* has the usual ship-related vulnerability issues that can result in either the vessel sinking or the loss of ability to complete the mission. Examples include structure damage that allow seawater intrusion, loss of propulsion, or loss of combat systems, such as radar or weapon systems. However, the *Sea Hunter*'s vulnerability is increased when considering the extra reliance on combat systems. If *Sea Hunter* were to lose its surface search radars and its electro-optical systems, it loses the ability to navigate and maneuver safely. The inability to detect other vessels or collision hazards effectively renders *Sea Hunter* unable to maneuver, resulting in a mission kill. The vessel would either have to be towed or rely on a friendly unit in the vicinity to serve as a guide. Additionally, the relatively small size of *Sea Hunter* limits the degree of component isolation that would otherwise decrease vulnerability. The placement of both the radars and electro-optical systems on the small deckhouse indicates a high probability, given a direct hit by a missile or high explosive round, of losing both radar and electro-optical systems.

In regards to floodable length, the MDUSV is capable of surviving with up to one main compartment flooded (Littlefield 2017). While this fact alone is not particularly noteworthy, given the ACTUV's relatively small length and displacement, this design aspect was obviously incorporated with the intention of increasing survivability.

c. Survivability Conclusion

While *Sea Hunter* has some obvious design cues that point toward survivability, there are also some glaring deficiencies—namely the lack of a threat suppression capability and engagement avoidance capability in the form of countermeasures. Considering the size, cost and autonomous nature of the vessel, some of these questionable vulnerabilities and susceptibilities are understandable. It is possible that the designers struck an acceptable balance in the cost verses performance characteristic. At the very least however, it would seem like the inclusion of a torpedo or missile countermeasure system would only increase the value of the system by decreasing its susceptibility and thus increasing the system's availability, assuming those additional systems could be included at an affordable cost. Given that the current design features no way to defend against an air, surface or subsurface launched propagator, this appears to be a major oversight and the biggest detractor of the vessel's survivability. As such, the CONOPS for the system would have to address the defensive shortcomings by providing combat support.

6. Detailed Design Architecture

With a proposed CONOPS established, the physical architecture can proceed to a more detailed design. For the purpose of brevity, this report will only present the delineation process for one high-level physical component. Figure 6 shows Level 1 and Level 2 physical components. Of the eight different Level 2 components, Combat Systems (Component 1.4) would appear to have the most value in demonstrating the delineation process, as shown in Figure 10.

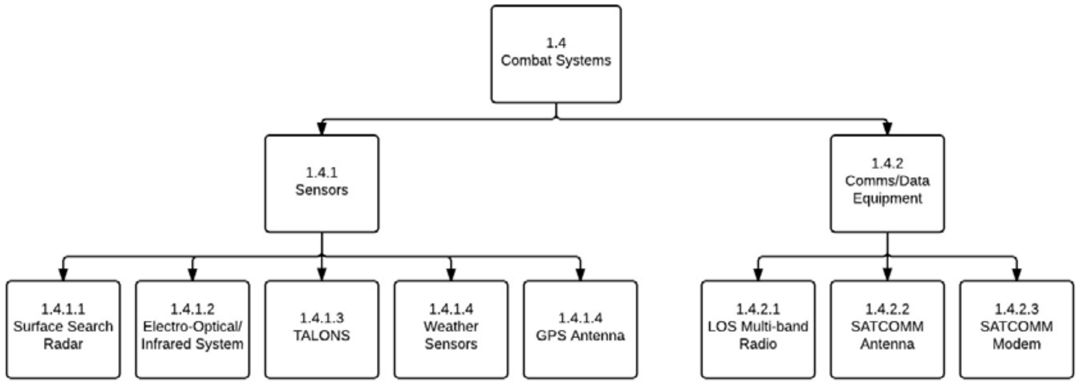

Figure 10. Level 3 Physical Decomposition of Combat Systems

Figure 10. shows the components that perform the Combat Systems related functions of the SuW variant MDUSV. At this point, the analysis is still in the detailed design phase, and as such refrains from specifying component details such as model or type that would be found in a lower level decomposition. What is important is to ensure that the needs, requirements and functions are met by the physical components and that all of the components meet a specified capability. In the case of Combat Systems, the components shown in Figure 10 directly correspond to the high level C2 needs and the functional requirements *Determine Organic Maritime Picture* and *Establish Comms/Data Link*. They also support certain elements of the all the remaining functions (*Screen Movement*, *Launch ASCMs*, *Reduce Susceptibility*, and *Determine Effects of 1^{st} Salvo*).

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IV. WARGAME SIMULATIONS

The final step in this analysis of a SuW variant MDUSV is to provide some validation of the system and its high-level design. This is performed by modeling the system in its proposed environment and simulating conditions similar to that which could be realistically expected, given its design and the proposed CONOPS- described in Chapter IV. This validation process helps ensure the system meets the customer's needs, in part by determine how effective the SuW variant MDUSV would be in an engagement. Furthermore, the modeling and simulation process also allows for trade space analysis by exploring the effects of changes to the system, for better or worse.

One of the first things most high-level stakeholders would want to know is, given an adversary's force size and capabilities, how many MDUSVs equipped with how many ASCMs are needed to have some measure of success in an engagement. In addition to the number of MDUSVs and ASCMs, what tactics work best for a given scenario? This chapter demonstrates two levels of detail in regards to wargame simulations. The first model, based on the Salvo Model, will utilize Microsoft Excel to perform comparative analysis of what might happen in an engagement. The second model, based on the ExtendSim software program, will demonstrate a more predictive model with more complex inputs.

A. SALVO MODEL

The Salvo Model, developed by distinguished NPS faculty member Wayne Hughes, offers a simplified means of determining the results of a missile-salvo exchange. The Salvo Model's equations provide a deterministic analysis given two homogenous and opposing forces. Similar to Lanchester's laws, which are used to calculate relative strengths of opposing forces, salvo theory is based on the premise of pulse fire, in which large amounts of destructive firepower, in this case delivered via ASCMs, are delivered instantaneously (Cares and Dickman 2016). Hughes' Salvo Model presents the concepts of staying power and combat power. His salvo equations mathematically prescribe a quantity of staying power and both offensive and defensive combat power. According to this model, staying power is the number of hits required to put a vessel out of action (not necessarily the same as sinking) (Hughes 1995). Offensive combat power is the number of missiles each vessel can fire per salvo, and defensive combat power is the number of incoming, attacking missiles a vessel can shoot down (Hughes 1995). As Cares and Dickman (2016) present in *Operations Research for Unmanned Systems*, mathematically, the equations are as follows:

$$\frac{\Delta B}{B} = \frac{\alpha A - b_3 B}{b_1 B} \quad \text{or} \quad \frac{\Delta A}{A} = \frac{\beta B - a_3 A}{a_1 A}$$

where

A = number of units in Force A
B = number of units in Force B
α = number of missiles fired by each A unit (*offensive combat power*)
β = number of missiles fired by each B unit (*offensive combat power*)

a_1 = number of hits by Force B’s missiles needed to put one A out of action (*staying power*)
b_1 = number of hits by Force A’s missiles needed to put one B out of action (*staying power*)
a_3 = number of incoming, attacking missiles that can be destroyed by each A (*defensive combat power*)
b_3 = number of incoming, attacking missiles that can be destroyed by each B (*defensive combat power*)

The left-hand side of both equations represents the fractional change (decrease) in Force A or Force B’s size (number of units). The salvo equations provide comparative analysis of what could happen in a single or multiple salvo exchange. The equations’ usefulness lies in their ability to compare one force’s ability to inflict damage against the other force, and vice versa. Additionally, they can be used repeatedly for multiple salvos. For example, the fractional change in each forces’ size in the first salvo can be applied the force size variables in the next salvo, with the process repeating itself until one force is completely destroyed.

B. EXCEL WARGAME SCENARIO

The scenario used for the Excel simulations utilizing the salvo equations diverges from the scenario used in the OA 4604 wargame. Since the salvo equations are limited in that they can only model one homogenous force against one other homogenous force (in size and capabilities), the Red Force AFP from the wargame scenario is not an ideal candidate for the Excel simulations. Instead, the scenario is altered to demonstrate the results of a more equal, force-on-force engagement. In this case, a group of SuW variant MDUSVs engage a squadron of hostile missile boats, vessels which are similar in size and capability to the MDUSVs. The homogeneous nature of the salvo equations dictates that each ship within a force have the same offensive combat power, defensive combat power and staying power.

The adversary (Red Force) vessel is based on the Chinese Type 022 missile boat, shown in Figure 11. The Type 022 is capable of carrying up to 8 ASCMs (Jane's IHS Markit 2017b). Based on its size, the author estimates one direct hit from an ASCM would put a Type 022 out of action. The Type 022 has a gun-based close-in weapon system (CIWS) for missile defense (Jane's IHS Markit 2017b). Assuming simultaneous launch of all the MDUSVs' (Blue Force) ASCMs and their simultaneous arrival on target, each Type 022 CIWS has an engagement window that allows it to destroy a maximum of 2 ASCM (for the purpose of the simulation). It should be noted that in the following scenarios, the Red Force consists entirely of Type 022 missile boats. The *Blue Force* reference in figure and table captions only refers to MDUSVs and does not include the main AFP vessels.

Figure 11. Chinese Type 022 Missile Boat. Source: Axe (2011).

1. MDUSV versus Type 022

In this first scenario, the MDUSVs operate over the horizon from the main AFP as picket boats. The Blue Force APF could consist of any variety or combination of LCSs or DDGs. In this scenario, the Red Force's goal is to destroy the manned ships making up the main Blue Force AFP, utilizing a squadron of Type 022s. As such, the Red Force Type 022s only fire 4 ASCMs during the initial salvo with the Blue Force MDUSVs with the intention of saving the other half of their ASCMs to launch against the Blue Force AFP.

The MDUSVs in this scenario are each equipped with four ASCMs and one Phalanx CIWS. Based on the survivability discussion presented earlier, the author assumes the MDUSVs can be taken out of action, though not necessarily sunk, with only one direct hit from an ASCM. Since the Type 022 is of similar size and displacement, the author assumes it too would only have a staying power of one.

With these assumptions and configurations, the equation variables for Red Force (B) and Blue Force (A) are shown in Table 2.

Table 2. Salvo Equation Values for Scenario 1

	Blue Force	Red Force
# of Units Variable Range (A and B)	2-16	1-4
Offensive Combat Power Variable Range (α and β)	1-4	4-8
Defensive Combat Power (a3 and b3)	2	2
Staying Power (a1 and b1)	1	1

Using Excel, the salvo equations and variables listed in Table 2 were input to the spreadsheet. The goal of the simulation was to determine the minimum number of MDUSVs and ASCMs needed to completely destroy the Red Force while not losing any MDUSVs. This represents the low-risk strategy, where the desire is to maintain the availability of MDUSVs by providing the best chance for success and minimizing losses. The input variables were number of MDUSVs (A) and number of ASCMS (α). The assumption is that the Red Force vessels would fire at least half of their eight ASCMs in a salvo exchange with MDUSVs. Table 3 also shows the results of sequentially increasing the number of Red Force ASCMs until the full complement of eight. The calculations cease after four Type 022s due to the impractical number of MDUSVs required (sixteen), as Table 3 demonstrates.

Table 3. Simulation Results for Scenario 1

# of Type 022 Vessels	# of Red Launched ASCMs per vessel	# of MDUSVs	# of Blue Launched ASCMS per MDUSV
1	4	2	2
	5	3	1
	6	3	1
	7	4	1
	8	4	1
2	4	4	2
	5	5	2
	6	6	1
	7	7	1
	8	8	1
3	4	6	2
	5	8	2
	6	9	1
	7	11	1
	8	12	1
4	4	8	2
	5	10	2
	6	12	1
	7	14	1
	8	16	1

Number of MDUSVs and ASCMs needed to destroy a given Blue Force configuration without sustaining losses

As shown in Table 3, completely destroying the Red Force without sustaining any friendly losses requires a significant advantage in terms of force size. This is particularly true if the Red Force launches more than four or five ASCMs. For example, a Red Force configuration of three Type 022s, each firing six of their ASCMs, requires a Blue Force configuration three times bigger (nine MDUSVs firing one ASCM each). Since the two opposing forces are equal in staying power and defensive power, it makes sense that the Blue Force would need, at a minimum, twice as many vessels to overwhelm the adversary. However, the required force ratio for Blue Force success only increases as the multiple of Red Force vessels and ASCMs increases.

2. Four-MDUSV Force versus Red Force

The scenario represents the situation of a task force with a given number of MDUSVs. Referencing the AFP construction in the OA4604 wargame, as shown in

Table 1, this squadron consists of four MDUSVs, each with four ASCMs and a CIWS. In this scenario, protection of the manned ships is the priority, and the task commander is willing to risk losing one or more MDUSVs. In order to show what a four-vessel force is capable of, Table 4 shows the results of engagements with Red Force configurations of varying numbers of vessels and ASCMs. The scenario continues to assume the ASCMs are evenly distributed amongst the vessels for both sides.

Table 4. Salvo Results of 4 MDUSVs Equipped with 4 ASCMs

# of Type 022 Vessels	# of Red Launched ASCMs per vessel	# of MDUSVs Lost	# of Type 022s Lost
1	4	0	1
	5	0	1
	6	0	1
	7	0	1
	8	0	1
2	4	0	2
	5	2	2
	6	4	2
	7	4	2
	8	4	2
3	4	4	3
	5	4	3
	6	4	3
	7	4	3
	8	4	3
4	4	4	4
	5	4	4
	6	4	4
	7	4	4
	8	4	4
5	4	4	5
	5	4	5
	6	4	5
	7	4	5
	8	4	5
6	4	4	4
	5	4	4
	6	4	4
	7	4	4
	8	4	4
7	4	4	2
	5	4	2
	6	4	2
	7	4	2
	8	4	2

Although the Blue Force is completely destroyed when facing anything more than two Type 022s firing six or more ASCMs, the Blue Force is able to inflict enough damage to destroy up to five vessels. A similarly-equipped, six-vessel Blue Force squadron is able to destroy up to eight vessels before losing all six MDUSVs.

Equivalent staying power and defensive combat power aside, the results of Table 3 and Table 4 indicate a need for a better ASCM defense. Otherwise, Blue Force has to rely on outnumbering their opponent. There are other methods that could reduce the need for such a large offset in terms of size, such as employing a tactical advantage. For example, there exist modified salvo equations that include "Scouting Effectiveness" and "Defensive Readiness" factors. These values refer to the element of surprise and defensive readiness posture, respectively. The effect of their variation can be significant, especially within the context of DL, as shown by YM Tiah (2007), in his thesis entitled "An Analysis of Small Navy Tactics Using a Modified Hughs' Salvo Model."

However, both values are assumed to be one in the previous scenarios for the purpose of minimizing assumptions. Referencing the Survivability section of Chapter III, the next section explores the results of a more robust ASCM defense system.

3. SeaRAM Modified Variant

In this scenario, the regular SuW-variant MDUSVs are supplemented with one modified MDUSV. This modified version does not contain any ASCMs. Rather its purpose is solely to defend the other MDUSVs against incoming, hostile ASCMs. This theoretical integrated air and missile defense (IAMD) variant contains a SeaRAM system. SeaRAM features the self-contained air-search radar from the Phalanx CIWS. The difference from CIWS is that underneath the radar housing is a Mark 49 missile launching system with eleven RIM-116 Rolling Airframe missiles (Jane's IHS Markit 2017d). The SeaRAM system seems appealing for the MDUSV application due to its ease of integration. The inclusion of a radar and tracking system as well as a fire control system negates the need for additional systems to be installed and integrated with the MDUSVs operating system.

In the first scenario with the SeaRAM variant, the MDUSVs stay close to each other and the SeaRAM variant in order to remain under the SeaRAM's umbrella of protection. As in the previous scenario, it is assumed that the incoming hostile ASCMs are evenly distributed among the MDUSVs. As such, the eleven RIM-116 missiles from the SeaRAM variant are evenly distributed for defense of the MDUSVs. It is also assumed that one RIM-116 missile is capable of destroying one ASCM, with 100% kill probability. The results are shown in Table 5. The SeaRAM variant is not in included in the number of MDUSVs listed in the table.

Table 5. Results with SeaRAM Defense Ship

# of Type 022 Vessels	# of Red Launched ASCMs per vessel	# of MDUSVs	# of Blue Launched ASCMS per MDUSV
1	4	1	3
	5	1	3
	6	1	3
	7	1	3
	8	1	3
2	4	2	3
	5	1	6
	6	1	6
	7	1	6
	8	3	2
3	4	2	5
	5	2	5
	6	4	3
	7	5	2
	8	7	2
4	4	3	4
	5	5	3
	6	7	2
	7	9	2
	8	11	2
5	4	5	3
	5	7	3
	6	10	2
6	4	7	3
	5	10	2
7	4	9	3

The inclusion of one SeaRAM defense ship significantly reduces the number of MDUSVs needed to prevent any friendly losses. However, like the previous scenario, the outcome is heavily dependent on the Red Force salvo doctrine. If the Type 022 vessels fire more than half of their ASCMs, the Blue Force is overwhelmed unless they vastly outnumber the Red Force.

C. EXTENDSIM WARGAME

The ExtendSim modeling program allows for more complex simulations than the Salvo Model and its mathematical theorems. Rather than the comparative analysis of the Salvo model, ExtendSim provides a means of predictive analysis. It also is not restricted to homogeneous attributes for a represented force.

The author's intent for the ExtendSim modeling was two-fold: to increase the level of detail in the salvo exchange with vessel-specific analysis, and to factor in more dynamic attributes of a salvo exchange that could not be modeled by salvo equations. In particular, the author wanted to explore the concept of increasing the probability of one or two specific ships being targeting by ASCMs.

One of the more unique possible concepts of the MDUSV is the idea of a "missile sponge." The concept is simple: dedicate a specific vessel (or vessels) to attract a larger percentage of the incoming ASCMs in an attempt to prevent other vessels from being targeted. The concept is not new of course, but the concept of sacrificing one or more vessels for the sake of other vessels is often not easily embraced, nor practiced, as part of prescribed TTPs in the USN. However, the unmanned nature removes a substantial portion of the ethical element involved with the practice. Despite this, the intent is not to consider the vessel expendable.

Rather, the idea is to dedicate a MDUSV to the defense of the ASCM-launching MDUSVs by increasing its probability of being targeting but equipping it with an adequate defense system to warrant a sufficient probability of survival. This ship, referred to here as a "defense ship," provides an umbrella of protection for the SuW variant MDUSV squadron by engaging incoming ASCMs and luring them away from the other

MDUSVs. This model capitalizes on the low-risk offered by the unamend vessels while maintaining availability of both the defense ships and SuW variant MDUSVs.

Increasing the probability of being targeting by incoming ASCMs can be accomplished by increasing the signature of the defense ship, such as the radar cross section (RCS) or electromagnetic signature or infrared signature. Since the adversary ASCM in the simulations, the C802, is an active radar homing missile, RCS is the proposed signature-reduction method (Jane's IHS Markit 2017a). This is reflected in the ExtendSim model by increasing the probability of ASCMs selecting the defense ship.

The ExtendSim simulations build on the scenarios presented in the previous section, but adds additional factors such as probability of hit and kill for ASCMs, SeaRAM, chaff and CIWS; detection range; classification time with mean and standard deviation and missile velocity. The overarching goal of these simulations, similar to that of the Salvo Model simulations, is to explore various methods and tactics that could be utilized successfully for an AFP operating with MDUSVs. Rather than analyzing several scenarios with sequentially increasing ASCMs and vessels, this section considers a few different defense configurations. It also only analyzes the Blue force. Since the Type 022 vessel only has a CIWS for missile defense, the salvo equations are assumed to be sufficient to determine the approximate offensive force, in terms of number of ASCMs, needed to destroy them.

For each scenario, a total of 300 runs was conducted in order to establish a normal distribution. The input parameters that were held constant for each run are shown in Table 6. Jane's online references for the C802 ASCM, RIM 116 missile and SeaRAM system provided values for metrics such as velocity and range. All other values are notional and were assigned for the purpose of the simulation.

Table 6. Input Parameters Held Constant over 300 Runs

Probability of C802 Hit	Initial C802 Range (m)	C802 Velocity (m/s)	Number of C802s	C802 Detection Range (m)	Blue CIWS Classification Mean Time (s)	Blue CIWS Classification Stdev Time(s)	Max Blue CIWS Range (m)	Prob Blue CIWS Kill
0.8	100000	333.67	44	2400	5	2	2000	0.3
Mean Blue CIWS Engagement Time (s)	**Number of RIM 116s**	**RIM 116 Velocity (m/s)**	**Probability of RIM 116 Hit**	**RIM 116 (missiles /sec) Fire Rate**	**RIM 116 Fire Rate Stdev (s)**	**SeaRAM Engagement Range (m)**	**Min SeaRAM Range (m)**	**SeaRam Detection Range**
4	11	850	0.9	11	0.6	9000	1000	5600

1. Scenario 1: One Defense Ship versus 44 Incoming ASCMs

In this scenario, four MDUSVs, each with one CIWS and four Harpoon canisters, are defended by one defense ship equipped with a single SeaRAM system. Red Force fires 44 ASCMs from six or more Type 022s. The results of the MDSUV casualties are shown in Figure 12.

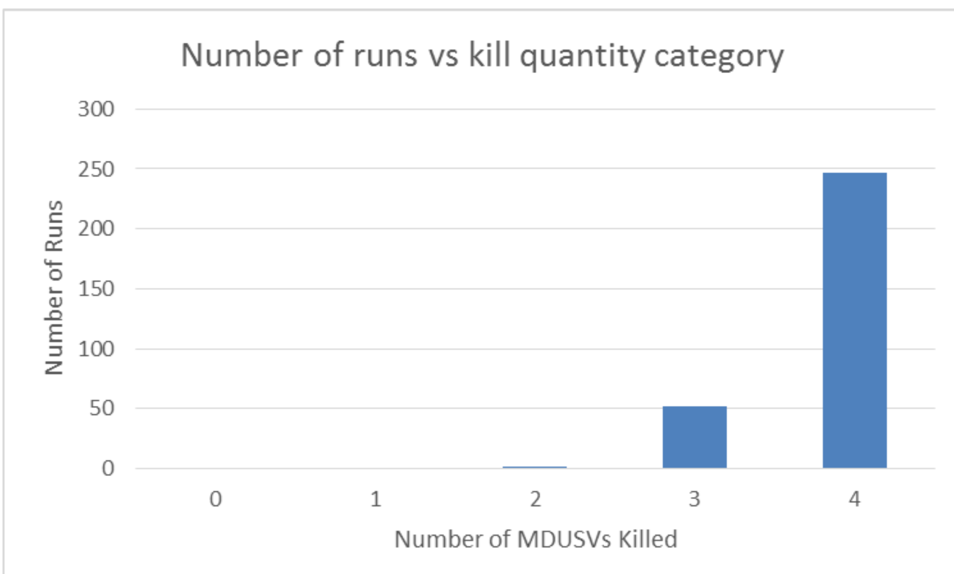

Figure 12. Kill Quantity Distribution for Scenario 1

From Figure 12 it is clear that the defense ship's single SeaRAM, equipped with eleven RIM-116 missiles, is overwhelmed by 44 ASCMs. The individual CIWS on each MDUSV is not sufficient defense either. Clearly, a more robust defense is needed. A second trial was performed, only in this case, to include the single defense ship equipped with two separate SeaRAM systems, each with its own detection and tracking radar and integrated fire control system. Two SeaRAM systems increases the number of RIM-116 missiles to 22. The MDUSV casualty results are shown in Figure 13.

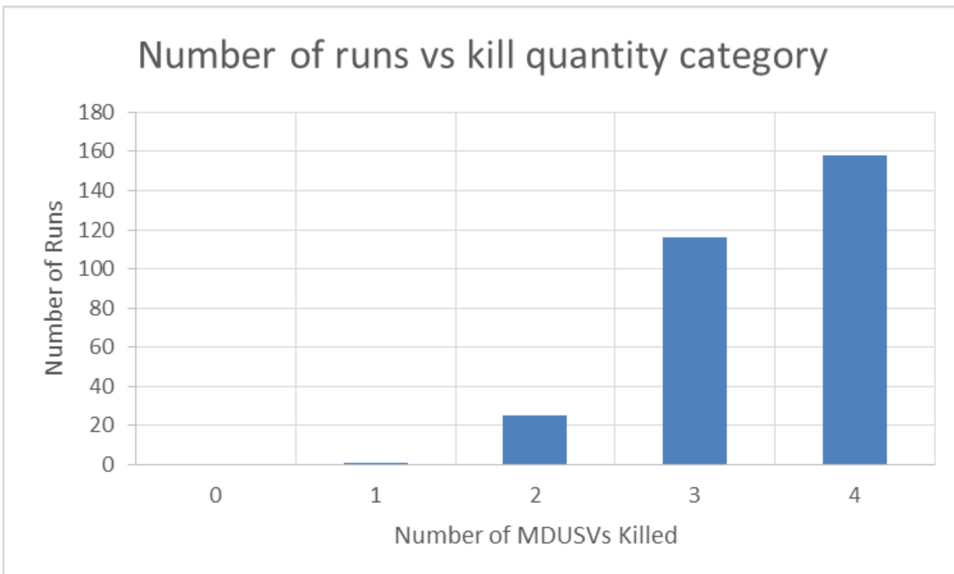

Figure 13. Kill Distribution for Scenario 1 with 2 SeaRAM Systems

Figure 13 shows fewer runs with four MDUSV losses, indicating an increased defensive capability. However, the sustained losses are still too high; the distribution signifies a high probability of losing all four MDUSVs. Further improvements in the defensive capabilities are needed.

2. Scenario 2: Two Defense Ships versus 44 Incoming ASCMs

Obvious defensive improvements include increasing the number of RIM-116 missiles available. Considering the weight of a SeaRAM system, it is physically infeasible to install more than two such systems on one MDUSV without significantly increasing the size of the vessel. Since the probability of CIWS successfully killing an

ASCM is only 0.30 (for the purpose of these simulations), it would be prudent not to rely on CIWS and instead, match the number of ASCMs with RIM-116s. Two defense ships with two SeaRAM systems each provides a total of 44 RIM-116s missiles. The second defense ship provides an additional target, effectively reducing the probability of the SuW variant MDUSVs being targeted. The probability of being targeted for each Blue Force vessel is shown in Table 7.

Table 7. Scenario 2 ASCM Targeting Probability per Vessel

Ship	MDUSV 1	MDUSV 2	MDUSV 3	MDUSV 4	Defense Ship 1	Defense Ship 2
Probability	0.1	0.1	0.1	0.1	0.3	0.3

The MDUSV casualty results are shown in Figure 14.

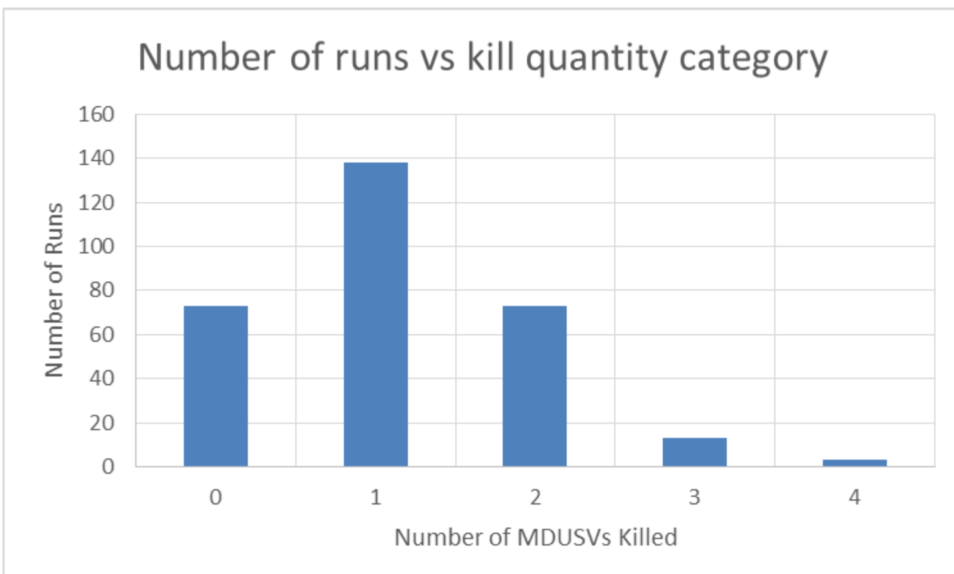

Figure 14. Kill Distribution for Scenario 2 with 2 Defense Ships

Figure 14 shows a significant decrease in the number of MDUSVs killed, with a distribution centered around one. However, there are still a significant number of runs with two MDUSVs killed. This indicates a high probability of one or more MDUSV casualties. A third and final scenario will explore an additional defense capability.

3. Scenario 3: Two Defense Ships with Countermeasures versus 48 ASCMs

Ship-launched countermeasures, in the form of chaff, are arguably the best defense against ASCMs (Schulte 1994). For this final scenario, the Mark 36 Super Rabid Bloom Offboard Countermeasures (SRBOC) Chaff and Decoy System is installed on the two defense ships. The Mark 36 SRBOC is a program of record with the USN and installed on many USN ships (BAE Systems 2017). For the purpose of this simulation, the Mark 36 system relies on input from the tracking radar of the SeaRAM system. Rather than inputting a specific number of Mark 36 rounds, the number of engagements was recorded to see how many canisters were needed. The input parameters of the Mark 36 for the ExtendSim simulations are shown in Table 8.

Table 8. Mk 36 Input Parameters

Mk 36 Range (m)	Mk 36 Prob of Kill	Mk 36 Mean Engagement Time (s)
3000	0.6	1

The final change to the configuration was increasing the probability of the defense ships being targeted (simulated by increased RCS). The probability of being targeted for each Blue Force vessel is shown in Table 9.

Table 9. Scenario 3: ASCM Targeting Probability per Vessel

Ship	MDUSV 1	MDUSV 2	MDUSV 3	MDUSV 4	Defense Ship 1	Defense Ship 2
Probability	0.075	0.075	0.075	0.075	0.35	0.35

The MDUSV casualty results are shown in Figure 15.

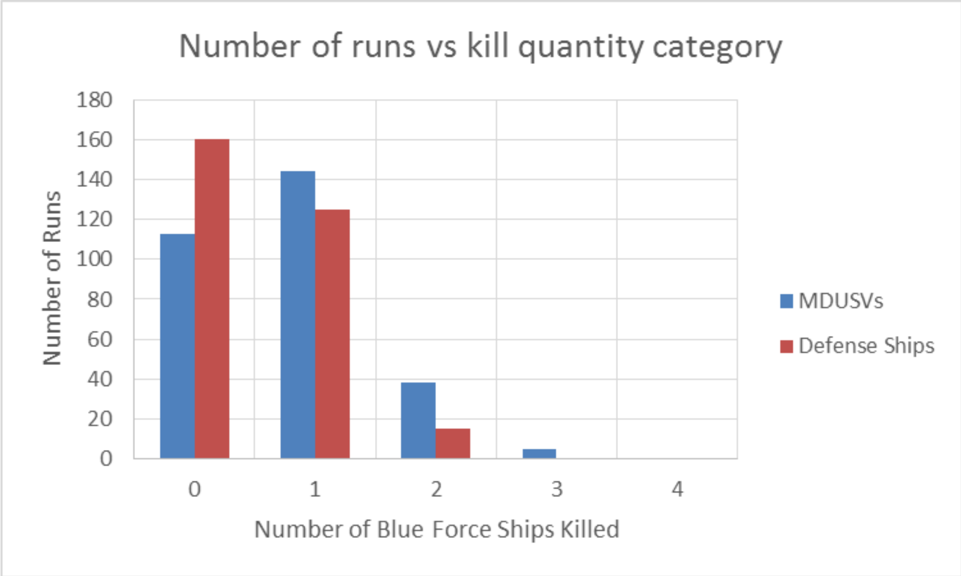

Figure 15. Kill Distribution for Scenario 3 with Mk 36 SRBOC

Compared to two defense ships without Mark 36, there are significantly more runs with zero MDUSV casualties and significantly less runs with two or more casualties. This indicates that the Mark 36 system is effective in increasing the IAMD capability.

D. STATISTICAL ANALYSIS

Statistical analysis and tests applied to the ExtendSim data can provide additional insights and confirmation of the initial indications. Both the software programs Excel and SAS' JMP Pro were used for the statistical analysis.

The metric of interest is the number of MDUSVs taken out of action or "killed" as described in the figure captions. The intention of changing the configuration from scenario to scenario was to seek an improvement in the ability to reduce the number of MDUSVs lost. In order to confirm that trend, hypothesis testing is applied to two sequential scenarios. The subscript of each hypothesis refers to the ExtendSim scenario number.

Given that the goal of this analysis is to recommend potential changes to the MDUSV, the author focused on Scenarios 2 and 3, both of which provided superior performance to Scenario 1. The intent is to determine if the addition of the Mark 36 SRBOC system does indeed make a difference. The null hypothesis can be stated as follows:

$$H_0: \mu_2 = \mu_3 \quad \text{versus} \quad H_A: \mu_2 \neq \mu_3\,,$$

where μ_2 is the mean number of MDUSVs killed in Scenario 2, and μ_3 is the mean number of MDUSVs killed in Scenario 3.

The JMP Pro program provides the ability to conduct a t-test. The results are shown in Figure 16.

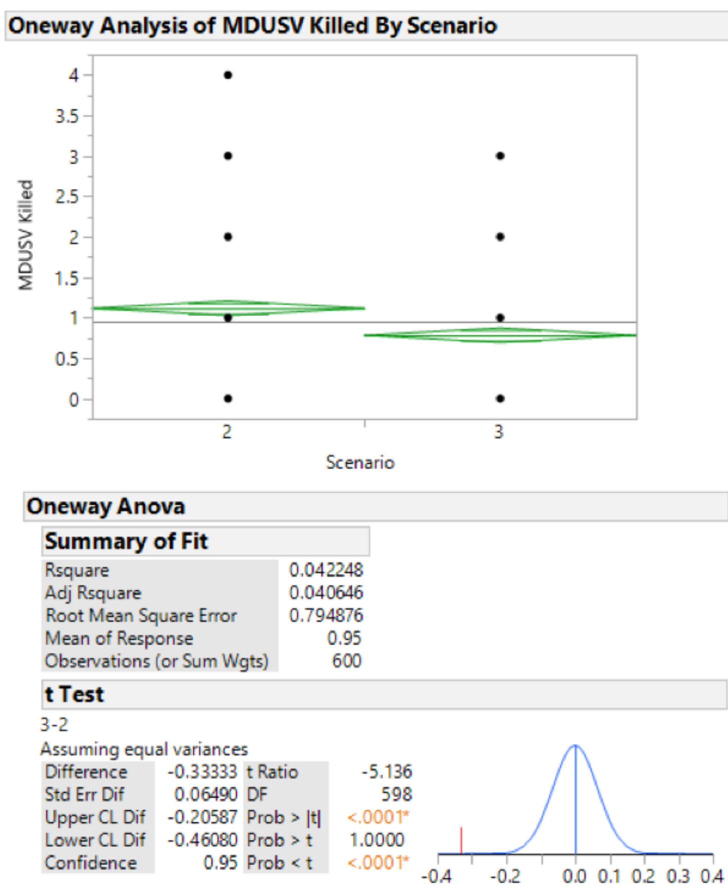

Figure 16. T-test Results of a Means Comparison between Scenario 2 and Scenario 3

As shown in Figure 16, there is a statistically significant difference between the performance in Scenarios 2 and 3. Table 10 presents additional information regarding the mean, standard deviation, and confidence intervals for each scenario that further highlights the improvement in performance from Scenario 2 to Scenario 3. Specifically, the upper 95% confidence bound for Scenario 3 (characterizing the near worst case performance for Scenario 3) is 0.87 MDUSVs lost, while the lower 95% confidence bound for Scenario 2 (characterizing the near best case performance for Scenario 2) is 1.02 MDUSVs lost, indicating that the installation of the SRBOC in Scenario 3 resulted in significant improvements when compared to the isolated addition of the RIM-116 in Scenario 2.

Table 10. Comparison of Statistical Parameters between Scenario 2 and Scenario 3

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Scenario	1	16.66667	16.6667	26.3785	<.0001*
Error	598	377.83333	0.6318		
C. Total	599	394.50000			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
2	300	1.11667	0.04589	1.0265	1.2068
3	300	0.78333	0.04589	0.6932	0.8735

Std Error uses a pooled estimate of error variance

V. CONCLUSION

A. CONCLUSIONS

As stated in the Introduction, the goal of this thesis is to evaluate how the ACTUV platform could be utilized as a SuW tool in Distributed Lethality. Building on the Distributed Lethality model's need to have platforms capable of posing a threat and forcing the adversary to disperse his forces, this report analyzes how the ACTUV could meet this need as a lethal and cost-effective addition to the surface navy by fully integrating with an AFP.

The first research question, as presented in the Introduction, is as follows:

- Does the ACTUV have potential to be an effective SuW system for DL?

The analysis provided in chapters III and IV present supporting arguments that the ACTUV can indeed be an effective SuW system to support DL. The architectural development process determines the overarching needs of DL-based SuW, as well as the high-level needs for the MDUSV to fulfill a SuW role and, consequently, how the MDUSV fulfills those needs by mapping those requirements to functions and physical components. The high-level design includes a SuW variant that is both physically feasible and considers factors such as availability of components and survivability of the system as a whole. The logistics model provides a realistic way to maintain the system within the confines of DL. The cumulative effect of the proposed model is one that is possible and even feasible to employ, while capable of fully meeting the system requirements

The second research question is as follows:

- How can the ACTUV be integrated into an Adaptive Force Package to support SuW, especially within DL?

The ACTUV already has inherent design features that support ease-of-integration within a traditional AFP. Its communications suite and even the original ASW-based ACTUV CONOPS account for working with other conventional, manned platforms. The vessel's long range and significant endurance, coupled with the potential for lower frequency of logistical servicing, enable it to be an exceptional system for DL's challenging operational model. With the exception of the vessel itself, most of the components, such as communication equipment and the Harpoon missile system, are systems familiar to the USN, decreasing the need for extensive, additional training. Although, as a system, the SuW variant MDUSV is more complex than other unmanned and autonomous systems in use by the USN today, it is entirely possible that the TTPs will not need to be significantly more complex. Integrating a team of MDUSV-specific maintainers and watchteam operators on a manned ship, such as an LCS, would likely be similar to the inclusion of a Fire Scout detachment.

The final research question is as follows:

- How should the ACTUV be used, in terms of system configuration and tactics, as a SuW component in DL?

Chapter IV provides key insights on how best to employ the MDUSV. Without dramatically increasing both the size, complexity and cost of the vessel, the Harpoon-equipped, SuW variant MDUSV proposed in this report certainly poses a lethal threat. It also has certain limitations. As pointed out in Chapter IV, the need for an ASCM defense is crucial if the desire is to minimize risk while employing them in an over-the-horizon capacity. However, implementing a sufficient IAMD capability is also feasible, based on the addition of a SeaRAM defense ship variant. In any case, the salvo model simulations demonstrate what a SuW variant MDUSV AFP is capable of in regards to force-on-force salvo exchanges. With multiple MDUSV AFPs, it is possible to effectively disperse an adversary's forces and thereby dictate the terms of a force-on-force engagement, increasing the odds of success.

Depending on the size of the adversary, the required number of MDUSVs for a successful campaign with minimal losses could be quite large, as shown in Table 3 and Table 4. As long as the Navy continues to focus on implementing DL, however, the need for an offensive platform, capable of engaging an enemy surface fleet, will continue to exist. Additionally, the scenarios in Chapter IV represent a select few configurations, with the intent of replicating less-than-ideal situations in regards to the number of MDUSVs available and the size of an opposing force. By increasing the MDUSV AFP size and its missile defense capabilities, the results would likely be much more favorable. Incorporating risk analysis and being selective, when possible, about when and how to employ the system against an enemy, would also increase its success. As presented, however, the MDUSV represents a potential cost-effective solution that gives fleet commanders flexibility and operational analysists more ways to challenge our adversaries.

It may be that the SuW variant MDUSV's most appealing traits are realized when one considers the alternatives. As stated before, DL implies sending ships into harm's way to challenge an opposing force. With the USN's traditional model, that means sending manned ships with procurement and operating costs an order of magnitude higher than that of the MDUSV's, into a potentially high-risk situation. In addition to the risk associated with operating in a hostile environment, there is an inherently high number of ships required to successfully conduct DL.

The USN recently determined that it needs to increase its fleet size to 355 (Cavas 2017). As Cavas points out, there are many ways to reach that goal, and building more LCS and pursuing a frigate class based on the LCS is certainly an option and one being discussed. When comparing the operating and procurement costs of the MDUSV to those types of ships however, and the potential capability of the SuW variant as proposed in this report, the MDUSV makes for a compelling case. It is because of these reasons that the author concludes that the MDUSV system is worthy of further analysis and investigation as a tool for SuW and DL.

B. CONTINUED RESEARCH

As a new system with multi-mission and multi-role potential, the MDUSV comprises many topics of research. This thesis addresses proposed CONOPS for just one particular warfare area. Even within SuW, there are many other avenues to consider for research. The development of this thesis revealed several topics that were outside the proposed scope but worthy of further exploration.

1. Platform Design

The current iteration of the MDUSV's design would appear sufficient for many different mission types. However, some alterations, such as increasing the hull size, could increase the mission capability even more. For example, the missile choice for the simulations in Chapter IV was restricted to those capable of being launched from deck-mounted canisters. If the vessel's hull depth was increased such that it could accommodate VLS, other ASCM options could increase the MDUSV's lethality even more. While this would require a significant increase in hull size, it increases the number of ASCM options, and therefore the availability of weapons for the MDUSV to employ against the enemy. Raytheon is developing an anti-ship seeker for the Tomahawk when it restarts the production line in 2019 (Jane's IHS Markit 2017e). With a 1,000-mile range, the ASCM variant of the missile, called the Maritime Strike Tomahawk, will give the surface navy a significant standoff weapon, reducing the need for a complex IAMD system to defend against incoming ASCMs (Jane's IHS Markit 2017e). According to Jane's Online, the Long Range Anti-Ship Missile (LRASM) is another ASCM in development with the USN capable of being launched from both a VLS and as a deck-mounted canister (Jane's IHS Markit 2017f). Its 500-mile range would also give the MDUSV a tactical advantage over C802-equipped ships (Jane's IHS Markit 2017f). In any case, future availability of other ASCMs could increase the effectiveness of the MDUSV as a SuW platform and could warrant another feasibility analysis.

An increase in hull size could also increase the payload capacity for multiple defense systems. For example, a defense ship with one SeaRAM system and one Mark 49 Guided Missile Launching System would have 31 RIM-116 missiles at its disposal. The two systems have a combined above deck weight of 27,000 lbs, or 7,000 lbs over the limit for the current design. However, a defense ship so configured could negate the need for more than one defense ship.

2. MDUSV-Centered AFPs

As previously mentioned, *Sea Hunter* is currently being tested for its ability in ASW and MW. This thesis presents its potential as a SuW platform and also proposes a variant with IAMD capability. The potential ability to perform in multiple warfare domains suggests the possibility of an AFP comprised solely of MDUSVs that fulfill multiple warfare roles. However, a more likely concept is an AFP configured of one manned ship with multiple MDUSVs. For example, an Aegis destroyer could provide the local watch team supervision of MDUSVs while providing IAMD. The rest of the AFP could comprise of SuW variant MDUSVs, ACTUVs for ASW and MW variant MDUSVs. This model would reduce the tasking of conventional manned ships while reducing operational costs.

3. Use of TALONS to Achieve Tactical Advantage

By significantly increasing the range of surface search radar and communication relay equipment, TALONS represents a potential ability to greatly increase the striking ability of an AFP. A TALONS-equipped MDUSV could be sent over the horizon to determine where the enemy is, serve as an early-warning system against incoming ASCMs, or guide friendly ASCMs towards their targets. It could also serve as a communication relay between manned ships and MDUSVs operation over the horizon, further enhancing the physical AFP configuration for communication model in the Class 311-154O’s capstone project. In any case, the use of TALONS represents another potential technological opportunity well suited to the MDUSV.

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