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SYSTEMS ENGINEERING CAPSTONE REPORT

HIGH VALUE UNIT SELF-ESCORT AGAINST UNMANNED AERIAL AND SURFACE THREATS

by

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September 2023

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AND SURFACE THREATS**

Michael H. Darnell, Joshua M. Kejsar, Wesley Kenyon, and Christine D. Norton

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ABSTRACT

The Department of the Navy is seeking to improve capabilities for self-escort of high value units (HVU) against unmanned system (UxS) threats. This project applies a systems engineering approach to generate a framework to analyze potential combinations of systems to enable a counter-UxS (C-UxS) capability. First, a systems architecture describes employment and integration of C-UxS capability, particularly the level of integration with the HVU and the distribution of supporting functions. Two hypothetical physical architectures supply alternate conceptual designs. An “Echo/Inyx” alternative implements electronic warfare capabilities throughout the engagement space, while a “RamJammer” alternative includes a kinetic capability for close-range defense. Second, an adaptation of the government-developed Modeling and Simulation Toolkit (MAST) supplies a state-machine based method for C-UxS simulation. To support capability analyses, the project applies a weighted scoring model to output from the simulation that uses a range-based defense profile to rank alternatives. Finally, a hypothetical case study describes an HVU escort scenario and shows the relative benefit of the C-UxS self-escort capability, using the two conceptual alternatives as exemplars. The correspondence between weighted score and the probability of HVU intercept demonstrates the utility of the score as a single metric for distinguishing operational capability between alternatives.

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LIST OF ACRONYMS AND ABBREVIATIONS

AGL	above ground level
AI	artificial intelligence
AOR	area of responsibility
C2	command and control
CIO	chief information officer
CNN	convolutional neural network
COTS	commercial off the shelf
C-UAS	counter-unmanned aerial system
C-UxS	counter unmanned system
DARPA	Defense Advanced Research Projects Agency
DOD	Department of Defense
DODAF	Department of Defense Architectural Framework
DOE	design of experiments
DON	Department of the Navy
EO/IR	electro-optical/infrared
EW	electronic warfare
F2T2EA	find, fix, track, target, engage, assess
FAA	Federal Aviation Administration
FAC	fast attack craft
FIAC	fast inshore attack craft
GCS	ground control station
GNSS	global navigation satellite system
GPS	global positioning system
HVU	high value unit
ICOM	input, control, output, mechanism
IDE	integrated development environment

IDEF0	integrated computer aided manufacturing definition for functional modeling 0
ISIS	Islamic State of Iraq and Syria
ISR	intelligence, surveillance, and reconnaissance
JCO	Joint Counter-small Unmanned Aerial Systems Office
JP	joint publication
LiDAR	light detection and ranging
LML	lifecycle modeling language
KIAS	knots indicated air speed
MAST	Modeling and Simulation Toolkit
MDS	micro-doppler signature
METT-TC	mission, enemy, terrain and weather, troops and support available, and civilian considerations
ML	machine learning
MLS	messaging layer security
MOE	measure of effectiveness
MSL	mean sea level
NPS	Naval Postgraduate School
NRP	Naval Research Program
NSWC	Naval Surface Warfare Center
OPNAV	Office of the Chief of Naval Operations
OPNAV N9	Deputy Chief of Naval Operations for Warfighting Requirements and Capabilities
OSM	orchestrated simulation through modeling
OV	operational viewpoint
RCS	radar cross section
RF	radio frequency
RL	reinforcement learning
SAM	surface to air missile
SDR	software defined radio

SoS	system of systems
sUAS	small unmanned aerial system
SV	systems viewpoint
SVM	support vector machine
UAS	unmanned aircraft system
UAV	unmanned aerial vehicle
USD R&E	Undersecretary of Defense for Research and Engineering
USV	unmanned surface vessel
UxS	unmanned system

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EXECUTIVE SUMMARY

This project explores current limitations for defense of high value units (HVV) in restricted movement scenarios against unmanned aircraft systems (UAS) and unmanned surface vessels, collectively termed unmanned systems (UxS). It applies a systems engineering approach to supply a framework for the appropriate mix of systems to enable a C-UxS capability, resulting in three deliverables: a systems architecture, a modeling and simulation tool, and an analysis case study.

Department of Defense strategic guidance from 2021 describes how low-cost UxSs deployed in swarms can augment existing materiel capabilities and change the character of war by implementing artificial intelligence and autonomy (Department of Defense 2021). Recent experience in the Russian War in Ukraine has highlighted the magnitude of UxS usage, with the Royal United Services Institute estimating that Ukraine is facing 10,000 UAS losses per month (Watling and Reynolds 2023).

Reflecting this recent guidance, the Department of the Navy is seeking to improve capabilities for self-escort of HVVs against UxS threats. The proliferation of UxSs increases their likelihood of use as threats against HVVs. Recent instructions (Chief of Naval Operations 2020) have highlighted a need to reduce vessel escort requirements, creating a need for a C-UxS capability to enable self-escort of HVVs.

This project creates a framework for assessing alternatives to address the needed C-UxS capability. First, a systems architecture describes employment and integration of C-UxS capabilities, using self-escort of an HVV from an unprotected port to open water as a foundation. The project leverages a range-based defense profile described by Behling et al. (2022) to generate a concept of operations, resulting in measures of effectiveness that characterize C-UxS capabilities by their ability to prevent UxSs from intercepting the HVV. Then, a functional architecture uses vignettes to generate functions for the C-UxS system and interacting assets. Two hypothetical physical architectures supply alternate conceptual designs. An “Echo/Inyx” alternative implements electronic warfare capabilities throughout the engagement space, while a “RamJammer” alternative includes

a kinetic capability for close-range defense. These alternatives use the architecture to ensure coverage of operational requirements in support of the C-UxS mission.

The second deliverable implements an adaptation of the government-developed Modeling and Simulation Toolkit (MAST), resulting in a state-machine based method for C-UxS simulation. This is informed by the architecture and supplies a mechanism for showing the relative efficacy of different alternatives. The simulation implements state-machines that model agent behavior for components of the mission scenario, including the HVU, threat UxSs, and C-UxS system components. To support capability analyses, the project applies a weighted scoring model to output from the simulation that uses the range-based defense profile to rank alternatives. The “Echo/Inyx” and “RamJammer” alternatives are used as exemplars for defining state-machine composition. Model verification is performed by defining a scenario set in the port of Hampton Roads, Virginia, and using the alternatives to examine the impact of extreme parameter settings on the weighted score.

Finally, a hypothetical case study describes an HVU escort scenario and shows the relative benefit of the C-UxS self-escort capability. Notional data supports a conceptual analysis of the relative effectiveness of C-UxS capabilities and capability compositions. A design of experiments is applied to parameters for each alternative, supporting a Monte Carlo experiment for the impact of the parameters on the weighted score and the probability of HVU intercept. A weighted score implements weights that reflect priorities for avoiding intercepting the HVU and minimizing threats close to the HVU. When compared with a scenario without a C-UxS capability, results from the experiment show that jamming parameters have the greatest effect on a C-UxS system’s effectiveness. For both alternatives these have between five- and ten-times greater impact than other parameters on the weighted score. This impact carries over to comparisons between the alternatives, with the limited impact of kinetic capabilities resulting in an average probability of HVU intercept for the “Echo/Inyx” alternative approximately one third that of the “RamJammer” alternative. The correspondence between weighted score and the probability of HVU intercept demonstrates the utility of the score as a single metric for distinguishing between alternatives.

This project addresses only a subset of the problems posed by UxS to HVU escort. Incorporating controlled data will improve the relevance of analysis. This project supplies tools that allow for input of controlled system performance data and other metrics, including sensor performance metrics, degraded system behavior modes, and potential response behaviors of the HVU. Other extensions of this project include assessing how a congested environment affects the systems that may support C-UxS capability and including terminal effects and associated operational impact.

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I. INTRODUCTION

This project explores current limitations for defense of high value units (HVV) in restricted movement scenarios against unmanned aircraft systems (UAS) and unmanned surface vessels, collectively termed unmanned systems (UxS). Department of Defense (DOD) strategic guidance from 2021 describes how low-cost UxS deployed in swarms can augment existing materiel capabilities and change the character of war by implementing artificial intelligence and autonomy (Department of Defense 2021, 6). Recent conflict experience in Ukraine and Nagorno-Karabakh has shown how militaries that are organized for engagements against comparable tiers of systems may encounter difficulties against relatively lower-tier UxS. In Ukraine, while the offensive application by Ukraine and Russia of UAS is similar, the Ukrainian military possesses a relative advantage in counter UAS technology (Lowther and Siddiki 2022), leading to a greater impact on Russian forces. Similarly, in the 2020 conflict between Armenia and Azerbaijan in Nagorno-Karabakh, the Armenian military relied on dated Soviet equipment and higher-tier air defense systems such as the S-300 (Shaikh and Rumbaugh 2020). These proved vulnerable to Azerbaijani UAS operations and contributed to Azerbaijani effectiveness in disabling armor and air defenses and in weakening Armenian logistics. Additionally, as of May 2023 the Royal United Services Institute estimates that Ukraine is facing UAS losses of approximately 10,000 systems per month (Watling and Reynolds 2023, 4), indicating that these are systems which see significant use in conventional conflict. USVs have also been utilized in the Ukrainian conflict in ways that threaten HVVs and ports, with Russian forces demonstrating limited tactical capability for eliminating the USV threat (Sutton 2022).

These examples show that the U.S. military collectively has much to gain from investigating and investing in technologies that can effectively counter UxS. This project supports that effort.

A. STATEMENT OF NEED

In 2020, the Department of the Navy (DON) updated existing guidance for transit protection operations in support of HVUs. Where in prior guidance dating to 2014 fleet commanders were required to assign “at least two armed escort vessels” (Chief of Naval Operations 2014) for HVU transit protection operations, the updated guidance states that fleet commanders may determine escort requirements “based on the results of local and [area of responsibility (AOR)] specific risk and threat assessments.” (Chief of Naval Operations 2020) This means that fleet commanders have added flexibility for distributing resources within their AOR. However, given the persistent threat posed by UxS, fleet commanders and HVU need tools that can manage this threat and at the same time support freeing resources for higher priority missions. Fleet commanders cannot take advantage of the flexibility in the updated mission guidance if there are no changes to the tools that they have available for escort.

1. Problem Statement

The DON is seeking to improve current capabilities for self-escort of HVU against unmanned aerial and surface threats. The proliferation of this capability among both nation-state and non-nation-state actors, as well as its low relative cost compared to other engagement strategies, increases its likelihood of appearance when performing threat assessments for HVU escort. Existing methods for enabling escort, avoidance, and defense against UxSs are optimized for high-tier peer threats, which may require additional vessels or other resources to enable escort capability. Recent instructions from the office of the chief of naval operations (OPNAV) (Chief of Naval Operations 2020) have highlighted a need to reduce vessel escort requirements. This creates a need for a capability to enable self-escort of HVUs, particularly against lower-tier UxSs.

2. Research Objectives

This project takes a systems engineering approach to supply a framework for identifying the appropriate system, or mix of systems, to enable a counter unmanned system (C-UxS) capability. It does this through a three-step process, and with three primary deliverables:

- First, a systems architecture describes employment and integration of C-UxS capability, particularly the level of integration with the HVU and the distribution of supporting functions. This is supported through a review of the current literature, operational environment, and state-of-the-art capabilities for C-UxS.
- Second, a simulation of the C-UxS capability, informed by the functional allocation in the architecture, supplies a mechanism for showing the relative efficacy of different systems allocations given a particular use case.
- Third, a hypothetical case study describes a potential HVU escort scenario and supplies the relative benefit of the self-escort capability and the appropriate mix of capabilities for the scenario.

B. SYSTEMS ENGINEERING PROCESS

This project takes the form of a capability development study to explore alternatives for accomplishing a specified operational capability. A tailored systems engineering process supports this, using a framework developed by Blanchard and Fabrycky (2011) that is summarized in Figure 1. This consists of a stakeholder and requirements analysis that supports a preliminary systems architecture which is validated through simulation.

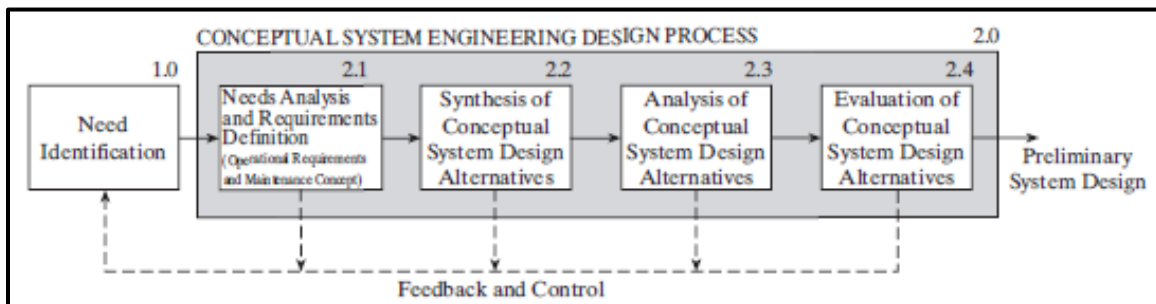


Figure 1. Conceptual Systems Engineering Process. Source: Blanchard and Fabrycky (2011, 106).

While Figure 1 provides a high-level conceptual framework, a modified agile process framework, summarized in Figure 2, supports individual process steps. This framework describes weekly iterations composed of brainstorming project activity, accomplishing project tasks, and obtaining feedback from advisors and other stakeholders as applicable. This process is iterative, breaking individual tasks into smaller subtasks for individual action.

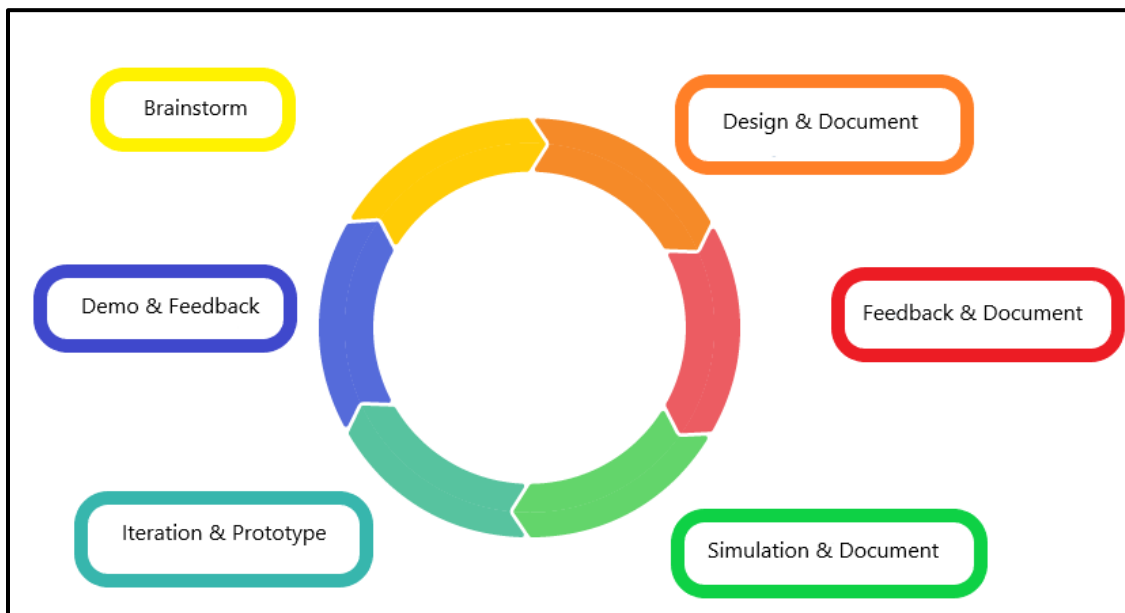


Figure 2. Agile Process Framework

Figure 3 provides a summary of project incremental milestones integrated with the systems engineering framework from Figure 1. This is displayed as an input, control, output, mechanism (ICOM) diagram. In this diagram, each process block transforms inputs on the left into outputs on the right, by mechanisms on the bottom and under the conditions of the controls to the top. Outputs from each process block are inputs to the next block in the sequence.

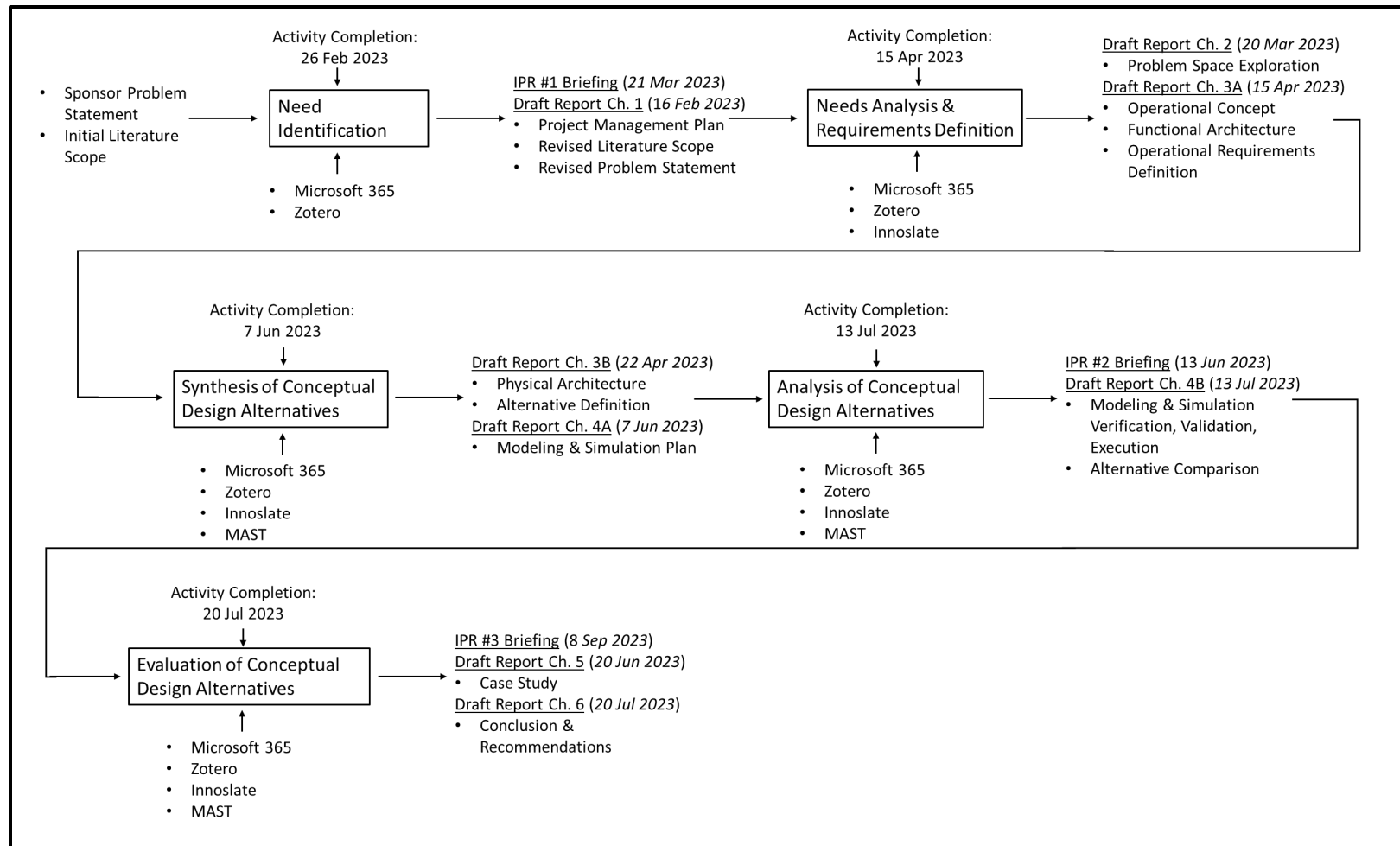


Figure 3. Project ICOM

C. BENEFIT OF THE STUDY

Multiple stakeholders will benefit directly or indirectly from the capability framework in this study. Table 1 supplies a summary of the stakeholders to this research.

Table 1. Stakeholder Summary

Stakeholder	Description
<i>Naval Research Program (NRP)</i>	NRP is the resource sponsor for this research. According to the NRP, the “NRP is funded by the Chief of Naval Operations and supports research experience for Naval Postgraduate School faculty members and students which focuses on the Navy and the Marine Corps.” (NRP n.d.)
<i>Deputy Chief of Naval Operations for Warfighting Requirements and Capabilities (OPNAV N9)</i>	OPNAV N9 is the topic sponsor for this research. According to the DON, OPNAV N9 “establish[es] requirements, set[s] priorities and direct[s] overall planning and programming for expeditionary warfare, surface warfare, undersea warfare, air warfare, unmanned warfighting systems and nuclear weapon systems to include associated manpower, support, training, and readiness.” (Chief of Naval Operations 2022) This research will inform future requirements and systems development for Navy C-UxS.
<i>Naval Postgraduate School (NPS)</i>	NPS is the recipient of funding for this research proposal and is responsible for execution of the proposal within agreed to timelines. NPS is a graduate school operated by the United States Navy which offers certificates, master’s, and doctoral degrees.
<i>Navy Surface Fleet</i>	The Navy Surface Fleet is a primary stakeholder which may require C-UxS capability to support mission tasks.
<i>Naval Submarine Force</i>	The Naval Submarine Force is a primary stakeholder which may require C-UxS capability to support mission tasks.
<i>Joint Counter-small Unmanned Aerial Systems Office (JCO)</i>	According to the U.S. Army, the JCO “leads and directs joint Counter-small [UAS] doctrine, requirements, materiel, and training to establish joint solutions to address current and future small UAS threats.” (Headquarters, Department of the Army, Deputy Chief of Staff, G-3/5/7 2021) The JCO is a U.S. Army-led organization that works with the services and interagency stakeholders to develop synchronized, multi-domain Counter-small UAS solutions.
<i>Civilian UAS Operators</i>	Civilian UAS operators are interested in keeping their ability to use privately owned UAS in authorized ways. Civilian UAS Operators are defined as authorized civilian operators of UAS. Operators may need a license and registration for the UAS if required by their jurisdiction.
<i>Federal Aviation Administration (FAA)</i>	The FAA is the agency proponent for regulations in the U.S. that govern civilian operations of UAS. The FAA has an interest in consistent communication of operating requirements to UAS stakeholders.

The DON regularly performs escort of HVU in support of mission requirements. According to the DON, these HVUs include all nuclear-powered units, as well as other vessels “whose loss or removal from service would have significant consequences on the [U.S.] Navy’s ability to meet its warfighting requirements.” (Chief of Naval Operations 2020) The escort of an HVU may require time-intensive tasking of one or more vessels or other units, which results in these resources being unavailable for other missions. The recent proliferation of UxS threats among both state and non-state actors may result in an increase in areas that require escort of HVUs against this threat class.

The NRP and OPNAV N9 will use the results from this project to add to current knowledge for application of C-UxS capabilities. The results from this project will support further development of requirements, doctrine, and tasks for conducting C-UxS as part of HVU self-escort. The results from this project will also support resource allocation among potential capability solutions for C-UxS.

Fleet commanders responsible for HVU escort will benefit from this project through capabilities that reduce labor and resource requirements for HVU escort, resulting in flexibility to reassign assets and conduct other mission tasks.

D. SUMMARY OF CHAPTERS

Chapter II supplies a background and explores existing literature for the topic areas that are relevant to the project. Specific topic areas include maritime escort, the current technology domain for UxSs and C-UxS capabilities, and the state of autonomy, artificial intelligence (AI), and machine learning (ML) as applicable to UxSs and C-UxS capabilities. This supplies a baseline for future analysis in the report, including the description of the operational concept, functional architecture, and physical architecture in Chapter III, and the application of project modeling and simulation discussed in Chapters IV and V.

Chapter III describes the systems architecture for the HVU C-UxS mission. This architecture supplies a common frame of reference for describing the supported capabilities, supports operational requirements analysis for employment and integration of a C-UxS capability, and supplies a framework for comparison of potential alternatives.

First, a mission engineering approach supports an operational analysis for a baseline concept of operations and reference missions for the project. The project leverages a range-based defense profile described by Behling et al. (2022) to generate a concept of operations for the scenario, resulting in measures of effectiveness (MOEs) that characterize C-UxS capabilities by their ability to prevent UxS from intercepting the HVU. Second, a functional architecture supplies a hierarchical description of what the system will do to conduct the C-UxS mission. Finally, two hypothetical physical architectures allocate systems to functions to support alternatives comparison and traceability to operational requirements. The two hypothetical physical architectures supply alternate conceptual designs. An “Echo/Inyx” alternative implements electronic warfare (EW) capabilities throughout the engagement space, while a “RamJammer” alternative includes a kinetic capability for close-range defense. These alternatives use the architecture to ensure coverage of operational requirements in support of the C-UxS mission.

Chapter IV describes the methodology for validating the system architecture and comparing potential alternatives. This is done through a customized application of the Modeling and Simulation Toolkit (MAST) developed by Naval Surface Warfare Center (NSWC) Dahlgren Division. The project sets up a state-machine based method for C-UxS simulation, discusses how this method is applied in MAST, and executes verification of the tool. To support capability analyses, the project applies a weighted scoring model to output from the simulation that uses the range-based defense profile to rank alternatives.

Chapter V presents a hypothetical case study application to an HVU transiting through a restricted maneuvering scenario. Notional data supports a conceptual analysis of the relative effectiveness of C-UxS capabilities and capability compositions. A design of experiments (DOE) is applied to parameters for each alternative developed in Chapter III and executed in MAST as discussed in Chapter IV. The resulting analysis shows how this application of MAST can effectively support analyses for C-UxS in HVU escort scenarios.

Chapter VI concludes the report, discusses the results of the project’s research objectives, and supplies recommended areas for future study.

II. BACKGROUND AND LITERATURE REVIEW

This chapter supplies a background of topic areas that are relevant to the project. A synthesis of existing literature supplies a baseline for future analysis in this report, including the description of the operational concept, functional architecture, and physical architecture in Chapter III, and the application of project modeling and simulation discussed in Chapters IV and V. This chapter starts with a review of maritime escort, with a focus on recent events involving UxSs that may inform the operational use case. The chapter then describes the current state of the technology domain for UxSs and C-UxS capabilities to supply a physical framework for later discussion of physical architecture and alternatives. Finally, it describes the state of autonomy, AI, and ML, as applicable to UxSs and C-UxS capabilities.

A. MARITIME ESCORT: HISTORICALLY RELEVANT EVENTS AND MODERN INFLUENCING FACTORS

1. Relevant Historical Events

The threats evaluated as part of this study and their capabilities are not without historical precedent. The threat of small craft attacks that are comparable in scale to USVs being evaluated dates to 2000 with the bombing of the USS Cole. Using nothing more than a small boat loaded with explosives, two terrorists successfully detonated a bomb alongside the USS Cole, an Arleigh Burke class destroyer, while it was parked pier side in Aden, Yemen, killing 17 sailors and injuring 40 (Federal Bureau of Investigation n.d.). This represented the dawn of asymmetric small boat threats, a threat category which includes USVs. The threat of small boats grew to include the concept of Fast Attack Craft/Fast Inshore Attack Craft (FAC/FIAC), where fast moving small boats present a significant asymmetric threat to U.S. Navy vessels. One relevant example is a 2008 naval dispute between the United States and Iran, where five Iranian speed boats maneuvered towards and threatened U.S. Navy ships for half an hour (Shanker and Knowlton 2008).

These small surface threats continue to pose a major concern for navies around the world but have at least in part given way to the threat of USVs. In October 2022, in the midst of the Russian War in Ukraine, seven remotely operated USVs swarmed and attacked the Russian-controlled port of Sevastopol (Sutton 2022). These USVs were inexpensive and technologically simple, likely not utilizing any autonomy or advanced swarming tactics, but nonetheless they wreaked havoc on one of Russia's most strategic ports and forced the Russian navy to expend resources that likely cost more than the USV platforms trying to defeat them.

Unmanned aerial threats have gained prominence as well. During the rise of the Islamic State of Iraq and Syria (ISIS) in 2017, ISIS fighters built and utilized small homebuilt or commercial drones armed with explosives to harass U.S. and coalition forces (Warrick 2017). Explosive-laden commercial drones were utilized in a suspected attempt to assassinate Venezuelan President Maduro in 2018 (Marcolini and Koettl 2018). Cheap commercial and homebuilt drones have continued to find relevance in the Russian War in Ukraine, seeing utilization by both sides for intelligence, surveillance, and reconnaissance (ISR) and kinetic missions (Lowther and Siddiki 2022). In 2022, an Iranian-built drone attacked and damaged a Liberian-flagged commercial tanker, a category of ship that could easily be categorized as an HVU (United States Navy 2022). In a more innocent case, a drone pilot was able to land his drone aboard the United Kingdom's Queen Elizabeth aircraft carrier and the only indication the Royal Navy had that the event had taken place was when the pilot self-reported at the Navy base in the Highlands (British Broadcasting Corporation 2017). This last example shows how the threat from drones may come from a source that is simply non-compliant rather than directly hostile.

Three important takeaways can be made from the historical events involving FAC/FIAC, USV, and UAS threats. One is that these capabilities pose an asymmetric threat to high-end forces such as the U.S. Navy, meaning they exploit atypical vulnerabilities in attacked systems. A U.S. Navy ship is likely to be better equipped to deal with an anti-ship cruise missile than it is a small boat, for example (Tiwari 2008). A second is that the value proposition these types of threats pose is imbalanced, with a UAS

such as the DJI M600 used in the attack in Venezuela costing off-the shelf \$4,599 per system (Chaundy 2016). Smaller less capable drones, such as those used by ISIS or in Ukraine today, can cost only a few hundred dollars and force a defending entity to spend significant high-end resources such as Stinger Surface-to-Air Missiles (SAMs) or expensive Radio Frequency (RF) jamming systems. Finally, autonomy has seen limited application thus far in real world situations, likely not exceeding waypoint flight systems present in many Commercial Off the Shelf (COTS) unmanned systems or programmable in hobby control boards such as Pixhawks.

2. Modern Influencing Factors

The methods to defend against UxSs are influenced by several factors. As previously mentioned, there is already a recognized gap in the defense against small boat threats, which are similar in size to USVs that may be used in an attack (Tiwari 2008). Knowing in advance that a USV threat is inbound is critical to determining deterrence and engagement options. Since many detection options are horizon limited, identifying threats early is critical in an attempt to leave open low-tech engagement choices such as crew-served weapons (Kessler et al. 2006). In the case of UASs, if a commander does not have a capability that is tailored to UAS defense then this may mean using advanced weapons such as expensive SAMs, weapons that are typically more expensive than the cost of the threat and of which the commander likely has a limited inventory (Hawkins 2017).

Beyond the threat posed by USVs and UASs, the limitations of manning in the Navy play a significant role in potential solutions for C-UxS systems. Recent reporting shows that even without adding systems requiring operators to the fleet, the Navy is unable to sufficiently staff ships. A recent report by the Government Accountability Office found that only 14% of Navy officers received seven or more hours of sleep a day during a deployment (U.S. Government Accountability Office 2021). Adding workload to an already fatigued fleet is not an option. C-UxS capabilities must minimize workload impact on sailors.

3. HVU Defense Research

While there is limited publicly available research on the defensive capabilities of Navy ships against UxSs, many studies that focus on other scenarios can be extended to apply to an HVU self-escort scenario. The small size and inexpensive nature of these threats mean that it is a tactical loss to use expensive high-end kinetic munitions alone on them (Pham et al. 2012; Thiessen 2022).

One can then extend the threat envelope to exploring threats such as FAC/FIACs. Using intercepting defending vessels which may include autonomous defensive boats, a ratio of one defender per four attackers may be considered sufficient (Ding 2012). This is especially important when considering options such as explosive laden defensive boats. Although it may not meet the limited manning demands that are in the scope of this study, prior simulation has found crew-served weapons aboard commercial ships had a better chance of defending the commercial ship than offboard patrol craft in a contested and congested environment (Walton et al. 2005). These simulations, however, made critical assumptions about the results of attacking small boats, namely that a hit is almost guaranteed to be considered a mission kill, i.e., eliminate the combat effectiveness of the attacking boat. In reality, small boats, which include likely platforms for USV threats, are often made of foam-filled hulls encased in fiberglass or wood (Tiwari 2008). These materials are inherently buoyant, which means that a small projectile must penetrate a mission critical area such as the engine to achieve a mission kill. This reduces the vulnerable surface area of the boat and means that simulations which include a lethality component should consider the probability of hitting these vulnerable areas.

B. UNMANNED SYSTEMS: TECHNOLOGICAL STATE

This section supplies an overview of the current state of UxS technology, including small USVs and Group 1 and Group 2 UASs. It will address the definition of UxS technology groups, relevant mission areas, modern warfare applications, and areas for advancement. Information from this section supplies a necessary background for assessment of relevant technologies and predictions of future applications to analysis in future chapters.

1. Unmanned Aerial Systems—Group 1 and 2

UASs are aircraft that operate without personnel onboard, with smaller UASs, commonly known as drones, categorized as Group 1 and Group 2 (Table 2). UASs serve to remove the pilot, crew, and operators from the platform and move operations to a remote location to control or autonomously command the aircraft. This means that a UAS typically works as part of a system which includes all necessary components needed to control the aircraft. The DOD classifies UASs into groups based on gross weight, operating elevation, and speed. Table 2 supplies these group definitions.

Table 2. UAS Groups Definitions. Source: Department of Defense (2021, 29).

UAS Category	Maximum Gross Takeoff Weight (lbs.)	Normal Operating Altitude (feet)	Speed (KIAS)
Group 1	0-20	< 1200 AGL	100 knots
Group 2	21-55	< 3500 AGL	< 250 knots
Group 3	< 1320	< 18,000 MSL	< 250 knots
Group 4	> 1320		Any Airspeed
Group 5	> 1320	> 18,000 MSL	Any Airspeed

Legend: AGL – above ground level; MSL – mean sea level; KIAS – knots indicated air speed

UAS mission categories may include imagery, surveillance, monitoring, and payload delivery. Elements such as the size of the aircraft, endurance, maximum gross weight allowance for payloads, and level of autonomy and artificial intelligence may limit the ability of a UAS to support specific missions. For Group 1 and Group 2 UASs, the major areas affecting the suitability for specific mission categories include endurance, level of autonomy, communications, sensors, and payloads.

The endurance of a UAS is connected to the available flight time, and may limit the distance a UAS can travel to execute a mission as well as the how long the vehicle may be away from home base before needing to return. Endurance is driven by a tradeoff between durability, weight, energy generation and storage, and functionality. For Group 1 UASs, flight times are typically under an hour. For Group 2 UASs, flight times may go up to multiple hours though are typically less than 24 hours (National Aviation

Intelligence Integration Office 2022). After endurance, level of autonomy as related to flight control is the next most prominent area affecting the aircraft's ability to execute various missions. Today, UASs may use Global Positioning System (GPS) for position and navigation, with flight control occurring on a spectrum between constant operator interaction and semi-autonomous control. For Group 1 UASs, autonomous flight is often a function of routes programmed prior to flight, resulting in minimal required operator input during a short mission duration. Group 2 UASs may achieve autonomous flight through incorporating AI and ML algorithms to enhance the ability of the UAS to conduct longer range and time missions with minimal operator input (Joint Air Power Competence Center 2021, 16).

In addition to endurance and level of autonomy, UAS may equip payloads for communications, sensors, and other mission critical functions that affect their suitability for specific mission categories given the weight, operating elevation, and endurance of the assigned vehicle. Communications for Group 1 and 2 UASs primarily rely on RF for remote control and data transmission, and cellular or satellite communication for longer range operations. The latter are more common for Group 2 UASs. Sensors onboard a UAS support mission execution, flight navigation, and obstacle avoidance or deterrence. Group 1 and 2 UAS sensors often include cameras, light detection and ranging (LiDAR), and thermal sensors (used for aerial imaging, mapping, and inspection). For military applications, these UASs have also employed electro-optical/infrared (EO/IR) cameras, synthetic aperture radar, and signals intelligence sensors for surveillance, reconnaissance, and targeting missions (Abdullah 2022).

UASs may also equip specific payloads to support mission critical functions. Group 1 and 2 UASs support a variety of military applications including sensing missions and may function in cooperative groups or swarms to support targeting and kinetic engagements. To support sensing operations, UASs employ a variety of sensors for missions such as counterterrorism, battlespace awareness, and surveillance and reconnaissance of potential targets and to monitor areas of interest. Group 1 UASs have also been used to support ground forces as a communications relay, extension of battlespace situational awareness, and to deliver supplies. To date, both Group 1 and

Group 2 UASs have been used to provide real-time video and imagery of potential targets and areas of interest, with Group 2 commonly supporting longer range missions. Systems such as the MQ-9 Reaper allow forces to gather ISR information without putting personnel at risk (United States Air Force 2021, 82).

To support advanced targeting and kinetic engagements, UASs may use swarm tactics, i.e., perform missions cooperatively in groups, and use technology including sensors and weapons to support engagement of a target. Group 1 UASs may equip laser designators and other targeting sensors to supply targeting information for other weapons, such as lasers, missiles, and artillery. Additionally, Group 2 UASs may supply more powerful information such as radar, laser, and electro-optical data for advanced targeting. UASs have also been used with swarm tactics to overwhelm defenses, and to confuse both systems and operators. For example, in 2018 a swarm of 13 Group 1 UASs were used to attack a Russian military base in Syria, with some UASs carrying explosive payloads. While a defense system successfully repelled the attack, the event demonstrated for the first time the ability to use UAS swarms in a coordinated attack (Lubrano 2018).

2. Unmanned Surface Vessels—Class 1 and 2

USVs are naval vessels that function without personnel onboard. USVs are defined by class, with each class defined by capability and maximum length. Extra small (Class 1) USVs are less than 7 meters in length and have a max speed of 20 knots, and small (Class 2) USVs are less than 12 meters in length and have a max speed of 30 knots (O'Rourke 2021, 3). To date, these categories of USV are primarily used for maritime security, environmental monitoring, oceanographic research, and search and rescue. Future mission areas focus heavily on support to ISR as well as mission payloads for electronic and kinetic warfare. Class 1 USVs may have limited endurance ranging from a few hours to a day and typically support near-shore operations. Class 2 USVs support greater endurance for longer range operations, and typically can run semi-autonomously for several days at a time. The following paragraphs describe the technological state for

USV support to military operations through capabilities for endurance, autonomy, communications, sensors, and mission payloads.

Autonomy is less mature in the naval domain than for ground and aerial applications. USVs must be able to function autonomously for significant periods of time, all while abiding by applicable regulations for shipping and avoiding obstacles in variable environments including open ocean, shipping lanes, and during restricted maneuvering. In recent years, organizations have made progress in advancing autonomy and AI in the naval domain including through systems procured by the U.S. Navy. For example, the Defense Advanced Research Projects Agency (DARPA) has developed a small USV, called the Sea Hunter, that is designed to run autonomously for up to 90 days for surveillance, mine detection, and antisubmarine warfare. DARPA has demonstrated this capability with the U.S. Navy during multiple fleet exercises including Rim of the Pacific 2022 (Shelbourne 2022). To continue evolving USV autonomy, advancements are needed in AI/ML and algorithms, communications, and sensors to support autonomous navigation and decision making in increasingly variable operating environments. This includes the ability to navigate and avoid obstacles and detect and track other vessels and objects in the water. Additionally, advanced autonomy is needed to support new missions planned for Class 2 USVs to support longer endurance and more complex tasking assignments.

Communications to support both Class 1 and 2 USVs include the RF and satellite communications that are used today on crewed platforms. Future mission areas may stress current capabilities through requiring persistent, secure, and resilient connectivity for remote and congested surface applications. Communications must be supported with other vessels and with shore-based operators. Remotely or semi-autonomously monitoring and controlling USVs requires sharing data near real-time with others, which means that high bandwidth, low latency data links are required to support timely operations. USVs must also incorporate advanced network protocols and supporting interoperable elements to support distributed operations (Aliferis 2020). An example of this is in recent work by (Dietz, Davis, and Hale 2023), which implements a Messaging Layer Security (MLS) protocol in a UAS swarm system that supports asynchronous

group key management. According to Dietz, Davis, and Hale, the MLS protocol “makes it possible to forcibly remove [UASs] that have been hijacked, compromised, or malfunctioning” (Dietz, Davis, and Hale 2023, 6591). This is a valuable attribute for maintaining a robust UxS network in the face of adversary EW actions. Other work related to MLS in support of secure UxS command and control (C2) links is discussed in Britt, Leon, and Hale (2022). In addition to network protocols, advanced sensors are needed to feed autonomy necessary data to support situational awareness for decision making.

Mission areas for USVs vary depending on the vessel size. Both Class 1 and Class 2 USVs employ sensors such as radar, sonar, LiDAR, and cameras. Class 2 USVs will more often have available space and power margins to support advanced sensors for detection, classification, and monitoring for ISR and battlespace awareness. Class 1 USVs support missions such as coastal surveillance and security, environmental monitoring, search and rescue, mine counter measures, and antisubmarine warfare. These classes of vessel are also more likely to support UxS swarms due to size, cost, and attritability. In addition to these mission areas, Class 2 USVs also support exploration and oceanographic research and may carry larger payloads including weapons and more powerful sensors.

For maritime security missions, Class 1 USVs have been used both as assets in protecting security and as stressors to security. The Israeli Navy employs the Protector USV developed by Israeli Aerospace Industries. This is a Class 1 USV that equips a range of sensors (including EO/IR cameras) and weapons to support maritime security missions (BAE Systems 2007). Class 1 USVs have also been used for drug trade and to carry explosive devices, applications which may previously have used manned small boats.

3. UxS Technology Advancement and Coordination

Today, there is coordinated testing for pairing manned and unmanned technology to exercise manned-unmanned teaming concepts and develop concepts of operations and employment for how the fleet can best use unmanned technologies. In the next decade, it

is likely that advancements will be made to support unmanned system coordination across multiple domains, such as coordination between UASs and USVs. For example, for maritime surveillance UxSs may work together for comprehensive maritime surveillance coverage, with USVs closer to surface for detection and tracking of naval activity, and UASs supplying a wider field of view to support detection, classification, and tracking. For environmental monitoring, UxSs may work together to monitor environmental conditions in a variety of applications, including tracking oil spills, monitoring water activity and marine life, and classifying traffic in busy sea lanes. In this case, USVs collect samples of environment, and UASs supply an overhead perspective to detect and classify potential threats or obstacles.

In military operations, UxS teaming will supply greater situational awareness and a tactical advantage to the warfighter. However, to reach this point, there must be growth in UxS range and payload capacity, and advancements in autonomy and AI/ML. Group 1 UASs and Class 1 USVs are likely candidates to be utilized for swarms, with Group 2 UASs and Class 2 USVs supporting at lower qualities due to the relative difference in cost. It is likely the military will see rapid advancement in UxS technologies over the next few decades with the introduction of AI/ML leading to increased versatility of application and effectiveness of unmanned systems supporting ongoing operations.

C. CURRENT COUNTER-UNMANNED SYSTEMS CAPABILITIES

This section supplies an overview of the current state of C-UxS technology to supply a basis for the functional and physical analyses provided in Chapter III. It begins with a review of current DOD doctrine applicable to countering unmanned systems and uses this as a lens to discuss the functions needed for this task. This supplies a framework for a survey of technologies supporting C-UxS.

The focus of this section is on technologies that support countering unmanned aerial systems. However, given the technologies that support unmanned capabilities discussed earlier in this chapter, there is overlap between technologies that supply capability for countering aerial threats and countering surface threats.

1. Doctrine

In the DOD, guidance from the Chairman of the Joint Chiefs of Staff describes joint doctrine as the “fundamental principles that guide the employment of [United States] military forces.” (Joint Chiefs of Staff 2019) It provides a common framework for the services and service components to conduct missions that are aligned with joint goals while conducting individual tasks. This means that doctrine supplies a valuable reference to ensure this project can pursue focused aims while supporting broad applicability.

This project uses joint doctrine as a basis for structuring a C-UxS engagement through use of a kill chain, as defined in controlled access and unclassified doctrinal publications (Joint Chiefs of Staff 2018; United States Air Force 2021). This describes a sequence of steps, i.e., find, fix, track, target, engage, and assess (F2T2EA) that when conducted successfully result in adequate mitigation of a threat and communication of that action to the appropriate authority. Table 3 supplies a description of each of these steps.

Table 3. Dynamic Kill Chain Process. Source: United States Air Force (2021).

<i>Kill Chain Step</i>	Description
<i>Find</i>	Detection of an emerging target
<i>Fix</i>	Determining the position and other data related to an emerging target with sufficient fidelity to permit engagement
<i>Track</i>	Maintaining continuous awareness of a target and its location
<i>Target</i>	Taking an identified, classified, located, and prioritized target; determining the desired effect and targeting solution against it; and obtaining required approval to engage
<i>Engage</i>	Performing action against the target
<i>Assess</i>	Determine whether desired effects and objectives were achieved

Michel (2019) and Kang et al. (2020) support an abstraction of the F2T2EA kill chain that directly describes the capabilities that are required to support C-UxS through a three-step process: sensing, C2, and mitigation. Table 4 supplies the steps and associated descriptions for the C-UxS kill chain and illustrates their alignment to the F2T2EA kill chain in Joint Publication (JP) 3-60.

Table 4. C-UxS Kill Chain. Source: Michel (2019, 5).
JP 3-60 **C-UxS** **Description**

<i>Find</i>		
<i>Fix</i>	Sense	Detect, identify, locate, and track the incoming unmanned system
<i>Track</i>		
<i>Target</i>	Command and Control	Decide how to respond to the incoming unmanned system
<i>Engage</i>		
<i>Assess</i>	Mitigate	Apply effects to the incoming unmanned system to achieve the desired objective

The following sections survey individual technologies and other key areas that support C-UxS capabilities. Importantly, a system that supports C-UxS may supply only a subset of the capabilities described in the C-UxS kill chain, potentially only supplying capabilities for sensing or mitigation (Kang et al. 2020, 168685). This means that this project may recommend solutions that supply all or only a subset of the described capability. The scope of required capability is dependent on the commander’s goals and the available resources for conducting the task.

2. Sensing

Kang et al. describe the C-UxS sensors as the mechanisms that “gather data from the environment and transmit the observed data to C2 systems” (Kang et al. 2020, 168684). The sensors for a C-UxS support distinguishing an adversary UxSs as a threat separate from environmental clutter as well as supplying adequate data for execution of

C2 functions. Sensors may be classified by the type of data that they ingest. The following are types of C-UxS sensors that are summarized in Table 5.

- **Acoustic/Ultrasonic.** Sound waves that propagate from the engine of a UxS can be used to distinguish it from background environmental noise and may supply a characteristic signature to support identification. Kang et al. indicate that acoustic sensors can be “vulnerable to wind and surrounding ambient noise sources,” (Kang et al. 2020, 168688); however, use of multiple sensors as well as algorithms that utilize a database of known UxSs can help to overcome this limitation.
- **Radio Frequency.** A UxS may be detected through its electromagnetic signature, obtained through passively eavesdropping on the transmission link between the UxS and its control station. RF sensors are relatively inexpensive and easy to implement, and are likely effective in detecting the majority of commercial UxS that are remotely controlled (Kang et al. 2020, 168688). This means that an RF sensor is most effective during normal operations when commercial UxSs are the likely threat but is less effective in a peer threat environment with UxSs that function autonomously.
- **Radar.** A radar is an active sensor that emits an electromagnetic signal and uses the return from that signal to support detection, identification, and tracking of UxSs. Variability in the return signal supports measuring the range and speed of the UxS, which is critical to adequate C2. As an active sensor, radar increases the electromagnetic signature of the host system and increases the likelihood that it may be detected. Most radar sensors are also limited to detecting systems with a large radar cross section (RCS), which limits their effectiveness in detecting small UxSs. Recent developments that exploit varying micro-doppler signature (MDS) characteristics due to micro-motions of vibrating and rotating structures on the UxS may help to overcome this limitation (Kang et al. 2020, 168690).

- **Electro-Optical/Infrared.** EO/IR sensors passively detect light that reflects from or is emitted by the UxS. This can provide high-density data that supports automated detection and identification of UxSs through ML algorithms, including lightweight and low-power solutions that are on-board a UxS (Cigla, Thakker, and Matthies 2018). The data quality is limited by the light source availability and the quality of the image in line of sight to the sensor. Multiple sensors that supply multiple perspectives help to mitigate this, as well as support depth perception for tracking purposes, but are limited by availability capacity on the host system.
- **Light Detection and Ranging.** A LiDAR system functions through emitting a laser pulse and recording the return of the laser when reflected from an object. Laser light can support a high-resolution three-dimensional image of the target UxS, but, as with EO/IR sensors, is limited by line of sight to the target.

Table 5. Examples of C-UxS Sensors. Adapted from Kang et al. (2020, 168689); Michel (2019, 18).

Source	Sensor	Active/ Passive	Examples Product (Company)
Sound Waves	Acoustic/ Ultrasonic	Passive	• Enforce Field (Booz Allen Hamilton) • Fencepost (General Atomics) • Detection Solution (Magna)
	Radio Frequency	Passive	• XPeller Gear (Hensoldt) • Multi-sensor Anti-Unmanned Aerial Vehicle (UAV) Defense System Solution (Hunan NovaSky Electronic Technology) • ICARUS (Lockheed Martin)
Radio Waves	Radar	Active	• Miniature Hit-to-Kill (Lockheed Martin) • MUSCL (Patria) • Safe Skies (SkyLock)
	EO/IR	Passive	• X-MADIS Mobile (Sierra Nevada Corporation/ RADA/ Ascent Vision Technologies) • MC-Horizon (MC TECH) • Mobile Anti-UAV Defense System (Liteye/ Blighter Surveillance Systems/ Chess Dynamics/ Enterprise Control Systems)
Light Waves	LiDAR	Active	• Venom (Northrop Grumman) • Antidrone (Kaspersky)

3. Command and Control

In Kang et al., the C2 elements of the C-UxS “perform computing tasks [...] and make decisions based on the received data, such as the detection/identification declaration, localization/tracking declaration, and time and method of the neutralization of [UxSs].” (Kang et al. 2020, 168684) These functions are often distributed among multiple platforms that coordinate C-UxS tasks as a system of systems (SoS), rather than by an individual system. Examples include a centralized network, in which all C2 functions are consolidated to a single system; a decentralized homogenous network, in which C2 functions are duplicated among multiple systems; and a decentralized heterogenous network, in which C2 functions are distributed among multiple systems.

C2 elements of a C-UxS system execute the following processes (Kang et al. 2020, 168686–87). These processes run iteratively; actions that occur in each step may result in updates to the preceding actions.

- **Detection/Identification.** Given input from the C-UxS sensors, the C2 system will process the data to supply a decision or recommendation on the type of UxS.
- **Classification.** Based on the type of UxS the C2 system will classify the UxS as friendly or adversary. It may also determine if, based on the type and classification of UxS, it is authorized for operation in the AOR for the C-UxS.
- **Localization.** C-UxS sensors will provide the C2 system with data to support determining the position and heading of the UxS. The C2 system may make decisions or recommendations for further action based on the UxS heading, e.g., if the UxS is moving towards or away from the area of responsibility for the C-UxS.
- **Tracking.** Updates from the C-UxS sensors to the C2 system support continuous awareness of the location and heading of the UxS. This supports any updates to the UxS classification or authorization, e.g., if changes to heading move it from an authorized to an unauthorized status.
- **Decision on Neutralization.** The C2 system operates in conjunction with any availability mitigation methods to apply appropriate effects to the UxS. If the C-UxS has multiple mitigation methods available, then the C2 may have internal processes that determine the appropriate mitigation technique based on the type, classification, and behavior of the UxS.

4. Mitigation

Kang et al. describe the C-UxS mitigation systems as the mechanisms that “perform [UxS] neutralization based on the decision of the C2 system.” (Kang et al. 2020, 168684) Kang et al. further indicate that the mitigation systems for a C-UxS support applying effects to a UxS to achieve objectives identified by the commander through the C2 system, in order to “warn, control, disrupt, disable, [or] destroy” (Kang et al. 2020, 168687) the UxS. Mitigation systems may be classified by the vector through

which they can apply effects. The following are types of C-UxS mitigation systems that are summarized in Table 6.

- **RF/Global Navigation Satellite System (GNSS) Jamming.** If a UxS is controlled remotely, then the C-UxS system can employ mechanisms that disrupt the connection between the UxS and its control station. For effects that operate in the RF spectrum, this involves applying power to single or multiple frequencies, with the objective to reduce the signal to noise ratio for the transmission to the UxS on that frequency (Kang et al. 2020, 168691). This will then either disrupt the command signal to the UxS or cause the operator to increase their transmission power, potentially revealing their position. If a UxS is controlled by or navigates via a GNSS link, then mitigations that disrupt this signal may cause the UxS to crash or operate in a degraded mode. UxSs that have multiple navigation mechanisms, or which can navigate autonomously, are less vulnerable to RF/GNSS jamming.
- **Spoofing.** If the C-UxS system is provided with sufficient knowledge of the control mechanisms for the UxS, then it may be possible to either fully or partially take control of the UxS. Spoofing may also involve a denial-of-service attack in which the device is flooded with traffic that prevents normal network communications, resulting in loss of connection with a control station (Thiessen, Van Bossuyt, and Hale 2022, 281). Spoofing mitigations are appropriate only for UxSs that have some form of connection with a control station, potentially through RF, GNSS, Wi-Fi, or cellular link. This type of mitigation may require exquisite sensors or knowledge of the UxS to effectively implement (Hooper et al. 2016).
- **High-power Microwave.** Mitigation systems equipped with high-powered microwaves can project a narrowband electromagnetic wave that disrupts or disables electronic systems on the UxS, possibly causing the UxS to crash. These systems must be aimed directly at the UxS and

require adequate tracking of the UxS to achieve effect (Kang et al. 2020, 168692). High-powered microwaves also required significant power to operate (Radasky, Baum, and Wik 2004), which limits their suitability for non-integrated or portable applications.

- **Lasers.** Mitigation systems that employ lasers come in two primary categories: low powered lasers, intended to disrupt optical sensors onboard a UxS; and high-powered lasers that apply thermal effects to destroy or disable a UxS or its components (Kang et al. 2020, 168692). As with the LiDAR sensors described earlier in this chapter, lasers for mitigation systems are sensitive to weather conditions, and can be disrupted by rain or cloud cover. Lasers also require a line of site to the target UxS, and adequate tracking capability to maintain an effective bearing.
- **Projectiles.** Kinetic projectiles including bullets, missiles, rockets, and mortar systems can damage or destroy a UxS through impact or explosive effect. However, projectiles move relatively slowly and, especially at long ranges against small UxS targets, can require relatively complex and expensive guidance elements to achieve effect (Kang et al. 2020, 168693). If a projectile misses, then it may present a hazard to other systems or personnel in the vicinity. Additionally, kinetic damage to a UxS can result in catastrophic failure to the UxS, which limits failure investigation, retrieval of the UxS for the purposes of exploitation, and may cause collateral damage when the UxS crashes.
- **Collision UxS.** A UxS may be designed to collide with an adversary UxS. This requires that the friendly UxS has components, including sensor and C2 elements, that can maintain a track of the adversary UxS. The friendly UxS also requires propulsion and guidance systems that allow it to close with the adversary UxS at relatively high speed. EO/IR sensors, when paired with image recognition algorithms, can support a continuous track of the adversary UxS that results in an intercept (Cigla, Thakker, and

Matthies 2018). Common to other kinetic effects, collision UxSs may cause collateral damage on impact with the adversary UxS.

- **Nets.** Cannons or friendly UxSs (Guvenc et al. 2018) can project nets that will disable or capture an adversary UxS. If the UxS is captured successfully, then this can support forensic analysis and exploitation. Nets are limited due to their low relative range and are primarily useful against smaller UxSs.
- **Birds of Prey.** Trained birds of prey have demonstrated ability to intercept and destroy small commercial unmanned aircraft (Atherton 2016). Using a bird to support C-UxS may result in the bird's injury or death.

Table 6. Examples of C-UxS Mitigators. Adapted from Kang et al. (2020, 168691); Michel (2019, 18).

Category	Subcategory	Examples Product (Company)
Nonphysical	RF/GNSS Jamming	• INT-AU001 Anti UAV Rifle (4Intelligence) • Ctrl+Sky Jammer (Advanced Protection Systems) • Small Form Factor (CACI)
	Spoofing	• (Alion Science and Technology) • dronetaker (Chenega Europe) • DFU3000 (Citadel Defense)
	High-power Microwave	• Phaser (Raytheon) • Windshear (Raytheon)
	Lasers	• HEL Effector Wheel XX (Rheinmetall) • High Energy Laser Weapon System (MBDA Deutschland) • ADAM (Lockheed Martin)
Physical	Projectiles	• I-Dome (Rafael Advanced Defense Systems) • Mobile Low, Slow, Unmanned Aerial Vehicle Integrated Defense Systems (Leonardo DRS/Moog) • Miniature Hit-to-Kill (Lockheed Martin)
	Collision UxS	• Anvil (Anduril) • Coyote (Raytheon) • DroneBullett (AerialX) (Chenega Europe)
	Nets	• SKYNET Mi-5 (ALS) • Skynet (AMTEC Less Lethal Systems) • NetGun X1 (Drone Defence)
	Birds of Prey	Not Applicable

D. AUTONOMY, ARTIFICIAL INTELLIGENCE, AND MACHINE LEARNING

The integration of autonomy, AI, and ML in UxSs has been a rapidly developing area of research in recent years. The increasing complexity and diversity of UxS and C-UxS applications have made it necessary to explore the potential benefits and challenges associated with these technologies. AI and ML have been identified as key drivers for enhancing the autonomy of UxSs and improving their capabilities. This has led to the development of advanced algorithms and techniques for data analysis and pattern recognition, which enable UxSs to make more informed decisions and operate with greater efficiency, adaptability, and overall autonomy. This section will examine the current state of research in autonomy, AI, and ML in UxSs, specifically showing key developments that correspond to C-UxS.

1. Autonomy

Autonomy in the context of UxSs refers to the ability of the system to operate independently of human control, input, or oversight. This capability can be used in a variety of ways in counter UxS operations and strategies. One crucial use of autonomy in this context is in the development of autonomous defensive systems to detect, track, and engage combatant UxSs. The U.S. Navy has developed the AN/SLQ-59 lightweight towed array acoustic surveillance system, which can autonomously detect and track UxS threats in the water using advanced signal processing algorithms (Rogoway 2019).

A study by Göge et al. (2015) explored the use of autonomy in UxSs designed for surveillance and reconnaissance operations. The authors suggested that autonomy could be used to identify potential targets effectively and accurately. This would make UxSs more effective in surveillance and reconnaissance operations as well as target acquisition and identification. A study by Orfanidis et al. (2019) explored the use of autonomy in UxSs specifically for C-UxS operations. The findings of this study show that autonomy could improve the accuracy and efficiency of UxSs, while reducing the risk of collateral damage. The authors suggested that autonomy could be used specifically to improve UxS

targeting, navigation, and communication, which would make them more effective in C-UxS operations.

Another use of autonomy in C-UxS operations is in the development of autonomous offensive capabilities. For example, the U.S. Air Force has developed the Air Force Collaborative Small Diameter Bomb, which uses autonomous swarming tactics to overwhelm enemy air defenses (Air Force Research Laboratory 2021). Swarm-based autonomous systems work together to achieve a common goal, such as protecting a target or conducting a search and rescue operation. Swarm-based systems have advantages over individual UxSs, including improved coverage and redundancy, increased resilience to attacks, and the ability to adapt to changing environments.

The U.S. Army has developed the long-range precision fires system, which uses autonomous targeting capabilities to strike enemy UxSs from long range (Goure 2021). In this example autonomy was used to improve the efficiency of human operators in C-UxS operations. The U.S. Navy has developed the common control system, which allows operators to control multiple UxSs with a single interface and leverages autonomy to simplify tasking and reduce operator workload (Ball 2016). These examples illustrate the point made in a thesis by Queralta (2022). The author found that autonomy had the potential to improve the accuracy, efficiency, and effectiveness of UxSs in various operations, including intelligence gathering, surveillance, and reconnaissance. However, the author also noted that the use of autonomy in UxSs raised ethical and legal questions, particularly when it came to the use of lethal force.

Finally, autonomy can support the development of effective C-UxS strategies. The DOD has established the JCO, which is responsible for developing a coordinated approach to countering the UxS threat (Headquarters, Department of the Army, Deputy Chief of Staff, G-3/5/7 2021). This office is using autonomous capabilities to develop integrated defensive systems that can detect, track, and engage UxS threats across the battlefield. A literature review of autonomy uses in C-UxS operations and strategies reveals key trends and research directions in this field. One significant area of research is the development of autonomous UxSs that can detect and identify potential threats, such as enemy UxSs or improvised explosive devices and take appropriate action to neutralize

them. Researchers have developed autonomous systems that can detect and track UxSs using radar and other sensors and engage them with countermeasures, such as jamming or spoofing. In a study, Johnsen et al. (2018) investigated the use of autonomy in UxSs for intelligence gathering. The study found that autonomy could improve the accuracy of UxSs in identifying and tracking targets. The authors suggested that autonomy could improve the efficiency and effectiveness of UxSs in intelligence gathering operations, particularly in complex environments.

In conclusion, autonomy is a critical capability for addressing the challenges of UxSs and C-UxS in modern warfare. Autonomy can be used to develop defensive and offensive capabilities, improve operator effectiveness, and support the development of effective C-UxS strategies. Autonomy can also improve the accuracy, efficiency, and effectiveness of UxSs in C-UxS operations. Autonomy has been used to improve UxS targeting, navigation, target identification, and communication, which make them more effective in C-UxS operations. As UxSs continue to proliferate on the battlefield, the importance of autonomy in countering this threat will only increase.

2. Artificial Intelligence

AI in the context of UxSs is one method of achieving autonomy and has various applications in C-UxS operations. The use of AI algorithms has led to developments in autonomous defensive and offensive systems. AI could also be used for enhancing operator performance and improving the effectiveness of C-UxS strategies, as well as detecting, tracking, and engaging UxS threats. This area of research and development focuses on developing AI algorithms that enable UxSs to detect and track other UxSs and targets in real-time. For example, DARPA has developed the Aerial Dragnet system, which uses AI algorithms to detect and track small drones that pose a threat to military operations (SouthFront 2021). ML techniques, such as deep learning and neural networks, have been applied to analyze sensor data and identify objects of interest, such as UxSs or enemy vehicles. These techniques enable UxSs to identify targets more accurately and quickly than traditional methods, improving their situational awareness. A study by Szabadföldi (2021) explored the use of AI in UxSs for surveillance and

reconnaissance operations. The authors suggested that AI could be used to identify potential targets more quickly and accurately, which would make UxSs more effective in surveillance and reconnaissance operations.

AI can also enhance the effectiveness of offensive UxS capabilities. Research has focused on the development of AI-based swarm systems, which enable a group of UxSs to work together to achieve a common goal. Swarm-based UxSs have advantages over individual UxSs, including improved coverage and redundancy, increased resilience to attacks, and the ability to adapt to changing environments. For instance, the U.S. Navy's Low-Cost UAV Swarming Technology program uses AI algorithms to coordinate and control swarms of drones to overwhelm enemy defenses (Orfanidis et al. 2019). Similarly, the Air Force Research Laboratory's Golden Horde program uses AI algorithms to coordinate multiple munitions in a swarm attack against enemy targets (Air Force Research Laboratory 2021).

AI can also enhance operator performance by improving the human-machine interface in UxS control systems. In a study, Digney (2006) investigated the use of AI in UxSs for intelligence gathering. The study found that AI could be used to improve the accuracy of UxSs in identifying and tracking targets, particularly in complex environments. Putting this into practice, the U.S. Air Force's Skyborg program uses AI to develop a low-cost autonomous system that can function as an AI wingman for manned aircraft (Harper 2020). The Skyborg program aims to reduce the workload of human pilots by supplying autonomous decision-making capabilities to the UxS.

Another area of research is the development of AI-based countermeasures to neutralize enemy UxSs. A study by Hu et al. (2021) explored the use of AI in UxSs for C-UxS operations. The authors suggested that AI could be used to improve UxS targeting, navigation, and communication, which would make them more effective in C-UxS operations. For example, researchers have developed AI-based algorithms for jamming or spoofing UxS communications, disabling or disrupting their operations.

Finally, AI can support the development of effective C-UxS strategies. For example, researchers have developed reinforcement learning (RL) algorithms that enable

UxSs to learn from their experiences and adjust their behavior accordingly. These algorithms enable UxSs to adapt to changing circumstances, such as a moving target or a dynamic battlefield. The DOD has established the JCO, which uses AI to develop integrated defensive systems that can detect, track, and engage UxS threats across the battlefield (Headquarters, Department of the Army, Deputy Chief of Staff, G-3/5/7 2021). The JCO aims to develop a coordinated approach to countering the UxS threat using AI and other advanced technologies.

The use of AI in UxSs has shown the potential to improve the accuracy, efficiency, and effectiveness of UxSs in C-UxS operations. AI algorithms have been used to improve UxS targeting, navigation, and communication, which make them more effective in C-UxS operations. Existing AI algorithms are used to improve the accuracy of UxSs in identifying and tracking targets, making them more effective in intelligence gathering operations. Further development is needed to fully unlock the potential benefits of AI in UxSs.

3. Machine Learning

Like AI, ML has potential applications in C-UxS operations, such as developing autonomous defensive and offensive systems, enhancing operator performance, and improving the effectiveness of C-UxS strategies. In the context of autonomous defensive systems, ML algorithms can aid in detecting, tracking, and engaging UxS threats. For example, a study by Taha and Shoufan (2019) proposed an ML-based approach for detecting and tracking small drones using video data. The proposed approach uses a convolutional neural network (CNN) for drone detection and a Kalman filter for drone tracking.

ML can also enhance the effectiveness of offensive UxS capabilities. The first step in C-UxS operations is to detect and identify unauthorized UxSs in the target area. Traditional methods such as radar and acoustic sensors have limited accuracy, as they can be easily fooled by stealth technology and low-altitude flights. Machine learning algorithms have shown potential in improving the accuracy of UxS detection. For example, deep learning algorithms have been applied to detect and classify UxSs based

on their visual features. CNN have been used to recognize types of UxSs by analyzing their images and videos. Support vector machines (SVM) have also been used for UxS classification based on their acoustic signatures. A study by Rovira-Sugranes et al. (2022) proposed an ML-based approach for optimizing swarm behavior of UxSs. The proposed approach uses a genetic algorithm for swarm optimization and a Q-learning algorithm for autonomous decision-making. In another study Kim et al. (2017) discuss the development of a ML algorithm to detect and track UASs in real-time using an aerial surveillance system. The algorithm was trained on a dataset of UAS images to recognize the unique features of UASs, such as their shape and size. The system's accuracy was evaluated using a test set of UAS images, and the results showed high accuracy in detection and tracking of UASs.

Once a UxS is detected, the next step is to track its movements and find its intentions. ML techniques have been applied to improve the accuracy and efficiency of UxS tracking. Taha and Shoufan (2019) present a comparative analysis of different ML algorithms for UAS detection and classification. They evaluated the performance of various algorithms, including SVM, convolutional CNN, and random forests, among others. The results showed that CNN achieved the highest accuracy for both detection and classification of UASs. Kurunathan et al. (2022) propose a ML-based target detection and classification algorithm for UAS operations. The algorithm uses a combination of deep learning and computer vision techniques to detect and classify high-value targets. The authors demonstrate the algorithm's effectiveness in detecting and classifying different types of targets, including vehicles, buildings, and personnel. For example, recurrent neural networks (RNN) have been used to predict UxS trajectories based on their previous movements. RL algorithms have been applied to develop optimal UxS tracking strategies by learning from previous interactions with UxSs. Taha and Shoufan (2019) present a ML-based approach for detecting and tracking drones in critical infrastructure protection scenarios. The algorithm uses a combination of deep learning and computer vision techniques to recognize the unique features of drones and track their movement. The authors evaluate the algorithm's performance in a real-world scenario and report high accuracy in detecting and tracking drones. Doyle et al. (2021) propose an

adaptive ensemble learning approach for C-UxS target classification and tracking. The algorithm combines different ML techniques, including SVM, random forest, and CNN, to improve the accuracy of target classification and tracking. The authors demonstrate the effectiveness of the algorithm in a real-world scenario and report significant improvements in classification and tracking accuracy compared to traditional ML approaches.

The final step in C-UxS operations is to neutralize or destroy unauthorized UxSs. ML algorithms have been applied to enhance the effectiveness of UxS neutralization strategies. For example, RL algorithms have been used to develop autonomous UxS interception systems, which can intercept and neutralize UxSs without human intervention. SVMs have also been used for UxS threat assessment, which can determine the potential danger of UxSs based on their behavior and intentions. ML can also enhance operator performance by improving the human-machine interface in UxS control systems. For example, a study by Reguera-Bakhache et al. (2021) proposed an ML-based approach for predicting operator performance in UxS control tasks. The proposed approach uses a decision tree algorithm to predict operator performance based on factors such as task complexity, UxS type, and operator experience. Finally, ML can support the development of effective C-UxS strategies. For example, a study by Qi et al. (2022) proposed an ML-based approach for predicting UxS behavior in the context of C-UxS operations. The proposed approach uses a Bayesian network to model UxS behavior based on various factors such as UxS type, environmental conditions, and operator actions.

In conclusion, ML has numerous applications in C-UxS operations and strategies. ML can enhance the capabilities of UxSs, improve operator performance, and support the development of effective C-UxS strategies. Various ML algorithms, including CNN, SVM, and random forest, have been proposed and evaluated for detecting and tracking UxSs. These algorithms use a combination of deep learning and computer vision techniques to recognize the unique features of UxSs and track their movement. ML techniques have shown potential in improving the accuracy and effectiveness of C-UxS operations as well. These techniques have been applied to various aspects of C-UxS

operations, including UxS detection, tracking, and neutralization. However, there are still some challenges that need to be addressed, such as the development of robust ML algorithms that can handle real-world scenarios and the integration of different sensors and technologies to enhance UxS detection and tracking accuracy.

E. SUMMARY OF CHAPTER

This section explored the existing literature for focus areas that are relevant to the problem of C-UxS in support of HVU self-escort. In the first subsection a survey of recent events involving UxSs and HVU established the relevance of this topic by describing the outsized impact which small and inexpensive UxSs may have on conventional operations. UxS threats occupy a spectrum from peer or near-peer hostile intent, through insurgent or unconventional action, and including non-compliant civilian control, each which may present a unique threat to an HVU mission. Following this, the second and third subsections set a technology baseline for UxSs and C-UxS capabilities through a survey of current and potential future system applications. Finally, the last subsection discussed real and potential applications for AI/ML and autonomy to the UxS mission. It showed how future capability growth to UxSs will come through effective use of AI/ML and autonomy. The following chapters draw from and extend this background through application to C-UxS in support of HVU self-escort.

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III. ARCHITECTURE DEFINITION

This chapter describes the systems architecture for the HVU C-UxS mission. This architecture has three main purposes:

- It provides a common frame of reference for employment and integration of a C-UxS capability with an HVU. It does this through models that are compliant with the DOD Architectural Framework (DODAF). This supports interconnectivity with other projects or capabilities within the DOD that may relate to this mission.
- It supports operational requirements analysis for employment and integration of a C-UxS capability. It does this through a logically consistent description of operational activities and system functions that support C-UxS. This description enables identification of requirements that appropriately distinguish between levels of capability, further supporting trades in systems composition.
- It supplies a framework for specifying alternatives for providing C-UxS capability to an HVU. Alternatives take the form of individual systems and SoS. The chapter describes hypothetical alternatives that use the architecture to ensure adequate coverage of, and traceability to, operational requirements in support of the C-UxS mission. A simulation in Chapters IV and V will use these hypothetical alternatives to demonstrate an analysis process for the relative benefit of a C-UxS self-escort capability.

To accomplish these purposes, this chapter describes three successive products. First, an operational analysis supplies the baseline concept of operations for C-UxS in support of HVU escort. This results in defined operational scenarios that supply the reference missions for this project. Second, a functional architecture supplies a hierarchical description of what the system will do to conduct the C-UxS mission. This

applies the functions and actors that are described in the operational analysis and describes the interconnectivity and data exchange requirements for accomplishing the higher-level functions. Finally, a physical architecture allocates individual systems and subsystems to functional activities. This supports generating alternatives that provide adequate coverage for the mission’s functional requirements and supports traceability of alternatives to operational requirements.

A. METHODOLOGY

To generate the systems architecture, this project leverages a combination of the methodology described in Dam (2014) as well as the Mission Engineering Guide promulgated by the Undersecretary of Defense for Research and Engineering (USD R&E) (Office of the Deputy Director for Engineering 2020). According to Dam, a systems architecture is a “fundamental and unifying structure defined in terms of elements, information, interfaces, processes, constraints, and behaviors” (Dam 2014, 18). This method focuses first on the mission that the capability is intended to accomplish, and then uses that mission to structure the actors, functions, and systems compositions that provide the needed capability. An overview of this methodology is shown in Figure 4. Specifically, the systems architecture is derived from analysis in step 2 (Mission Characterization) through step 4 (Design of Analysis) of this process.

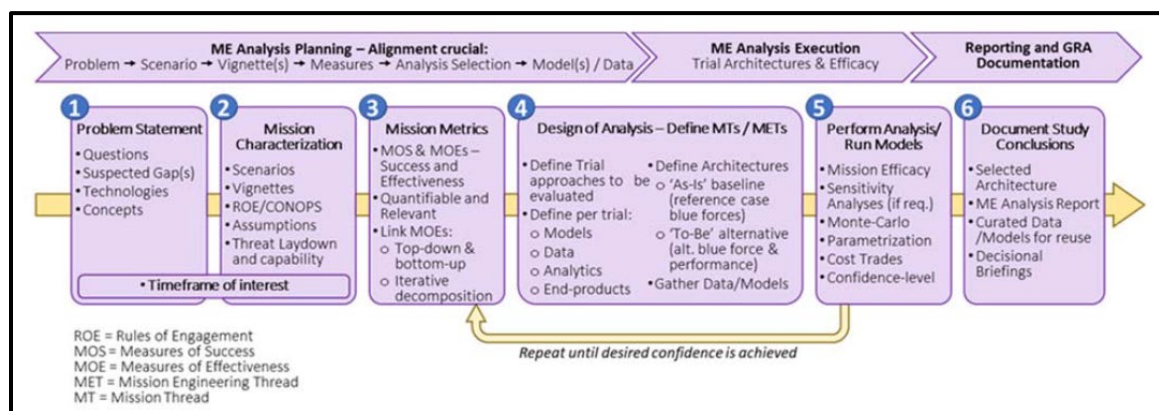


Figure 4. Mission Engineering Approach and Methodology. Source: Office of the Deputy Director for Engineering (2020, 5).

In conjunction with this mission engineering approach, this project takes the “middle-out” process as described by Dam (Dam 2014, 97) to inform construction of individual models in the architecture, shown in Figure 5. This process supports a project that has broad applicability to a general mission area, but which may not yet have a detailed set of operational requirements. This means that in following this process, the project will establish the levels of operational and functional detail required to derive requirements appropriate to the mission area. In reference to the process figure, this chapter takes prior work on steps 1 through 3 and performs step 4 (Capture Constraints) through step 9 (Allocate Actions to Assets).

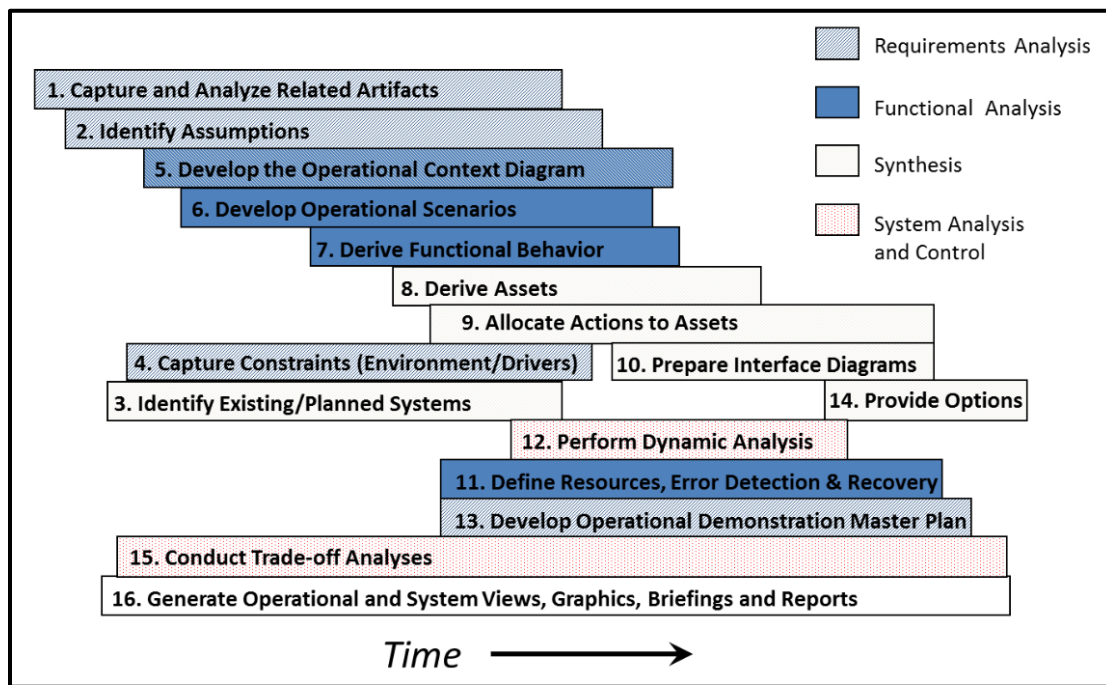


Figure 5. “Middle-Out” Process for Architecture Development. Source: Dam (2014, 97).

Detailed model development in this chapter follows the Lifecycle Modeling Language (LML) standard (LML Steering Committee 2022), applied in the Innoslate Model Based Systems Engineering tool developed by SPEC Innovations. According to Dam, LML is a “hybrid functional/object language” (Dam 2014, 58) that supports broad compatibility with standard MBSE products. Where applicable, models are compliant

with DODAF version 2.02 (DOD Chief Information Officer (CIO) 2010) and include representations of the Operational Viewpoint (OV) and Systems Viewpoint (SV). Table 7 is a summary of the DODAF models contained in this chapter.

Table 7. DODAF Model Summary. Adapted from DOD CIO (2010).

Model	Purpose	Representation
OV-1	Provide a high-level summary of the purpose, objectives, and scope of the project.	Graphic with text description.
OV-5a	Summarize the operational activities required to accomplish project objectives.	Functional Hierarchy
OV-5b	Describe the process flow between the required operational activities	Integrated Definition for Functional Modeling (IDEF) 0
OV-6c	Provide the actors and sequence of activity in a scenario and describe the functional flow between the actors.	Sequence Diagram
OV-5b/ OV-6c	Represent the sequence of functions as well as the inputs and outputs for each function.	Activity Diagram
SV-1	Describe how systems connect with each other and their methods for interfacing.	Systems Interface Description
SV-5b	Indicate which systems are accomplishing/responsible for which operational activity. Supports assessment of adequate coverage of required functions and any needs for robustness in systems employment.	Operational Activity to Systems Traceability Matrix

B. OPERATIONAL ANALYSIS

This section defines the operational intent for the HVU C-UxS mission and provides high-level traceability to stakeholder concerns. It does this by first defining the operational context for the mission in terms of commander's intent, enemy composition, terrain and weather, friendly force composition, time frame and time available, and any civilian or non-combatant considerations. It then establishes a high-level reference

mission scenario that provides a pictorial and narrative representation of the operational context. This mission scenario is composed of individual mission vignettes, depicted as sequential threads of tasks within the mission scenario. These mission vignettes support defining high-level functions for accomplishing the HVU C-UxS mission. They also support derivation of MOEs that characterize the ability to accomplish mission tasks and achieve commander's intent.

1. Operational Context

According to USD R&E, the operational context supplies the mission definition, or the “elements that describe the context of the mission.” (Office of the Deputy Director for Engineering 2020, 37) In the context of this project, this takes the problem statement from Chapter I and establishes the baseline elements of a scenario that support fulfillment of stakeholder intent.

This project addresses a small subset of the overall problem posed by HVU escort. HVU escort is a multi-layered operation that typically involves many actors to support defense against multiple threat classes. In addition to the UxSs addressed by this study, an HVU transiting from a harbor to open water may encounter threats including anti-ship mines (Miller 2019), FAC (Shanker and Knowlton 2008), and anti-ship missiles (Aydin 2000), to name only a few. Civilian watercraft and ships from allied and partner nations may require that the HVU and any escorts engage in constant communication to ensure adequate maneuvering space for the HVU to avoid collision. Each of these elements means that, depending on the type of HVU, a typical escort scenario may involve support from local port authorities, the U.S. Coast Guard (Sadler 2022), the U.S. Navy Maritime Expeditionary Security Force (Lewis 2020), and other assets under the control of the fleet commander.

To focus the project specifically on the problem that UxS threats pose to HVU escort, this project incorporates several key assumptions in the overarching mission definition, shown in Table 8. This summarizes the mission through the mnemonic METT-TC, or Mission, Enemy, Terrain and Weather, Troops and Support Available, Time Available, and Civilian Considerations. Additionally, this mission takes place in the

year 2025, which focuses the project by applying capabilities and materiel that are likely to be available in the near-term.

Table 8. METT-TC Summary for HVU Self-Escort

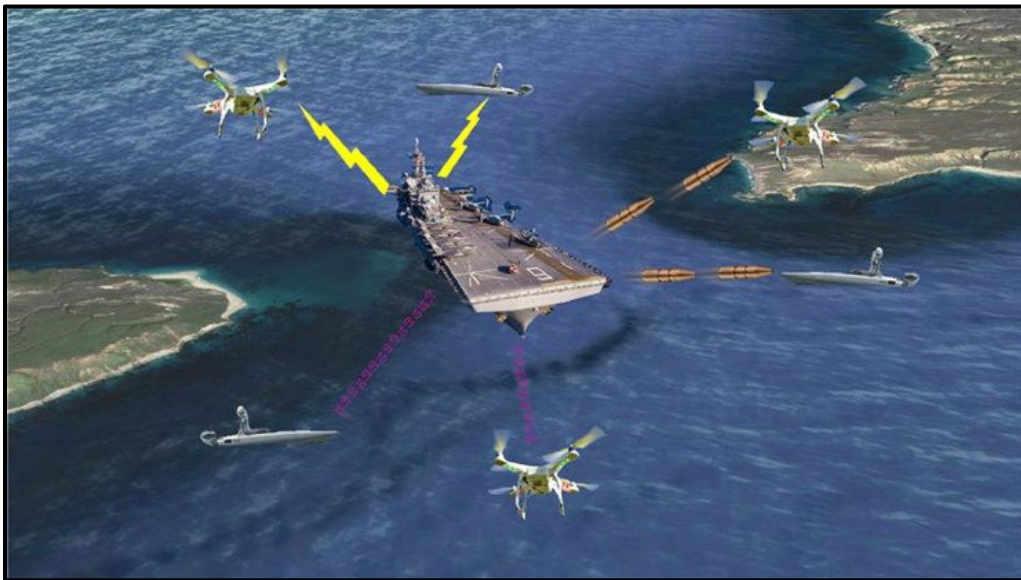
<i>YEAR</i>	2025
<i>MISSION</i>	Escort of a combatant craft HVU from an unprotected harbor in a contingency location through restricted maneuvering conditions to open water
<i>ENEMY</i>	UASs, Group 1-2 USVs, Class 1-2 Ground Control Station (GCS)
<i>TERRAIN and WEATHER</i>	Day, Unlimited Ceiling and Visibility Sea State 3 or less
<i>TROOPS and SUPPORT AVAILABLE</i>	Combatant Craft HVU Escort System(s) Area Commander Explosive Ordnance Disposal Team
<i>TIME AVAILABLE</i>	Less than 24 hours
<i>CIVILIAN CONSIDERATIONS</i>	Not Applicable

This definition describes a restricted maneuverability scenario, specifically navigation of an HVU from an unprotected harbor to open water. A restricted maneuverability scenario presents the HVU with limited options for maneuvering away from areas with likely UxSs (Marfo et al. 2015) and focuses the scenario on the dilemma imposed by UxSs. This is the case whether these are negligent, non-compliant UxSs operated by non-combatants, or enemy UxSs that express hostile intent. To avoid any confounding effects from weather and other environmental conditions, the scenario occurs during the day and in calm conditions with unlimited visibility. This supports the project's focus on the HVU escort components, including C-UxS systems, that supply options for response to UxSs. The project further limits the threat to Group 1 and Group 2 UASs and Class 1 and Class 2 USVs, each with a control link to a remote location. This focuses the project on the threat posed by low, small, and slow UxSs, distinct from larger threat classes.

2. Mission Scenario

According to USD R&E, a mission scenario “provides the overall context to the [...] analysis” (Office of the Deputy Director for Engineering 2020, 9) through traceability to high-level strategic objectives and by defining and describing the mission objective and conditions for success. The mission scenario is illustrated here through a DODAF OV-1 diagram in Figure 6 with accompanying narrative.

a. *High-Level Operational Concept*



The OV-1 depicts an HVU that is transiting from an unprotected harbor in a contingency location to the open ocean. This requires passing through a chokepoint that restricts the maneuverability of the HVU, and which allows hostile UASs and USVs to present a threat to the HVU. The HVU employs C-UxS mitigations against the threats through kinetic means, shown as bullets, and EW, shown as both lightning bolts and binary data streams.

Figure 6. HVU C-UxS Operational Concept (OV-1)

The OV-1 depicts an HVU that is transiting from an unprotected harbor in a contingency location to the open ocean. This requires passing through multiple areas that restrict the maneuverability of the HVU, which means that the HVU must respond to potential threats in these areas.

Operational guidance from the area commander includes an intelligence summary that indicates a high risk of encounter with UxSs during transit. These UxSs are operated from an unspecified ground control station (GCS) in the vicinity of the transit path and may include Group 1 through Group 3 small UAS (sUASs) and USVs. The purpose and payload of these UxSs is unknown; therefore, any defense strategy must consider these UxSs as potential improvised explosive devices and take appropriate procedures for explosive ordnance disposal.

A phased engagement strategy assists in prioritizing available assets and in characterizing the effectiveness of the C-UxS system. This project adopts the phase profile used in Behling et al. (2022) by using the range from the possible threat to the HVU to structure a defensive engagement. An illustration of the profile is depicted in Figure 7. This organizes the engagement into five phases that inform the prioritization for threat response and system performance.

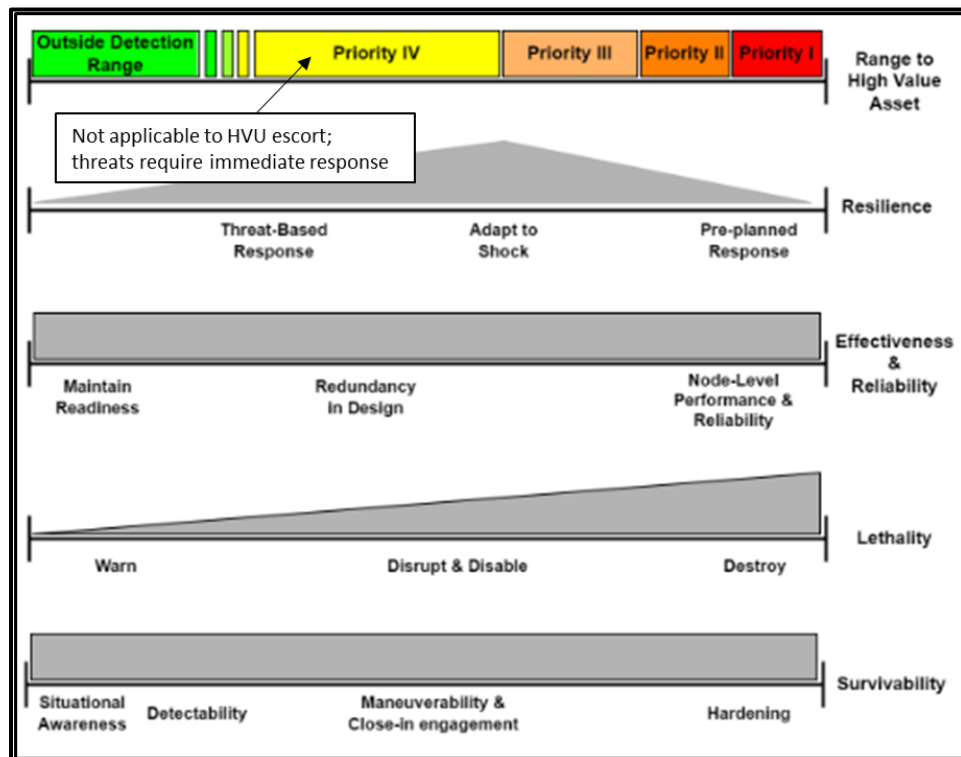


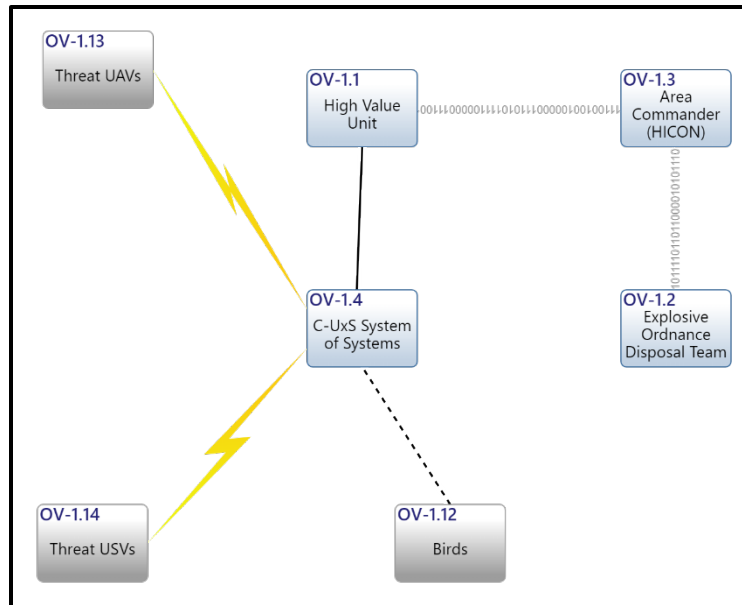
Figure 7. C-UxS Defense Profile and System Suitability Considerations. Adapted from Behling et al. (2022, 30).

Importantly, the phases in this profile provide for an opportunity for pre-planned threat response (Priority IV) before a system needs to employ any active defensive measures. This means, for example, that a fixed defensive position may have pre-placed measures or signature control mechanisms that can trigger if a threat moves into the Priority IV area. These conditions are not applicable to this mission scenario, since the HVU is transiting through an uncontrolled area to open water. This means that Priority IV threats are not part of this analysis.

Throughout this project the phases in Figure 7 are described as priority zones, i.e., Priority 1 Zone, Priority 2 Zone, and Priority 3 Zone. Objects within the zones are described in terms of their priority that aligns to the zone, e.g., Priority 1 threats are in the Priority 1 Zone.

b. Operational Resource Flow

Figure 8 provides the operational resource flow for the HVU C-UxS mission scenario using a logical OV-1 diagram. This diagram contains connections between the mission assets that display the required information flow in the mission scenario. This figure shows the HVU and associated C-UxS system that is required to perform the escort mission. Also depicted are the interfaces and relationships with other external systems, including the area commander, threat systems, and friendly systems. This shows how the HVU receives operational guidance from the area commander and employs the C-UxS system to perform defensive actions against possible threat systems.



The logical operational concept diagram shows assets defined for the mission scenario and their methods of interaction. The C-UxS SoS employs mitigations against the Threat UAVs and Threat USVs, uses sensors to detect Birds, and interfaces directly with the host HVU. The HVU receives guidance via digital communication from the Area Commander. The Area Commander also communicates with a subordinate Explosive Ordnance Disposal Team to support retrieval and exploitation of Threat UxSs.

Figure 8. HVU C-UxS Logical Operational Concept Diagram (OV-1)

c. *Measures of Effectiveness*

Given this mission scenario, MOEs can assist in quantitatively tracking ability of the HVU and constituent systems to achieve mission objectives. An MOE is a “measurable attribute and target value for success within the overall mission” (Office of the Deputy Director for Engineering 2020, 12) and assists in characterizing the ability of the system and support elements to achieve commander’s intent. A top-level MOE derived for this mission scenario is in Table 9.

Table 9. Scenario Measure of Effectiveness

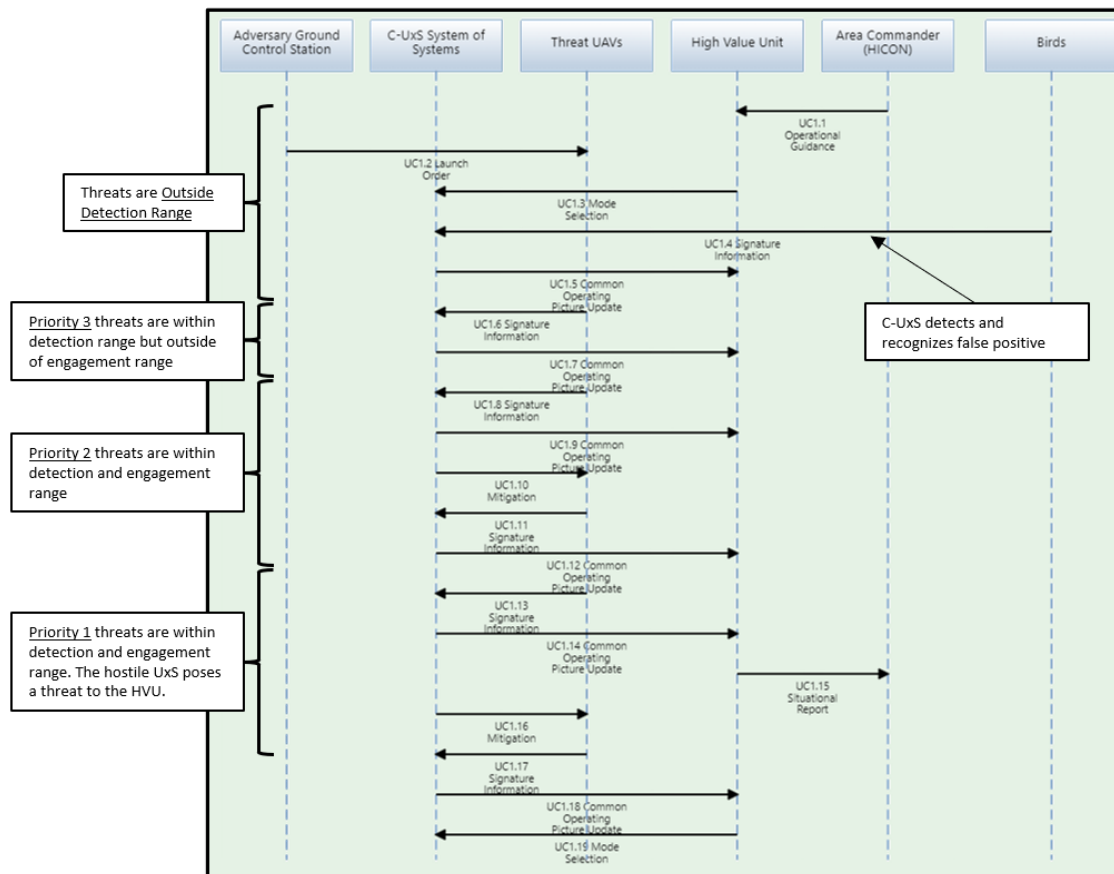
ID	Name	Measure
MOE.1	Priority 1 Zone UxS Penetration Ratio	$\frac{\text{Number of Hostile UxSs Reaching Priority 1 Zone}}{\text{Total Humber of Hostile UxSs}}$

3. Mission Vignettes

The mission scenario is comprised of multiple vignettes. A mission vignette “represent[s] a more narrowly framed subset of the scenario” (Office of the Deputy Director for Engineering 2020, 9) that is intended to focus analysis on specific behaviors and interactions that are important for the stakeholders. The vignettes for this project look separately at the threat posed by UASs and USVs.

a. *High Value Unit Encounter With UASs*

Figure 9 describes the mission thread for the HVU encountering a collection of threat UASs. This vignette begins with an HVU passing through a chokepoint between two landmasses while transiting to open water. The chokepoint creates a narrow deep-water channel with shallow areas on both sides, which imposes restricted maneuvering conditions on the HVU. Given an intelligence estimate from the area commander that predicts a possible threat from UxSs, the HVU commander recognizes that this chokepoint is a likely area to encounter UxSs. The HVU commander therefore orders the C-UxS system that is on board the HVU to actively sense possible threats.



This sequence diagram shows the asset interactions that compose the mission thread for an HVU encounter with threat UASs. Assets in the mission are shown across the top of the diagram, with lifelines extending down vertically. Arrows between the lifelines represent sequential actions generated from and received by each asset to execute the mission thread. The mission thread consists of four phases. In the first phase (steps UC1.1 through UC1.5), the HVU receives operational guidance from the area commander, deploys the C-UxS SoS, and detects a false positive in the form of Birds in the vicinity of the HVU. In the second and third phase (steps UC1.6 through UC1.12), the C-UxS SoS identifies threat UASs, monitors the threat as it moves closer to the HVU, and successfully mitigates a portion of the threat. In the last phase, the C-UxS SoS successfully mitigates threat UASs that are critically close to the HVU, which then provides a situation report to the area commander.

Figure 9. HVU Encounter With Threat UASs (OV-6c)

(1) Outside Detection Range

The C-UxS system begins sensing and tracking possible threats to the HVU. The C-UxS system detects occasional tracks that have erratic movement, and which are not on azimuth to the HVU. The C-UxS system decides that these tracks are likely to be birds based on their movement characteristics and assigns them a low probability of threat.

(2) Priority 3 Zone

The C-UxS system then detects four simultaneous airborne tracks that are moving towards the HVU. Based on their bearing and coordination, the C-UxS system assigns to them an increased probability of threat and categorizes this for the HVU commander. The possible threat tracks continue moving towards the HVU.

(3) Priority 2 Zone

When the airborne tracks come within range, the C-UxS system identifies them as threat sUASs and updates the track classification to hostile. The C-UxS system employs long range mitigation techniques to affect the hostile sUAS. This results in disabling two of the sUASs and causing a third to crash into the water. The two disabled sUASs perform a return to base function and the C-UxS system loses their track when they move out of range. The C-UxS system reports these lost tracks to the HVU commander, who then reports them to the area commander for further action, potentially to find the sUAS GCS.

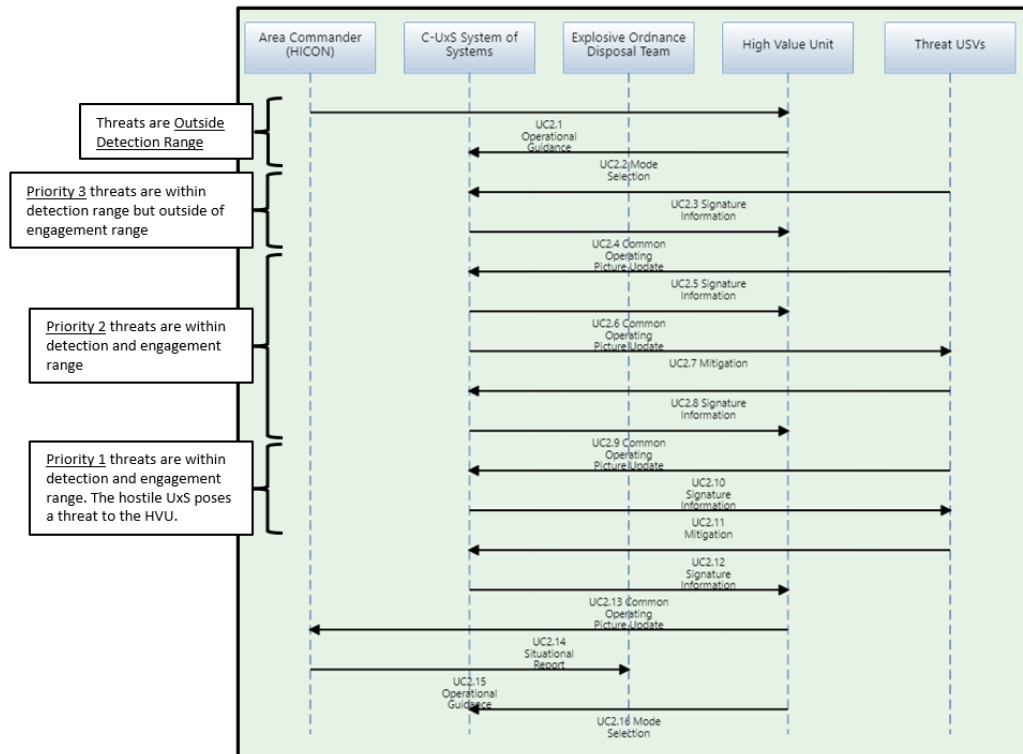
(4) Priority 1 Zone

The remaining sUASs continue moving towards the HVU. The C-UxS system performs short range mitigation techniques, resulting in the sUASs becoming disabled and crashing into the water. The C-UxS system determines that there are no remaining threat tracks and reports this to the HVU commander. The HVU continues through the chokepoint and reaches open water, at which point the HVU commander orders the C-UxS system to return to passive sensing of potential threats. This concludes the vignette.

b. HVU Encounter With USVs

Figure 10 describes the mission thread for the HVU encountering a collection of threat USVs. This vignette begins with an HVU passing through a chokepoint between two landmasses while transiting to open water. The chokepoint creates a narrow deep-water channel with shallow areas on both sides, which imposes restricted maneuvering conditions on the HVU. Given an intelligence estimate from the area commander that predicts a possible threat from UxS, the HVU commander recognizes that this chokepoint is a likely area to

encounter UxS. The HVU commander therefore orders the C-UxS system that is on board the HVU to actively sense possible threats.



This sequence diagram shows the asset interactions that compose the mission thread for an HVU encounter with threat USVs. Assets in the mission are shown across the top of the diagram, with lifelines extending down vertically. Arrows between the lifelines represent sequential actions generated from and received by each asset to execute the mission thread. The mission thread consists of three phases. In the first and second phase (steps UC2.1 through UC2.9), the HVU receives operational guidance from the area commander, deploys the C-UxS SoS, identifies and monitors threat USVs as they move closer to the HVU. The C-UxS SoS successfully mitigates a portion of the threat. In the last phase, the C-UxS SoS successfully mitigates threat USVs that are critically close to the HVU, which then provides a situation report to the area commander.

Figure 10. HVU Encounter With Threat USVs (OV-6c)

(1) Priority 3 Zone

The C-UxS system begins sensing and tracking possible threats to the HVU. The C-UxS system then detects four simultaneous surface tracks that are moving towards the HVU. Based on their bearing and coordination, the C-UxS system assigns to them an increased probability of threat and categorizes this for the HVU commander.

(2) Priority 2 Zone

The possible threat tracks continue moving towards the HVU. When the surface tracks come within range, the C-UxS system identifies them as threat USVs and updates the track classification to hostile. The C-UxS system employs long range mitigation techniques to affect the hostile USVs. This results in disabling two of the USVs. The two disabled USVs lose all propulsion and float on the water. The C-UxS system reports the USV track status to the HVU commander.

(3) Priority 1 Zone

The remaining USV continues moving towards the HVU. The C-UxS system performs short range mitigation techniques, resulting in the USV becoming disabled, losing propulsion, and floating on the water. The C-UxS system determines that there are no remaining threat tracks and reports this to the HVU commander. The HVU commander provides a situation report to the area commander, including a summary of the engagement and the location of the disabled USV. The area commander tasks an explosive ordnance disposal team for exploitation of the disabled USV. The HVU continues through the chokepoint and reaches open water, at which point the HVU commander orders the C-UxS system to return to passive sensing of potential threats. This concludes the vignette.

c. Measures of Effectiveness

MOEs that are specific to accomplishment of these vignettes are in Table 10.

Table 10. Vignette Measures of Effectiveness

ID	Name	Measure
MOE.2	Priority 2 Zone UxS Penetration Ratio	$\frac{\text{Number of Hostile UxSs Reaching Priority 2 Zone}}{\text{Total Humber of Hostile UxSs}}$

C. FUNCTIONAL ARCHITECTURE

This section defines how the assets that make up the mission scenario accomplish the operational tasks as defined in the vignettes. It does this by first identifying key assets from

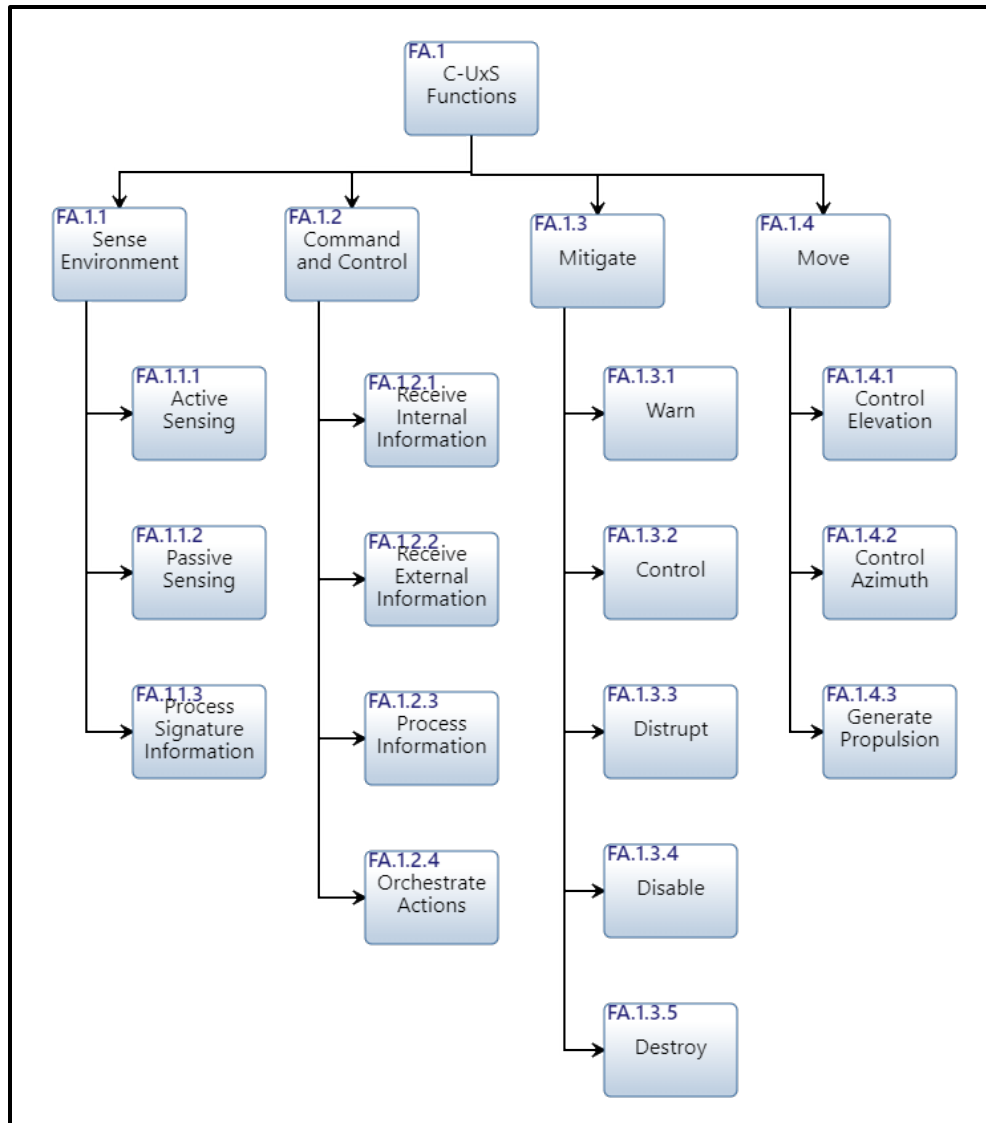
the mission scenario and describing the functional decompositions of these assets. This includes the functions and supporting subfunctions that are required to accomplish mission tasks with additional levels of decomposition as necessary. It then describes how the functions interact to accomplish higher-level functions and tasks in terms of internal and external interfaces and input/output requirements. Finally, given these definitions for functional interaction, the mission vignettes are then described through an activity diagram that illustrates the sequencing and timing for functional accomplishment.

1. Functional Decomposition

A functional decomposition identifies the logical composition of functions and subfunctions for a given asset that are required to accomplish its operational tasks. This section accomplishes a functional decomposition for the HVU escort mission scenario through multiple functional hierarchies, illustrated as separate operational activity decomposition trees in compliance with DODAF OV-5a. These describe the core functions for the mission scenario, first through the C-UxS SoS as the primary system of interest, and then through the HVU and Threat UxS with which it directly interacts. This supplies an initial framework for function-level measure of performance and for allocation of physical assets in the physical architecture.

a. Counter-Unmanned Systems System of Systems

The core function of the C-UxS SoS is to support HVU self-escort through countering adversary UxS. This means that the C-UxS SoS must provide an accurate and timely picture of UxS in the HVU operating environment and, upon detection of an adversary UxS, support decision making that results in effective measures against the UxS. Functions that support this mission are outlined in Figure 11. This shows how the C-UxS SoS must receive and process signature information, respectively through the Sense and C2 functions, and employ appropriate effect against UxSs through the Mitigate function. A Move function ensures the C-UxS can position for adequate sensor employment and support any required effects.



The C-UxS operational activity decomposition tree supplies the hierarchy of key functions for countering adversary UxSs. The C-UxS SoS must receive and process signature information, respectively through the Sense and C2 functions, and employ appropriate effect against UxSs through the Mitigate function. A Move function ensures the C-UxS can position for adequate sensor employment and support any required effects.

Figure 11. C-UxS Operational Activity Decomposition Tree (OV-5a)

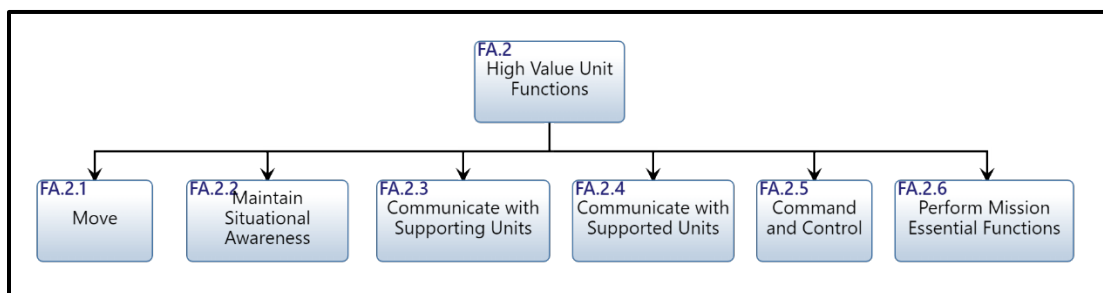
Table 11 supplies a description of each of the C-UxS supporting functions. Having a description for these and other functions in the model ensures a common frame of reference for physical allocation and other analyses.

Table 11. C-UxS Function Descriptions

Number	Name	Description
FA.1	C-UxS Functions	The ability to accomplish functions required of the C-UxS system to support HVU self-escort.
FA.1.1	Sense Environment	The ability to gather and process data from the environment.
FA.1.1.1	Active Sensing	The ability to stimulate and receive signature information from the environment.
FA.1.1.2	Passive Sensing	The ability to receive existing signature information from the environment.
FA.1.1.3	Process Signature Information	The ability to translate and reduce signature information.
FA.1.2	Command and Control	The ability to perform tasks and make decisions based on received data.
FA.1.2.1	Receive Internal Information	The ability to receive information from internal functions required to accomplish operational tasks.
FA.1.2.2	Receive External Information	The ability to receive information from external functions required to accomplish operational tasks.
FA.1.2.3	Process Information	The ability to process received data to achieve the desired operational objective. Consists of consolidating, sorting, and reducing received data.
FA.1.2.4	Orchestrate Actions	The ability to make decisions about what tasks are required.
FA.1.3	Mitigate	The ability to apply effects to targets of interest to achieve the desired objective.
FA.1.3.1	Warn	The ability to communicate with a target of interest to reduce the threat level.
FA.1.3.2	Control	The ability to directly control operation of a target of interest.
FA.1.3.3	Disrupt	The ability to temporarily interrupt operation of the target of interest.
FA.1.3.4	Disable	The ability to permanently prevent operation of the target of interest.
FA.1.3.5	Destroy	The ability to physically destroy the target of interest.
FA.1.4	Move	The ability to propel and navigate through the operating environment.
FA.1.4.1	Control Elevation	The ability to maintain or alter the elevation of the system.
FA.1.4.2	Control Azimuth	The ability to maintain or alter the direction of system motion.
FA.1.4.3	Generate Propulsion	The ability to alter speed when required.

b. High Value Unit

In the context of the mission scenario, the core function of the HVU is to transit through the restricted maneuvering areas of the operating environment to the open water, in accordance with guidance from the area commander. This means that the functions of the HVU must support its capabilities for movement, situational awareness, and communication through the operating environment. A C2 function provides a central coordination point for these functions. These functions are illustrated in Figure 12.



The HVU operational activity decomposition tree supplies the key functions for conducting HVU operations and integration with C-UxS during restricted maneuvering transit. The core function of the HVU is to transit through the restricted maneuvering areas of the operating environment to the open water, in accordance with guidance from the area commander. This means that the functions of the HVU must support its capabilities for movement, situational awareness, and communication through the operating environment. A C2 function provides a central coordination point for these functions.

Figure 12. HVU Operational Activity Decomposition Tree (OV-5a)

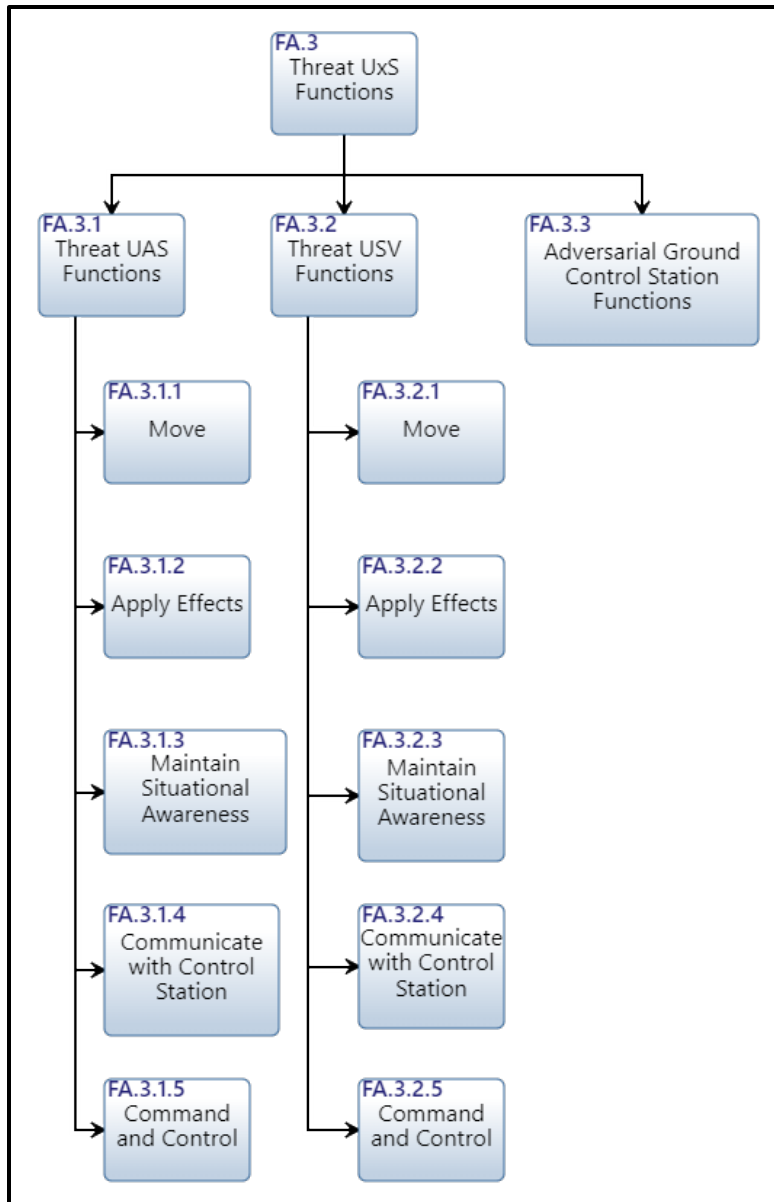
Table 12 provides a description of each of the HVU supporting functions.

Table 12. HVU Function Descriptions

Number	Name	Description
FA.2	High Value Unit Functions	The ability to accomplish functions required to achieve HVU operational intent.
FA.2.1	Move	The ability to propel and navigate through the operating environment.
FA.2.2	Maintain Situational Awareness	The ability to be aware of conditions in the operating environment.
FA.2.3	Communicate with Supporting Units	The ability to exchange information with supporting units.
FA.2.4	Communicate with Supported Units	The ability to exchange information with supported units.
FA.2.5	Command and Control	The ability to perform tasks and make decisions based on received data.
FA.2.6	Perform Mission Essential Functions	The ability to perform mission essential functions that are specific to the HVU.

c. Threat Unmanned System

The functional hierarchy for the Threat UxS is in Figure 13. The Threat UxS is composed of both the unmanned adversary systems, i.e., the multiple USVs and UASs, and the GCS that directs their operation. Including the GCS ensures the scenario can represent any capabilities or limitations that apply to communication between the GCS and the supporting units.



The Threat UxS operational activity decomposition tree supplies the key functions for conducting Threat UxS operations, including vehicles and control stations, for surveillance and possible engagement of an HVU during restricted maneuvering transit. The Threat UxS is composed of both the unmanned adversary systems, i.e., the multiple USVs and UASs, and the GCS that directs their operation. Including the GCS ensures the scenario can represent any capabilities or limitations that apply to communication between the GCS and the supporting units.

Figure 13. Threat UxS Operational Activity Decomposition Tree (OV-5a)

Table 13 provides a description of each of the Threat UxS supporting functions.

Table 13. Threat UxS Function Descriptions

Number	Name	Description
FA.3	Threat UxS Functions	The ability to accomplish functions required to achieve Threat UxS tasks.
FA.3.1.1	Move	The ability to propel and navigate through the operating environment.
FA.3.1.2	Apply Effects	The ability to affect the operating environment or assets located in the operating environment.
FA.3.1.3	Maintain Situational Awareness	The ability to be aware of conditions in the operating environment.
FA.3.1.4	Communicate with Control Station	The ability to communicate to and receive guidance from the control station.
FA.3.1.5	Command and Control	The ability to perform tasks and make decisions based on received data.
FA.3.3	Adversarial Ground Control Station Functions	The ability to perform functions required for ground control station tasks.

2. Functional Interaction

At a high level, the C-UxS system supplies operational effect against Threat UxSs through internal functions that transform inputs from the operational environment into outputs, by means of physical mechanisms. An integrated computer aided manufacturing definition for functional modeling 0 (IDEF0) diagram represents this exchange as part of the overarching HVU self-escort mission scenario. This diagram is part of a coordinated set of diagrams which, in coordination with the OV-1 in Figure 6, assist in setting the boundaries for the mission scenario. It does this through a consistent structure and nomenclature that illustrates and ensures adequate coverage for the necessary functional interactions. Figure 14 provides the overall structure and nomenclature for an IDEF0. Descriptions of the nomenclature are provided the figure, as defined in Buede and Miller (2016).

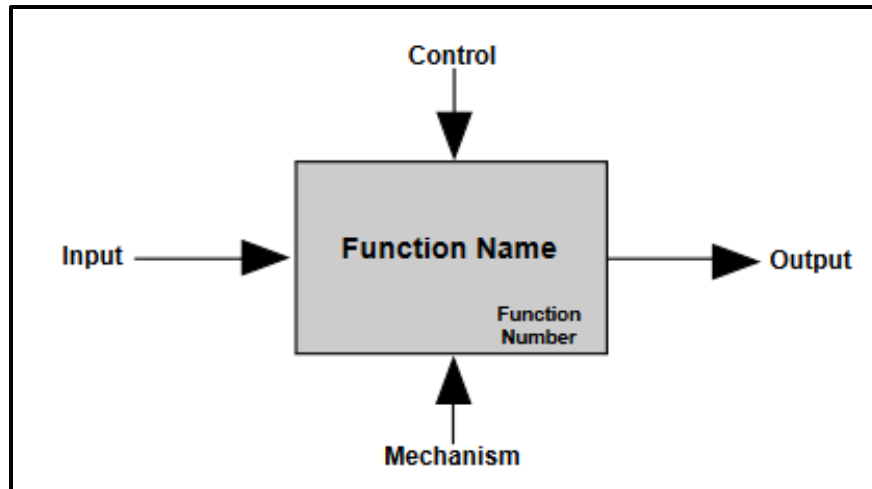


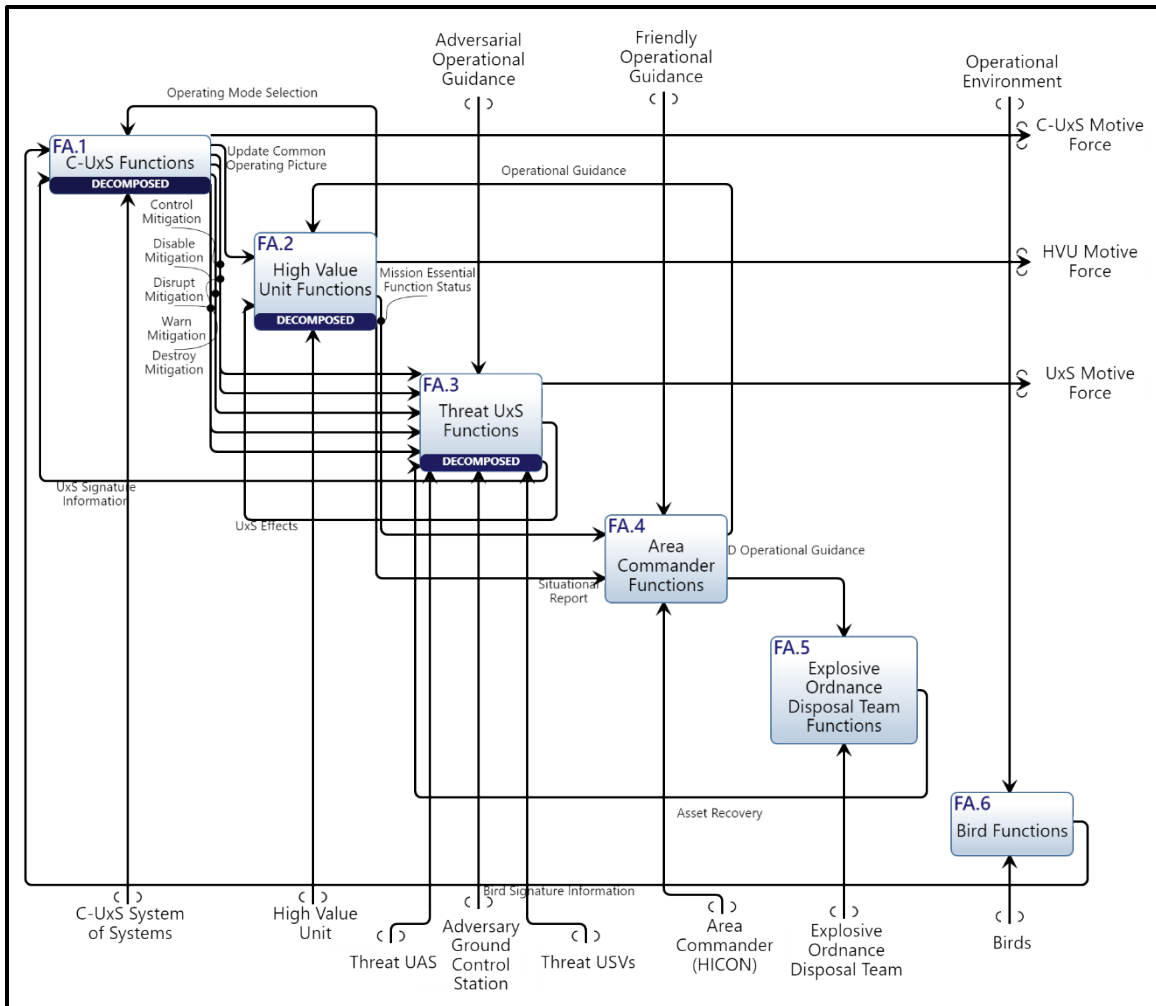
Figure 14. IDEF0 Box Format. Source: Defense Acquisition University (2001, 51).

- **Functions** are transformations that turn inputs into outputs.
- **Inputs** and **Outputs** represent a flow of material, energy, or data.
- **Controls** guide the function process and may act as a trigger for the function.
- **Mechanisms** accomplish functions.

Compared to alternative depictions of functional interaction including activity diagrams and functional flow block diagrams, IDEF0 diagrams excel at showing relationships between hierarchical functional decompositions, and explicitly represent the controls that guide the behavior of functions. The IDEF0 diagrams here also support comparison with prior work by Behling et al (Behling et al. 2022) and Arteché et al (Arteché et al. 2017).

Using this structure and nomenclature, Figure 15 shows the high-level IDEF0 for the HVU self-escort scenario. IDEF0 diagrams supporting each of the constituent functions are contained in Appendix A. In general, this illustrates how the C-UxS system (block FA.1) achieves effect on the Threat UxS (block FA.3) through a variety of possible mitigations. Signature information obtained from the Threat UxS or from other noncombatant assets (block FA.6) is received and processed by the C-UxS system to

inform the choice of proper mitigation. Overall C2 for the mission scenario is provided through the HVU (block FA.2) and Area Commander (block FA.4) which receive processed signature information from, and provide operational guidance or action to, supporting assets. The HVU may also receive effect from the Threat UxS if the mitigations from the C-UxS system are unsuccessful.



The IDEF0 diagram represents functional exchange as part of the overarching HVU self-escort mission scenario. The C-UxS system (block FA.1) achieves effect on the Threat UxS (block FA.3) through a variety of possible mitigations. Signature information obtained from the Threat UxS or from other noncombatant assets such as birds (block FA.6) is received and processed by the C-UxS system to inform the choice of proper mitigation. Overall C2 for the mission scenario is provided through the HVU (block FA.2) and Area Commander (block FA.4) which receive processed signature information from, and provide operational guidance or action to, supporting assets. The HVU may also receive effect from the Threat UxS if the mitigations from the C-UxS system are unsuccessful.

Figure 15. HVU Self-Escort Operational Activity Model (OV-5b)

An activity diagram, also known as an extended functional flow block diagram, applies timing and control logic to the IDEF0 to show specific process threads (Buede and Miller 2016, 87). In this context, an activity diagram supplies the means to investigate the specific vignettes that are part of the overarching scenario. An activity

diagram for the first mission vignette, the HVU encounter with Threat UASs, is included in Appendix B.

D. PHYSICAL ARCHITECTURE

This section establishes conceptual physical architectures for hypothetical alternatives to accomplish the HVU self-escort mission scenario. Table 14 supplies a high-level description of these alternatives. In addition to supplying separate design points for comparison in Chapters IV and V, these alternatives illustrate the breadth of possible systems which may support the C-UxS mission. Traceability through the functional architecture demonstrates alignment with the baseline mission intent.

Table 14. Hypothetical C-UxS System Alternatives

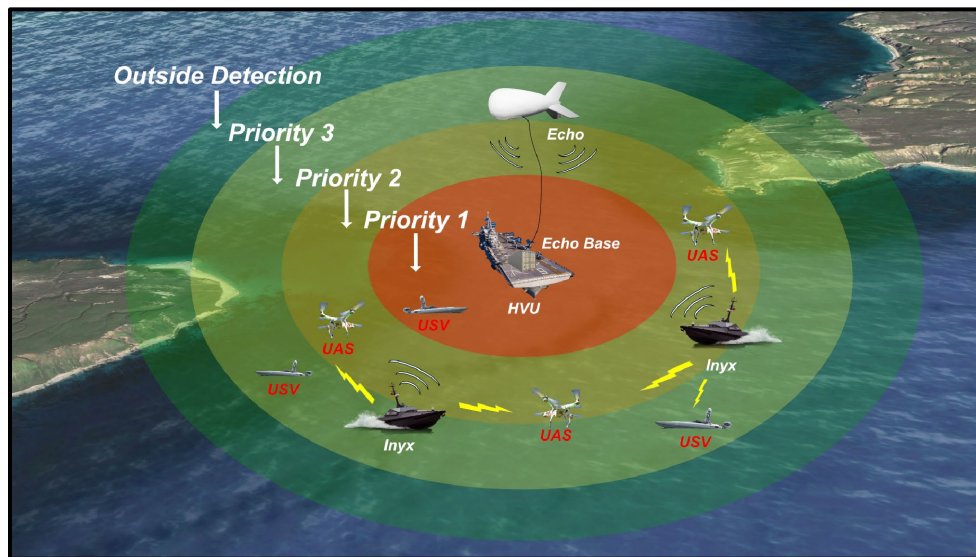
ID	Name	Platforms	Sensors	Mitigators
1	Echo/Inyx	Aerostat USVs Base Station	<u>Aerostat</u> : RF, EO/IR <u>Base Station</u> : Radar <u>USVs</u> : RF, Radar	<u>Aerostat</u> : RF/GNSS Jamming <u>USVs</u> : RF/GNSS Jamming
2	RamJammer	EW UASs Kinetic UASs Base Station	<u>EW UASs</u> : RF, EO/IR <u>Kinetic UASs</u> : EO/IR <u>Base Station</u> : Radar	<u>EW UASs</u> : RF/GNSS Jamming/Spoofing <u>Kinetic UASs</u> : Collision UAS (Ramming)

For each alternative, this section provides a high-level concept of operation and a description of the system composition. Graphical system interface descriptions display key system components and how they interface. Finally, resource allocation matrices illustrate how each alternative provides coverage for the necessary functions in support of the C-UxS mission.

1. Alternative 1: Echo/Inyx

The first hypothetical alternative explores C-UxS primarily through EW systems distributed through multiple platforms. An illustration of the operational concept is shown in Figure 16. Multiple USVs, designated Inyx, deploy around the HVU and provide an effects screen using both RF and GNSS jamming. Software defined radios

(SDR) aboard the Inyx USVs support flexible application through the multiple radio protocols which may be available to a threat UxS. An Aerostat, designated Echo, provides low-altitude overwatch of the HVU through optical and RF sensors, also supported through SDR. Primary threat detection occurs through these sensors, RF sensors and radar aboard the Inyx USVs, and through a radar located at a base station on the HVU. Each radar system can detect micro-Doppler signals in support of detecting and identify low, slow, and small UASs.



An Echo aerostat deployed at approximately 300 feet above sea level provides overwatch of the HVU using SDR for RF and optical detection. An Echo base station on board the HVU includes micro doppler radar in support of C-UxS. Inyx USVs deploy around HVU, each with an SDR for RF detection, SDR for RF jamming, SDR for GNSS jamming, and micro doppler radar. Engagements from the C-UxS system to UxSs are through relatively low-power RF and GNSS jamming aboard Inyx USVs, or by a failsafe jammer aboard the Echo aerostat.

Figure 16. Echo/Inyx Operational Concept

The operational concept in Figure 16 shows key expected changes from the baseline operational concept that are applicable to this alternative. In this alternative, the HVU initiates the active sensing section of the transit by deploying the Echo aerostat and emitting with the on-board C-UxS radar. The aerostat and USVs detect potential threats in the Priority 3 Zone and provide an initial EW effects screen when the threat increases

to the Priority 2 Zone. The USVs can achieve effect against threats that are imminent to the HVU in the Priority 1 Zone through EW at close range.

a. Systems Interface Description

The Echo/Inyx concept comprises multiple subsystems that interact to provide the capability described in the operational concept. These subsystems and their interconnections are displayed in Figure 17. This shows how the three primary platforms (the aerostat, base station, and USVs) interface through communications subsystems and have internal function orchestrated through C2 subsystems. Mobility, effects, and sensing capabilities are each achieved through separate subsystems for these purposes.

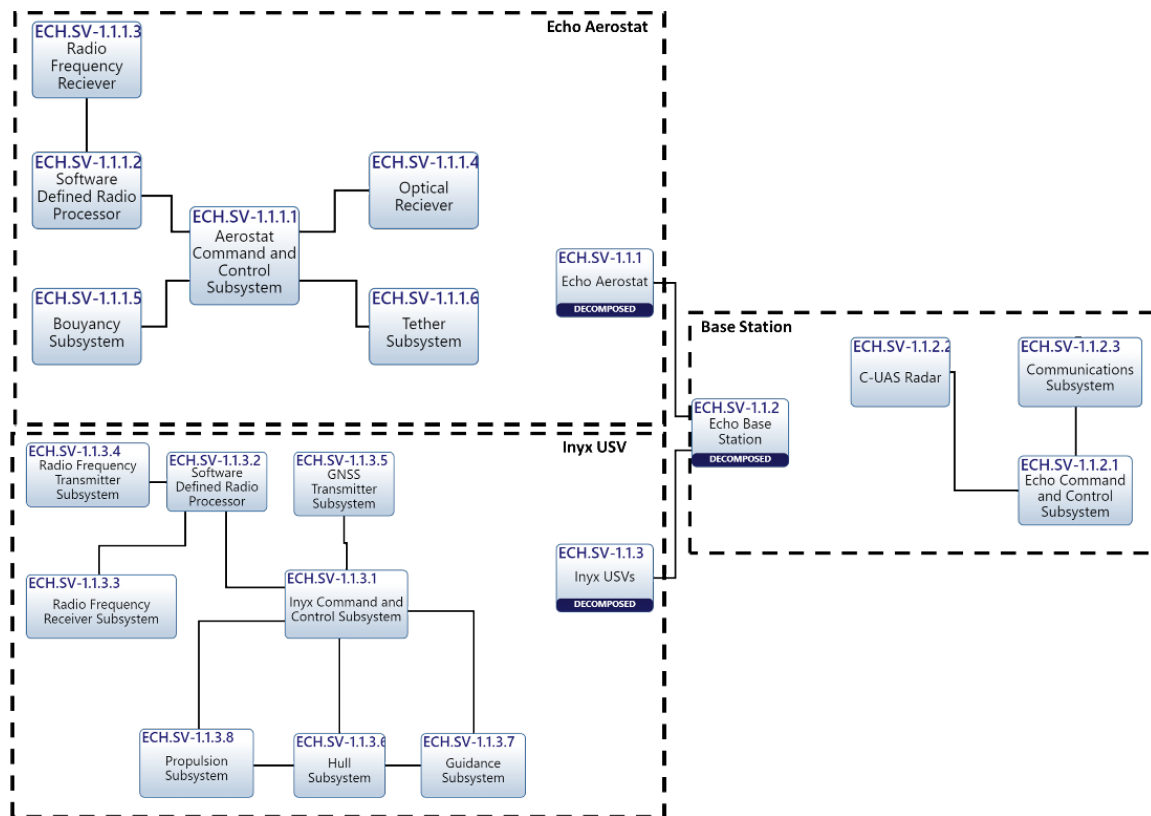


Figure 17. Echo-Inyx Systems Interface Description (SV-1)

b. Operational Activity to Systems Traceability

Figure 18 shows the traceability of the subsystems in Figure 17 to the C-UxS functions as described in Section B, which shows how the alternative subsystems are likely to support the required C-UxS functions. This matrix supports a review of system functional coverage and robustness (i.e., functions covered through multiple subsystems), and supplies a mechanism for allocating functional requirements to subsystem components.

Based on this matrix, the Echo-Inyx alternative only supports mitigation functions for controlling or disrupting a threat UxS. While this limitation may affect this alternative's capability to mitigate threats that are survivable against EW effects, it does possibly mean that threats which are successfully mitigated can be retrieved for further exploitation. The analysis in Chapters IV and V uses this alternative to explore the impact of this functional coverage.

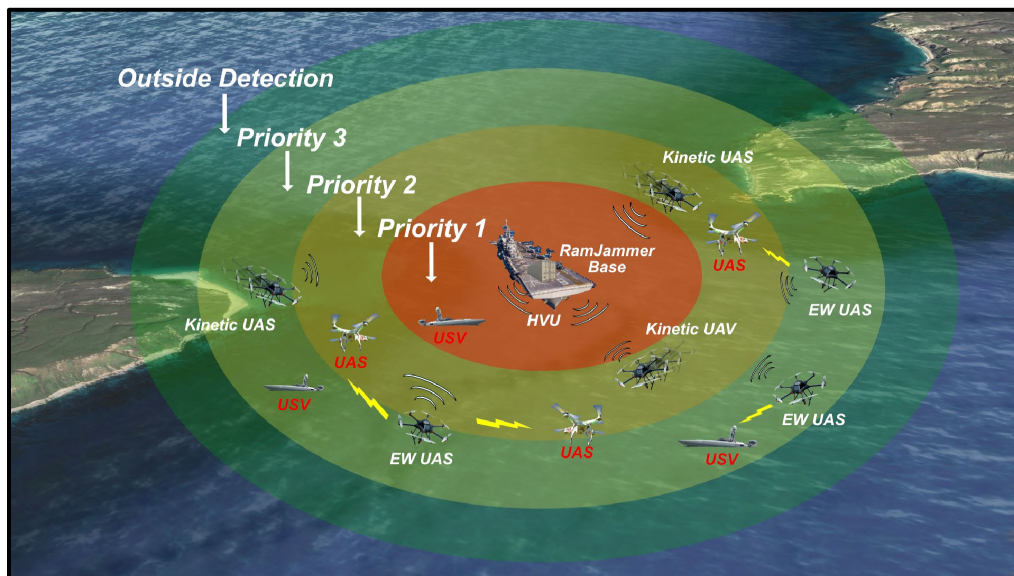
2. Alternative 2: RamJammer

The second alternative, designated RamJammer, supplies a defense-in-depth of the HVU, using multiple modes of mitigation aboard UASs for effect. An illustration of the operational concept is shown in Figure 19. Three EW UASs provide an initial contact screen for the HVU and use a combination of RF and EO/IR sensors to characterize incoming threats. EO/IR sensors provide feedback through an image recognition subsystem in support of automated identification of potential threats. Given a confirmed threat, the EW UASs use feedback from RF sensors on board the UASs to apply RF and GNSS jamming and spoofing to disrupt and potentially control threat UxSs. Kinetic UASs with a ramming function are capable of engaging threats that leak past the EW UASs. Primary threat detection occurs through RF and EO/IR sensors on board the UASs, and through a radar located at the base station on the HVU.

Two limiting factors for this alternative are the sensing and maneuvering capabilities of the kinetic UAS in the inner defense ring. Given these limiting factors, a kinetic UAS capability is included in this alternative to support demonstrating a variety of design points in this project's model. The analysis in Chapters IV and V uses this alternative to explore the impact of the limitations inherent in the kinetic UAS capability. UxS and C-UxS are rapidly evolving areas, and use of controlled data will improve the relevance of any analysis supported by this project.

Collision-based C-UxS systems have seen some success in limited demonstrations, including the Anvil system developed by Anduril (Anduril n.d.) and the DroneBullet system developed by AerialX (AerialX n.d.). These systems rely on computer imaging algorithms to maintain a track of the adversary UAS and obtain relatively high maneuverability through quadcopter propellers. However, the sUAS that these systems are designed to counter are also often equipped with multiple propellers, resulting in a similar level of maneuverability. This limitation may be partially mitigated through equipping the defensive UAS with an explosive device, as is the case with the Coyote UAS developed by Raytheon (Raytheon n.d.), but this eliminates any possibility for reuse of the defensive UAS. Additionally, while Cigla et al. demonstrated that stereo vision can improve detection and collision avoidance capabilities for UAS operating in proximity

(Cigla, Thakker, and Matthies 2018), this capability has not yet been robustly demonstrated for collision in a competitive environment. Because of this, collision-based C-UxS systems may have limited effectiveness until there are technological improvements that address these limitations.



Multiple C-UxS UASs perform defense-in-depth of the HVU. A combination of RF/GNSS jamming and spoofing and kinetic UAS collision minimizes risk to HVU essential functions. Three EW UASs are equipped with RF and EO/IR sensors, supported through on-board image recognition. Mitigation subsystems support RF/GNSS spoofing and jamming based on feedback from RF sensors. Three kinetic UASs support engagement of threats that leak past the EW UASs. EO/IR sensors support threat detection and tracking through on-board image recognition. Ramming capabilities on the UASs support kinetic engagement. A base station is equipped with micro doppler radar for threat detection.

Figure 19. RamJammer Operational Concept

The operational concept in Figure 19 shows key expected changes from the baseline operational concept that are applicable to this alternative. In this alternative, the HVU initiates the active sensing section of the transit by deploying the UASs and through emitting with the on-board C-UxS radar. The base station detects potential threats in the Priority 3 Zone which it then hands off to the EW UASs for interrogation and identification. EW UASs provide effect on targets inside of the Priority 2 Zone. Targets

that leak past the EW UASs and which present an imminent threat to the HVU in the Priority 1 Zone are engaged by the Kinetic UASs.

a. Systems Interface Description

The subsystems and interconnections that support the RamJammer concept are displayed in Figure 20. This shows how the base station and the two classes of UASs interface through communications subsystems and have internal function orchestrated through C2 subsystems. As with the Echo-Inyx alternative, mobility, effects, and sensing capabilities are achieved through separate subsystems for these purposes.

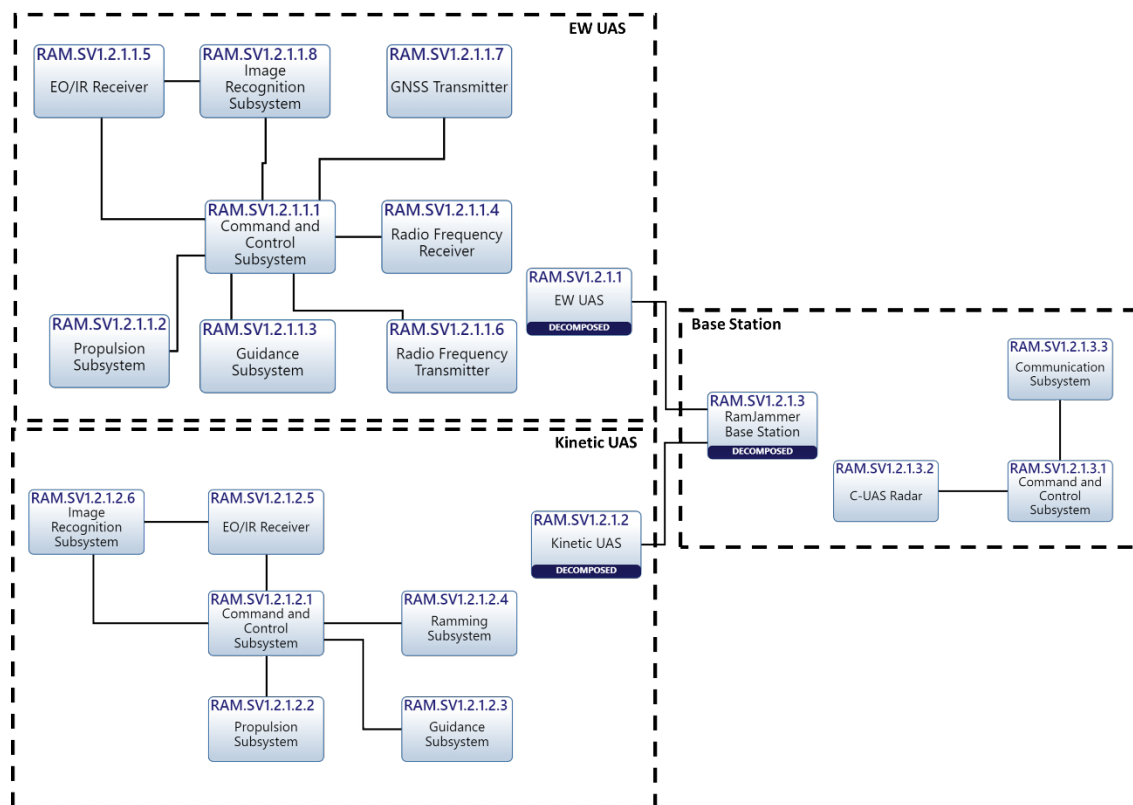


Figure 20. RamJammer Systems Interface Description (SV-1)

b. Operational Activity to Systems Traceability

Figure 21 shows the traceability of the RamJammer subsystems in Figure 20 to the C-UxS functions as described in Section B. Based on this matrix, the RamJammer

alternative supports mitigation function to control, disrupt, or destroy a threat UxS. The analysis in Chapters IV and V uses this alternative to explore the impact of this functional coverage.

Alternative #2: RamJammer (SV-5b)																				
	RAM.SV1.2.1 Ramjammer C-UxS	RAM.SV1.2.1.1 EW UAVs	RAM.SV1.2.1.1.1 Command and Control Subsystem	RAM.SV1.2.1.1.2 Propulsion Subsystem	RAM.SV1.2.1.1.3 Guidance Subsystem	RAM.SV1.2.1.1.4 Radio Frequency Receiver	RAM.SV1.2.1.1.5 EO/IR Receiver	RAM.SV1.2.1.1.6 Radio Frequency Transmitter	RAM.SV1.2.1.1.7 GNSS Transmitter	RAM.SV1.2.1.1.8 Image Recognition Subsystem	RAM.SV1.2.1.2.1 Command and Control Subsystem	RAM.SV1.2.1.2.2 Propulsion Subsystem	RAM.SV1.2.1.2.3 Guidance Subsystem	RAM.SV1.2.1.2.4 Ramming Subsystem	RAM.SV1.2.1.2.5 EO/IR Receiver	RAM.SV1.2.1.2.6 Image Recognition Subsystem	RAM.SV1.2.1.3.1 RamJammer Base Station	RAM.SV1.2.1.3.2 C-UAS Radar	RAM.SV1.2.1.3.3 Communication Subsystem	
FA.1 C-UxS Functions	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X			
FA.1.1 Sense Environment	X	X				X	X				X					X		X		
FA.1.1.1 Active Sensing	X															X		X		
FA.1.1.2 Passive Sensing	X	X				X	X			X					X					
FA.1.1.3 Process Signature Information	X	X	X						X	X						X	X	X		
FA.1.2 Command and Control	X	X	X								X						X	X		X
FA.1.2.1 Receive Internal Information	X	X	X								X						X	X		
FA.1.2.2 Receive External Information	X	X	X								X						X			X
FA.1.2.3 Process Information	X	X	X								X						X	X		
FA.1.2.4 Orchestrate Actions	X	X	X								X						X	X		
FA.1.3 Mitigate	X	X						X	X		X				X					
FA.1.3.1 Warn																				
FA.1.3.2 Control	X	X							X											
FA.1.3.3 Distrupt	X	X						X	X											
FA.1.3.4 Disable																				
FA.1.3.5 Destroy	X									X				X						
FA.1.4 Move	X	X		X	X						X		X	X						
FA.1.4.1 Control Elevation	X				X						X			X						
FA.1.4.2 Control Azimuth	X	X			X						X			X						
FA.1.4.3 Generate Propulsion	X	X		X							X		X							

Figure 21. RamJammer Operational Activity to Systems Traceability Matrix (SV-5b)

E. SUMMARY OF CHAPTER

This chapter supplies the systems architecture for this project, consisting of an operational, functional, and physical architecture. After an overview of the methodology, the operational architecture describes the overarching mission scenario for C-UxS in support of HVU self-escort. Mission vignettes supply the key assets and interactions among them that support this scenario. A functional architecture then takes the assets and sequences of tasks that comprise the mission vignettes and generates the functions for the key assets, specifically for the C-UxS system and the assets with which it interacts. This supports an overview of high-level measures and requirements that characterize system ability to achieve the required functions. Separate conceptual physical architectures then supply alternatives for system-level concepts that could apply to the C-UxS mission. Chapters IV and V use these concepts as input to a simulation and proposed analysis process.

IV. MODELING AND SIMULATION

This chapter describes model development for the HVU C-UxS scenario simulation. This model has the following purposes:

- It supports development of relevant environments to simulate the threat in a realistic scenario by using geographic maps, realistic threat vectors, and environmental logic to model a given operational environment.
- It supports development of elements, with modifiable underlying logic and parameters to model various threats, counter technology, and behaviors in simulation.
- It exports data from multiple runs to support alternative analysis and evaluation. For the scenarios described in Chapter III, a detailed description of the scenario simulations and data analysis is covered in Chapters V.

To accomplish these purposes, this chapter describes four simulation-focused topics. First, a modeling and simulation overview covers the tools used and high-level model design details. Second is a description of the simulation components, including HVU, threats, and C-UxS technologies used in alternatives analysis. This supplies context for the logic, behaviors, assumptions, and tactics considered when simulating each element. Third, this chapter discusses the verification method used and results to assess the tool prior to alternative analysis. Finally, this chapter discusses the simulation evaluation methods used to assess alternatives in Chapter V.

A. MODELING AND SIMULATION OVERVIEW

The methodology taken to conduct this analysis builds upon previous work using a phased range-based priority zone concept that focused on C-UxS operational energy analysis (Behling et al. 2022) and tailor the approach using a government-owned modeling and simulation tool for the purposes of capability analysis. Capability analysis in this context is built around a baseline scenario and a framework for normalizing results

across alternatives, using a weighted scoring system described later in this chapter. This allows the analysis of performance of multiple alternatives for their effectiveness in HVU protection from direct intercepts, as well as the assessment of their ability to reduce the number of agents getting within certain ranges of the HVU.

This project implements an adaptation of MAST to support analysis of C-UxS capabilities in support of HVU self-escort. MAST is a behavior-based modeling and simulation toolbox developed and owned by the NSWC Dahlgren Division (NSWC, Dahlgren Division 2020). This government-developed toolkit serves as a valuable resource for various applications within the defense and military domains. MAST is designed to facilitate agent-based simulations, providing users with a comprehensive environment to verify requirements, evaluate mission capabilities, and assess SoS impacts. At its core, MAST is built upon the orchestrated simulation through modeling (OSM) framework (NSWC, Dahlgren Division 2020). The OSM framework forms the foundation of MAST, offering a structured and organized approach to modeling and simulating complex systems. By implementing OSM, MAST enables users to effectively model and simulate a wide range of scenarios, from individual agent behaviors to large-scale system interactions.

As an agent-based simulation environment, MAST allows users to create and define intelligent agents that have their own behaviors, decision-making capabilities, and interactions with other agents and the environment. These agents can stand for various entities, such as vehicles, personnel, or systems, and can be configured to mimic real-world behaviors and dynamics. Each agent is made up of elements called subsystems, which each simulate subsystem functionality that might be found on the real-world agent type, such as a transmitter subsystem in MAST representing an antenna aboard a ship. Through MAST, users can observe and analyze how these agents interact and influence the simulated environment, supplying insights into the system's behavior, performance, and mission effectiveness.

The primary objective of MAST is to support the modeling and simulation needs of defense and military stakeholders. It serves as a powerful tool for validating requirements, assessing the capabilities of different mission scenarios, and evaluating the

impact of various SoS interactions. By using MAST, users can gain a deeper understanding of the implications and consequences of different operational decisions, helping to inform decision-making processes and optimize mission planning and execution. With its foundation on the OSM framework, MAST supplies a versatile and robust platform for users to explore, analyze, and enhance the performance and effectiveness of complex systems through comprehensive agent-based simulations.

B. SIMULATION COMPONENTS

Given a mission scenario that describes an HVU transiting through an area of restricted maneuverability to open water, this project implements a simulation set in the port region of Hampton Roads, Virginia, home of one of the largest Navy bases in the world, Naval Station Norfolk (US Navy n.d.). Hampton Roads is a representative case for restricted maneuverability and includes chokepoints and other navigation hazards that may challenge a fleet commander's ability to respond to a potential threat. The primary focus of the simulation is to assess the effectiveness of various countermeasures against UxS threats deployed by adversarial operators located at the east and west banks of the port. Figure 22 shows a representation of the route taken by the HVU in the baseline mission scenario in MAST.



Figure 22. Visual Representation of Simulated HVU Pathing

The simulation incorporates three key components to create a realistic and comprehensive baseline environment: the adversary UxS threats, the HVU, and a C-UxS base station. The UxS threat swarms, originating from the east and west banks, represent the hostile entities targeting the HVU. These swarms mimic the behavior and characteristics of real UxS threats, challenging the defensive capabilities of the HVU and the deployed countermeasures. The HVU itself plays a vital role in the simulation, standing for a high-value asset or entity that requires protection during its transit from the port to the open ocean.

The simulation also incorporates a C-UxS base station located aboard the HVU, which serves as an optional C2 hub for coordinating and managing C-UxS activities. The C-UxS base station enables real-time communication, data exchange, and decision-making with remote assets as required, enhancing the overall effectiveness of the defensive operations.

The C-UxS technologies assessed as part of this project include EW UAS, kinetic UAS, and EW USV. These technologies represent different approaches to countering UxS threats. EW UASs use EW capabilities such as jamming and spoofing to disrupt or neutralize hostile UxSs, while kinetic UASs engage threats through physical means. EW USVs operate on the water surface and employ electronic countermeasures to safeguard the HVU.

By integrating these components into the simulation, a dynamic and challenging scenario is created, replicating the complexities and threats faced by the HVU during its transit from the port to the open ocean. The simulation allows for the evaluation of different countermeasures and strategies, supplying valuable insights into the effectiveness of the C-UxS technologies and the overall defense of the HVU in a realistic and controlled environment.

1. Baseline Simulation Components

This section discusses the composition of the baseline components of the simulation, including subsystems, functions and state machines, and component interactions. Figure 23 shows an overhead view of the baseline mission scenario in MAST.

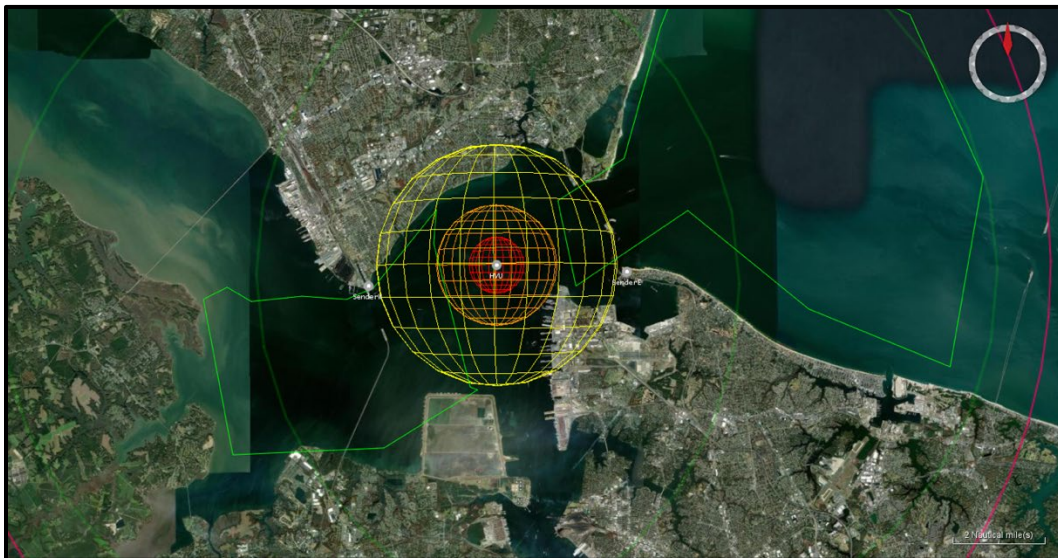


Figure 23. Overhead view of the MAST Baseline Simulation

a. Sender Agent

Remotely commanded UxS receive commands from a remote operator. The remote operator is simulated as the Sender agent in the baseline simulation. For each swarm, one coming from the east and one coming from the west, a respective Sender Agent is assigned to oversee operations of the swarm. The Sender has a Transmitter subsystem responsible for sending Heartbeat messages. Heartbeat messages are common in the UxS community and function as a safety measure and a method of maintaining communication between a ground station and a deployed asset (MAVLink n.d.). As long as this Heartbeat message is maintained, the deployed system will continue operating as expected. If the message is lost for more than a predetermined amount of time, then the system begins communications lost procedures. The Sender transmits its Heartbeat message once a second.

In addition to the Transmitter subsystem, the Sender agents also have a Sensor subsystem. This Sensor subsystem is intended to simulate the human operator's ability to visually see the HVU or to have some basic understanding of where the HVU might be. The Sensor subsystem will detect "tracks" much like a radar might, enabling the Sender to direct controlled swarms if the Sender has identified where the HVU is.

b. UAS and USV Threats

The FAA defines a swarm as "an operation of more than one [unmanned aircraft] in which all [unmanned aircraft] operate in unison to commands from one [pilot in command], who controls them all through a common link" (Federal Aviation Administration 2017). For the purposes of this paper, a swarm may be made up of some combination of USV or UAS agents. These threat swarms can be randomly spawned inside adjustable polygons, allowing for variable formations in the eastern and western directions. The number of agents per swarm is adjustable. The baseline scenario for this project sets this to two agents per swarm. Each swarm starts its mission at a specified altitude, with the altitude for USVs set to zero to simulate the USVs being on the water's surface.

Individual agents in the unmanned swarm are equipped with a Sensor subsystem, which is intended to simulate an onboard visual sensor such as a camera. The Sensor provides the operator with a visual representation of the targets or objects the unmanned swarm is tracking. Like any Sensor subsystem within MAST, the parameters of the subsystem such as range and identification distance can be adjusted to realistically simulate a visual spectrum sensor.

To ensure effective communication and control of the unmanned swarms, a Receiver system with an antenna is used on any UAS or USV agent. The Receiver receives Heartbeat messages from the Sender agent, who is responsible for controlling the unmanned swarms in the east and west regions. The Receiver's primary task is to manage communications by continuously monitoring the Heartbeat channel, as well as receive any tracks from the Sender and transmit any tracks the UAS or USV identifies to the Sender. Every second, the Receiver's Heartbeat Handler function checks for the presence of a Heartbeat, ensuring a stable connection between the Sender and Receiver. If the Sender is transmitting a Heartbeat message and that Heartbeat message can be received, the UAS or USV will either be in a *Follow Patrol Points* state or an *Intercept* state. The *Follow Patrol Points* state is an approximation that the Sender agent controlling the swarm will have some perception, either through optical means or other intelligence means, of the route that the HVU will be likely to take. Once the UxS is near the HVU, the state switches to the *Intercept* state to attempt an intercept on the HVU. Figure 24 shows a representation of the state space for the Heartbeat Handler function.

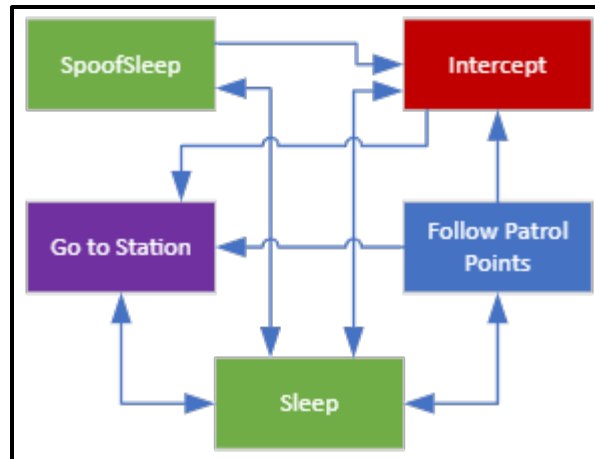


Figure 24. UAS Heartbeat Handler State Machine

If a Heartbeat message is not received after five seconds, generally caused by a reduction in the range of the Receiver driven by a Jammer, then a trigger is activated to change the behavior of the UxS. This behavior is intended to approximate the jamming of or loss of communications with the Sender agent. A UAS agent that has not received a Heartbeat after some period of time will attempt to return to its home position similar to many COTS UASs (DJI 2021) by transitioning to the *Go to Station* state, which in the case of the simulation is the Sender agent location. A USV agent that has not received a Heartbeat after some period will transition to the *Sleep* state and will instead stay where it last had a Heartbeat response. If the unmanned agent is experiencing spoofing, then this Heartbeat Handler switches to the *SpoofSleep* state to avoid interference with the Spoofing simulation.

To simulate GPS spoofing, the unmanned swarm employs a Spoof Check Sensor subsystem. The Spoof Check Sensor has two sensor states: *Not Jammed* and *Spoofed* and feeds into the Spoof Check state machine. In the normal state of the Spoof Check state machine, referred to as *Sleep*, the unmanned swarm operates normally. However, if the Spoof Check Sensor is triggered into the *Spoofed* sensor state, the Spoof Check state machine enters the *Spoofed* state. This triggers the Behavior state machine to activate the *Change Course* state. This behavior however can be changed to simulate a desired spoof behavior. For the purposes of the baseline simulation, spoofing is simulated as trying to

have the UxS move away from the HVU as fast as possible. Other responses to a spoofing action not implemented in the simulation may include a threat UxS applying spoofing effects to one of the friendly UxSs. Recommendations for future work in this area are included in Chapter VI. During the *Change Course* state, the unmanned swarm performs a U-turn maneuver at a speed of 50 knots, mimicking an attempt to drive the UxS away from the HVU. After 10 seconds, the swarm reverts to the *Sleep* state, ready to resume its normal operations unless the Spoof Check Sensor is still *Spoofed*, in which case the state machine would stay in the *Spoofed* state.

c. High Value Unit

The HVU is a vessel required to transit through restricted port areas to reach the open ocean. Its behavior is centered around efficiently navigating these constrained zones, and for the purposes of this analysis, the HVU's primary objective is to navigate from the port safely and securely to the open ocean, ensuring the protection of its valuable cargo or personnel.

The HVU in the baseline system technically is equipped with several subsystems. However, for the purposes of the alternatives being analyzed, all systems aboard the HVU are disabled, meaning that the C-UxS solutions under evaluation must be entirely independent of the HVU itself.

The HVU model has three tracked priority zones: Priority 3 (3 miles away), Priority 2 (1.5 Miles away), and Priority 1 (0.7 Miles away). These priority zones play a critical role in assessing the effectiveness of a C-UxS system, as they are key elements of the weighted scoring system that supports this analysis. Figure 25 shows the priority zone range rings in relation to the HVU. Radius definitions for the priority zones are a user-defined parameter and, following the concept of operations discussed in Chapter III, represent increasing levels of threat to the HVU. The ranges associated with these priority zones are set to notional values for the purposes of the simulation and may be redefined by the end user.



Figure 25. HVU Priority Zone Range Rings

d. Counter UxS (C-UxS) Base

The C-UxS Base serves as an optional component of the operational infrastructure for many C-UxS alternatives. In the baseline simulation, the C-UxS Base is located aboard the HVU. This mobile and adaptable base can be positioned in various locations as per operational requirements, which may impact scenario outcomes. The primary function of the C-UxS Base is to function as the central coordination hub for certain C-UxS capabilities and serve as the asset resident aboard the HVU as required for C-UxS alternatives.

One of the key subsystems of the C-UxS Base is its Radar subsystem. The C-UxS Radar subsystem is an adjustable system that enables the C-UxS system to detect and track objects in the surrounding area. This radar system provides variable inputs, including probability of threat detection, radar scan rate, and radar range. By changing the C-UxS Base radar parameters, the ability to detect, track, and time threats may vary. By monitoring the airspace and surface environment, the base can identify potential threats to provide timely information to friendly units and capabilities responsible for safeguarding the HVU.

In addition to radar functionality, the C-UxS Base is responsible for generating and providing track updates to the friendly units involved in protecting the HVU. These track updates convey vital information about the movement and location of objects of interest. By continuously updating friendly units, the C-UxS Base enables them to make informed decisions and respond effectively to potential threats or changing circumstances. The C-UxS Base acts as a central hub, facilitating seamless communication and coordination between friendly UxS via broadcast.

2. Components of Evaluated Alternatives

This section discusses the composition of the hypothetical alternative C-UxS systems included in the simulation. These compositions adapt the system definitions supplied in Chapter III to implement in MAST. System composition includes subsystems, functions and state machines, and component interactions.

a. RamJammer Alternative Components

The RamJammer alternative consists of two types of UAS: kinetic and EW capable. Both alternatives require a constant connection to a C-UxS Base as the sender to continue receiving broadcast track information for engagements.

The electronic option, "Jammers," is designed to remain airborne and hover around the HVU until a threat reaches a specified priority engagement zone. This type of aerial system offers flexibility in terms of input parameters, allowing users to adjust the number of assets deployed and the priority zone to trigger engagement. By maintaining a hovering presence, the EW capable aerial systems provide continuous surveillance and can swiftly respond to threats as they approach the priority engagement zone. The Jammers in this case enact the previously described Spoof behavior as well as jam the Heartbeat message of adversarial units, with the Spoof response in the simulation taking behavioral precedence.

On the other hand, the kinetic option within the RamJammer alternative, "Rammers", initially remains aboard the HVU as part of the C-UxS Base. These systems are equipped with two distinct triggers to execute their tasks effectively. The first trigger

initiates the launch and hovering of the kinetic aerial system around the HVU. Once the system is in the air, the second trigger is responsible for engaging threats as defined by a defined priority zone. Like the electronic capable aerial systems, the kinetic options offer configurable input variables to adapt to specific mission requirements. These variables include the number of kinetic assets available for deployment, the predetermined zone or distance at which the launch trigger is activated, and the designated zone or distance at which the engagement trigger is initiated. Such flexibility allows operators to tailor the system's response to changing scenarios and optimize its effectiveness based on the mission objectives and available resources. The Rammers attempt to execute a kinetic hard kill on adversarial UASs, attempt to physically ram them midair.

b. Echo/Inyx Alternative Components

The C-UxS surface system, Echo/Inyx, is an aerostat hovering above the HVU, called Echo, and several small USVs orbiting the HVU, called Inyx. The Echo aerostat, orbiting high above the HVU and tethered to the C-UxS Base, supplies a broad overwatch capability thanks to its ability to receive power from the HVU platform. A powerful Radar subsystem helps track possible hostile agents, a Transmitter subsystem communicates those tracks to the surrounding Inyx USVs, and a powerful, yet short range, Jammer subsystem supplies a last-minute failsafe defense capability. This failsafe Jammer subsystem is generally intended to provide a last-minute defense mechanism against hostile units that bypass the Inyx USVs.

Multiple Inyx USVs orbit the HVU at a specified distance equipped with their own Radar subsystem, albeit at a lower range compared to the Echo radar, a Receiver subsystem for receiving tracks from Echo, and a Jammer subsystem intended to jam communications and GPS of hostile agents. Inyx USVs are the frontline capability of this alternative, supplying a standoff jamming capability that can slow or prevent agents from entering priority zones. The Echo/Inyx alternative is built entirely around the principles of leveraging EW and does not have a kinetic engagement capability.

C. SIMULATION EVALUATION METHODOLOGY

This project proposes a weighted scoring model that uses a range-based defense profile to rank alternatives. Model output results in a single score that incorporates user-defined weights to categorize alternatives based on priorities for the comparison. This section describes the weighted scoring model in the context of other methods for defining comparison metrics and reviews benefits and drawbacks to defining a single score. It defines the formula for finding the weighted score and discusses the variable components that stand for user priorities.

1. Scoring Method

When comparing alternatives, it is common practice to use a defined methodology to aid in assessing and comparing complex systems (Kossiakoff et al. 2020, 297-307). As discussed in Kossiakoff et al., weighting factors accompanied by well-defined selection criteria can help simplify the alternative comparison process, such as by allowing teams to attach simple weight values to stand for the importance of given criteria. After deciding the desired selection criteria and weighting factors, alternative total scores can be found and used to compare alternatives. Given a set of weighting factors, this method of comparing alternatives has the benefit of permitting stakeholders to use the weights to explicitly rank components of analysis in order of priority. This ranking is then reflected in a single score for comparison. An analyst may then summarize a complex scenario in a single term, taking care to present this in the context of the chosen weighting factors.

Using a singular value to support alternative analysis, especially in a complex environment such as HVU self-escort against UxS threats, is not without its drawbacks. Parameters not critical to the decision-maker or having little effect on the desired end outcome can mask the true effectiveness or lack thereof of a given alternative (Greco 2005). Too many variables or too complex of a comparison method can also lead to decision makers seeing the value as a sort of “black box” output and reduce their trust in the score (2005). The weighting values being subjective can lead to potentially misinformed decisions and do not carry the same weight that objective MOEs may carry,

despite the underlying calculation of the final score often incorporating these objective measures (Kossiakoff et al. 2020).

2. Weighted Score Criteria

The scoring criteria for simulation results incorporate normalized scores that consider two selection criteria: the number of HVU intercepts across all runs and the final breached priority zone of each UxS threat. These criteria enable a comprehensive assessment of the simulation outcomes and prioritize the impact of threats based on their proximity to the HVU. A list of variables for the weighted score definition is in Table 15. The weighted score definition incorporates user defined variables that support prioritization based on range to the threat and intercept of the HVU. Unitless scaling factors are used to normalize the results for each variable so that the weighting factor defined by the user is driving the relative importance of simulation results, rather than being influenced by some function of the output data (Greco 2005).

Table 15. Weighted Score Variable Definitions (Unitless)

Source	Variable	Definition
Model Input	F_{Total}	Total number of runs
	$N_{TotalHostiles}$	Total number of hostiles
Model Output	F_{NoInt}	Runs with no HVU intercept
	$N_{AvgHostilePri[X]}$	Average number of hostiles entering Priority X Zone, where X is 1, 2, or 3
Analysis Input	S_{Int}	Intercept scaling factor
	S_{Pri}	Priority Zone entrance scaling factor
	W_{Int}	Intercept scoring weighting factor
	$W_{Pri[X]}$	Priority X Zone scoring weighting factor, where X is 1, 2, or 3

Given the variables defined in Table 15, the following formula supplies the weighted score of the scenario:

$$\text{Weighted Score} = \frac{F_{NoInt} S_{Int} W_{Int}}{F_{Total}} + S_{Pri} N_{TotalHostiles} \begin{bmatrix} W_{Pri1} & W_{Pri2} & W_{Pri3} \end{bmatrix} \begin{bmatrix} N_{AvgHostilePri1}^{-1} \\ N_{AvgHostilePri2}^{-1} \\ N_{AvgHostilePri3}^{-1} \end{bmatrix}$$

In a restricted movement scenario such as a harbor transit, a C-UxS capability tasked with protection of an HVU must reduce the threat of a direct intercept while also considering the risks of potentially hostile actors getting within certain distances of the HVU under protection. In the context of this analysis, this results in four separate areas for consideration: intercept of the HVU, the Priority 1 Zone, the Priority 2 Zone, and the Priority 3 Zone. For the purposes of the analysis conducted in this paper, the Priority 1 Zone is 0.7 nautical miles from the HVU, the Priority 2 Zone is 1.5 nautical miles from the HVU, and Priority 3 Zone is 3.0 nautical miles from the HVU. These ranges are set to notional values for demonstration purposes.

Weighting factors are applied to each of the four areas and can be defined to reflect the desired priority for their respective area. For example, if the analysis is intended to reflect a higher priority for the Priority 1 Zone, meaning that a simulation that includes threats arriving at this zone results should return a relatively lower weighted score, then the value associated with the Priority 1 Zone weighting factor (W_{Pri1}) should be relatively higher than other weighting factors. This may be the case if it is important to consider the enhanced risk that a hostile actor might pose outside of a direct intercept at such a close distance, ranging from EW to interruptions in mission critical operations.

The weighted score includes two parts, one which addresses intercepts with the HVU and the other which addresses the Priority Zones. Scaling factors are applied to each part to support normalizing the score components.

This system arrives at normalized weighted scores usable for comparing the effectiveness of different C-UxS capabilities in a highly dynamic environment, presuming that all alternatives are simulated with the same baseline threat group. A set of scripts developed in Python aid in the execution of this analysis and supply the ability to quickly conduct quality control, such as by outputting the number of hostile agents in

each set of runs and supplying additional outputs that may point to inconsistencies in simulation runs. Scripts in support of this analysis are in Appendix C.

3. Limitations and Assumptions

The weighted score focuses on operational MOEs in the context of an HVU self-escort scenario. Interpretation of the weighted scores means a direct comparison between weighted scores of alternatives and the baseline, assessing their operational effectiveness in this scenario. Consequently, there are constraints on what is accounted for, as the weighted scoring formula focuses on the ability for a system to prevent HVU intercepts from occurring as well as its ability to deny hostile agents' proximity-based access to the HVU. For example, if a given alternative has a weighted score of 30 and a second alternative has a weighted score of 60, the second alternative can be said to have twice the ability to prevent HVU intercept and deny hostile access to priority zones around the HVU in the self-escort scenario.

The applicability of the weighted score as a direct comparison between alternatives diminishes if there are other operational characteristics desired to be considered. If a decision maker wants to consider factors such as communications reliability during operations or operational resources consumed, the proposed weighted scoring would have reduced effectiveness since these factors are not directly accounted for. There are other factors that are important to consider when comparing alternatives, such as space required, weight, power, and cost, and thus the weighted score should be a factor in an overarching analysis of alternatives. Future work should evaluate incorporation of these other factors into the weighted scoring framework to function as a more comprehensive decision-making tool.

D. MODEL VERIFICATION

Model verification supports consistent analysis for the comparison of multiple C-UxS capabilities. The MAST models developed play a central role in analyzing the impact and effectiveness of potential C-UxS capabilities on impending UxS swarm threats to HVUs in restricted maneuvering. To ensure the credibility and accuracy of the model's results, verification processes were undertaken. Table 16 lists the user defined

values defined in Table 15 for model verification as well as for the hypothetical case study analysis conducted in Chapter V.

Table 16. Verification Values for User-Defined Variables (Unitless)

Variable	Definition	Value
F_{Total}	Total number of runs	100
$N_{TotalHostiles}$	Total number of hostiles	4
S_{Int}	Intercept scaling factor	100
S_{Pri}	Priority Zone entrance scaling factor	10
W_{Int}	Intercept scoring weighting factor	0.7
W_{Pri1}	Priority 1 Zone scoring weighting factor	0.15
W_{Pri2}	Priority 2 Zone scoring weighting factor	0.10
W_{Pri3}	Priority 3 Zone scoring weighting factor	0.05

Model verification is intended to verify that model parameters have the expected effect on the simulation results. Verification of model behavior is performed by taking certain input parameters running these at extreme possible values, rather than realistic values, over multiple runs. The impact of the weighted score is then assessed as either expected or unexpected. The assessment is based on assuming all other parameters are unchanged, would one reasonably expect an improvement or reduction in performance as a parameter is altered. Table 17 and Table 18 summarize the results from model verification.

Table 17. Model Verification Results, RamJammer Alternative

Parameter	Units	Value	Weighted Score (unitless)	Expected / Not Expected
C-UxS Radar Range	Miles	1	5.936	Expected
		8	36.346	Expected
Number of Rammers	Unitless	1	16.04	Expected
		10	55.49	Expected
Engagement Authorized Priority Zone	Unitless	Priority 1	28.24	Expected
		Priority 3	66.96	Expected

Table 18. Model Verification Results, Echo/Inyx Alternative

Parameter	Units	Value	Weighted Score (unitless)	Expected / Not Expected
Distance Inyx to Orbit HVU	Meters	500	73.18	Expected
		4500	46.95	Expected
Echo Failsafe Jammer Range	Miles	0.1	16.76	Expected
		2	79.89	Expected
Number of Inyx USVs	Unitless	1	57.75	Expected
		5	71.96	Expected

Running the case study alternatives with extreme variable inputs results in expected impacts on the final weighted score. For example, if a C-UxS system can identify or engage threats earlier, it is expected to score higher. This is reflected across several of the verification model runs, including the RamJammer C-UxS Radar Range and the Echo Distance Inyx to Orbit HVU. As discussed in earlier chapters, a key component of any C-UxS system is the ability to sense potential threats early, and that behavior is reflected in the modeling scoring.

E. METHODOLOGY LIMITATIONS

The methodology proposed is not without limitations, and understanding these limitations is key for effective application of the findings. First, comparison of multiple

alternatives requires that each alternative is evaluated against the same baseline threat scenario. For example, if the baseline threat scenario is two hostile UASs and four hostile USVs, all alternatives must be assessed against this same threat profile. Comparison against different threat scenarios may lead to misleading conclusions, or a representation of a capability that is not comparable against other alternatives.

Second, this methodology focuses on operational capability in the context of a HVU self-escort scenario. The scoring system proposed does not account for other comparison metrics such as cost, space, weight, or power. The final weighted score of alternatives should be one metric utilized in a holistic comparison of alternatives to ensure that decision makers are informed of every facet of the alternatives under analysis.

Third, the emphasis on the HVU self-escort scenario against UxS threats may make the methodology less relevant in diverse operational scenarios. The weighted score proposed places significance on HVU intercept as well as proximity of hostile agents to the HVU. It does not currently assess other operational parameters and, as such, caution should be used if a different operational scenario is assessed.

F. SUMMARY OF CHAPTER

This chapter applies the systems architecture developed in Chapter III to a modeling and simulation application in support of capability-based analyses. It sets up a state-machine based method for C-UxS simulation, discusses how this method is applied in MAST, and executes verification of the tool. The simulation defines agent types that represent core components of the mission scenario, including the HVU, threat UxS, and C-UxS system components, and implements state-machines that model asset behavior. To support capability comparison and trades analyses, the project proposes a weighted scoring model that uses a range-based defense profile to rank capability alternatives. The hypothetical “Echo/Inyx” and “RamJammer” alternatives defined in Chapter III are used as exemplars for defining state-machine composition. Model verification is performed by defining a baseline scenario set in the port of Hampton Roads, Virginia, and using the specified alternatives to examine the impact of extreme subsystem parameter settings on the weighted score.

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V. CASE STUDY

This chapter presents analysis of a hypothetical case study for applying C-UxS capabilities in support of HVU self-escort. All analysis in this chapter uses conceptual data and is for demonstration purposes. This analysis has the following purposes:

- It simulates the threat and countermeasures in a realistic scenario by using geographic maps, cut-out zones, and logic to model a given operational environment.
- It outputs data on HVU survival statistics to support analysis of effectiveness of countermeasures investigated.
- It calculates a weighted score to normalize comparing C-UxS capabilities when using a common baseline scenario.
- It supplies a hypothetical case study to show how application of MAST can effectively support analyses for C-UxS in HVU self-escort scenarios.

To accomplish these purposes, this chapter supplies an evaluation focused on the two hypothetical alternative solution sets outlined in Chapter III and summarized in Table 19. These conceptual alternatives illustrate applicability of the MAST simulation to C-UxS capability analysis, and use the functional architecture derived in Chapter III to show traceability to the baseline mission scenario. The alternatives defined here are conceptual and the metrics associated with them do not represent any actual capability.

Table 19. Hypothetical C-UxS System Alternatives

ID	Name	Platforms	Sensors	Mitigators
1	Echo/Inyx	Aerostat USVs Base Station	<u>Aerostat</u> : RF, EO/IR <u>Base Station</u> : Radar <u>USVs</u> : RF, Radar	<u>Aerostat</u> : RF/GNSS Jamming <u>USVs</u> : RF/GNSS Jamming
2	RamJammer	EW UASs Kinetic UASs Base Station	<u>EW UASs</u> : RF, EO/IR <u>Kinetic UASs</u> : EO/IR <u>Base Station</u> : Radar	<u>EW UASs</u> : RF/GNSS Jamming/Spoofing <u>Kinetic UASs</u> : Collision UAS (Ramming)

The chapter sequencing is as follows. First, the DOE is described. Second, a discussion of the scenario results and analysis supplies insight into the outcome and impact of the C-UxS capabilities. Finally, this chapter supplies a summary of conclusions from the simulation results and post-simulation analysis.

This chapter implements the weighted scoring methodology described in Chapter IV as a way of comparing alternatives and showing the impact of different alternative compositions. The values for the weighted scores and other baseline scenario inputs are defined in Table 20. The weight assignments here represent a user who is primarily concerned with avoiding threat intercept of the HVU, resulting in a W_{Int} value of 0.7. The Priority Zone weights reflect an order of priority where threats closest to the HVU are the most concerning, resulting in 0.15 for W_{Pri1} , 0.10 for W_{Pri2} , and 0.05 for W_{Pri3} , standing respectively for the Priority 1, Priority 2, and Priority 3 Zones. The sum of all the weighting factors is equal to one.

Table 20. User-Defined Variables for Case Study Analysis (Unitless)

Variable	Definition	Value
F_{Total}	Total number of runs	100
$N_{TotalHostiles}$	Total number of hostiles	4
S_{Int}	Intercept scaling factor	100
S_{Pri}	Priority Zone entrance scaling factor	10
W_{Int}	Intercept scoring weighting factor	0.7
W_{Pri1}	Priority 1 Zone scoring weighting factor	0.15
W_{Pri2}	Priority 2 Zone scoring weighting factor	0.10
W_{Pri3}	Priority 3 Zone scoring weighting factor	0.05

All analysis discussed here is in the context of these weights and the user priorities reflected by these weights. If the user priorities change, then any analysis using the tools presented here will need to implement different weighting factors to reflect the new priorities. Weights reflect the relative priority assigned to each priority zone and the intercept region. For example, if a user wishes to prioritize each area equally, then the weighting factors should each equal 0.25 so that all four have equal value and sum together to equal one.

As discussed in Chapter IV, this analysis implements a model that simulates UxS swarms seeking to intercept an HVU. The simulation is completed upon HVU intercept. Throughout this chapter, survival of the HVU is used to refer to cases where the threat UxS does not intercept the HVU.

A. DESIGN OF EXPERIMENTS

A full factorial DOE is employed to explore the effects of five variables per scenario, resulting in a set of 32 (or 2^5) combinations. To account for the inherent uncertainties and variations in the simulation, this analysis implements a Monte Carlo experiment using 100 iterations for each factor and level combination, resulting in 3,200 total iterations for each alternative. A limitation to the number of iterations is the

computational resources required to execute the model. Future work should revisit options within the simulation software that may decrease model run times as updates to the software are developed.

The main objective of the analysis is to assess the effectiveness of different alternatives compared against each other using a normalized weighted score. The full factorial design supports achieving this objective by allowing control for potential confounding variables and isolating the true effects of the variables of interest.

Table 21 and Table 22 define the factors for DOE analysis as well as the lower and upper levels used based on sensitivity analysis of each variable discussed in Chapter IV.

Table 21. DOE Factors and Levels (Echo/Inyx)

Variable	Units	Low	High
Inyx Orbit Distance	Meters	250	1400
Inyx Speed	Knots	10	35
Inyx Number of Units	Integer	2	8
Inyx Radar Range	Nautical Miles	0.5	5.0
Echo Failsafe Jam Range	Statute Miles	0.5	3.0

Table 22. DOE Factors and Levels (RamJammer)

Variable	Units	Low	High
Priority Zone Engaged	Integer	3	1
C-UxS Base Radar Range	Kilometers	1.0	5.0
C-UxS Base Radar Scan Rate	Seconds	0.1	5.0
Number of Rammers	Integer	3	10
Number of Jammers	Integer	1	10

Data processing is conducted through Python scripts that supports summarizing relevant data for analysis. Scripts utilized in support of this analysis are shown in

Appendix C. Model verification as discussed in Chapter IV supports fine tuning of the experimental procedures and verifying model logic for accuracy and consistency.

B. SCENARIO RESULTS AND ANALYSIS

The DOE analysis employs a full factorial regression to evaluate the impact of various system variables on the study results. This method allows for a systematic exploration of all possible combinations of the chosen variables, enabling a comprehensive understanding of how each factor influences the outcomes. Using the full factorial regression considers each significant system variable at multiple levels, ensuring a broad coverage of the parameter space. This supports identifying main effects and interactions between different variables and supplies valuable insights into the complex relationships among the variables.

The regression analysis quantifies the effects of each system variable on the study's results by fitting the data to a regression model, making it possible to determine the magnitude and direction of the impact that each variable has on the observed outcome. The results supply insight for discerning which variables are most influential in driving the variations in the results. Additionally, the full factorial regression approach enables analysis of statistically significant relationships between the system variables and the study's response variables. This supplies a robust basis for drawing meaningful conclusions and making informed decisions based on the empirical evidence generated during the experiment.

The following sections cover the output and analysis of results for each scenario. Each alternative is evaluated against an incoming swarm of four hostile UAS agents in the Hampton Roads scenario described in Chapter IV. An initial simulation of the baseline scenario supports a comparison between each C-UxS alternative against a baseline with no C-UxS capability. Table 23 supplies the output results from this baseline scenario based on 500 runs of the simulation.

Table 23. Analysis Output Results, Baseline Scenario

Result Parameter	Value (unit)
Average Time for Hostile UxS to Enter Priority 1 Zone	334.65 seconds
Average Time for Hostile UxS to Enter Priority 2 Zone	299.66 seconds
Average Time for Hostile UxS to Enter Priority 3 Zone	224.88 seconds
Average Number of Hostile UxS Agents to Enter Priority 1 Zone	1.31 Agents
Average Number of Hostile UxS Agents to Enter Priority 2 Zone	1.75 Agents
Average Number of Hostile UxS Agents to Enter Priority 3 Zone	2.54 Agents
Average Time to HVU Intercept (When the HVU is intercepted)	363.88 seconds
Percent of Runs with No HVU Intercept	0%
Average Weighted Score Across All Runs (Higher is Better)	7.65

As expected, the baseline scenario with no C-UxS solution results in the HVU being intercepted in every run. While the average number of agents entering the various priority zones may appear low, this can easily be explained by the understanding that without any countermeasures the first hostile UxS to reach the HVU will result in an HVU intercept and immediately terminate the simulation. This is shown through the comparatively low average time to HVU intercept, which is nearly half of the average time assessed in the following C-UxS alternatives.

Throughout this chapter, Pareto chart outputs from Minitab are used to visualize the effect of different variables and variable combinations on dependent variables such as the weighted score or average time to HVU intercept. Pareto charts show the standardized effect of each variable and variable combination in terms of a t-statistic that tests the null hypothesis that the effect is zero. A vertical line on each chart indicates results that exceed a level of significance of 0.05, meaning that there is a five percent or less probability that variables with standardized effects that cross this line have no impact on

the response. Any variables that result in an effect greater than the statistically significant line can be said to be statistically significant (Minitab 2023).

1. Echo/Inyx

Table 24 supplies the average results for dependent variables for the Echo/Inyx C-UxS alternative. The results are averaged across all 3,200 simulation runs in support of the analysis DOE.

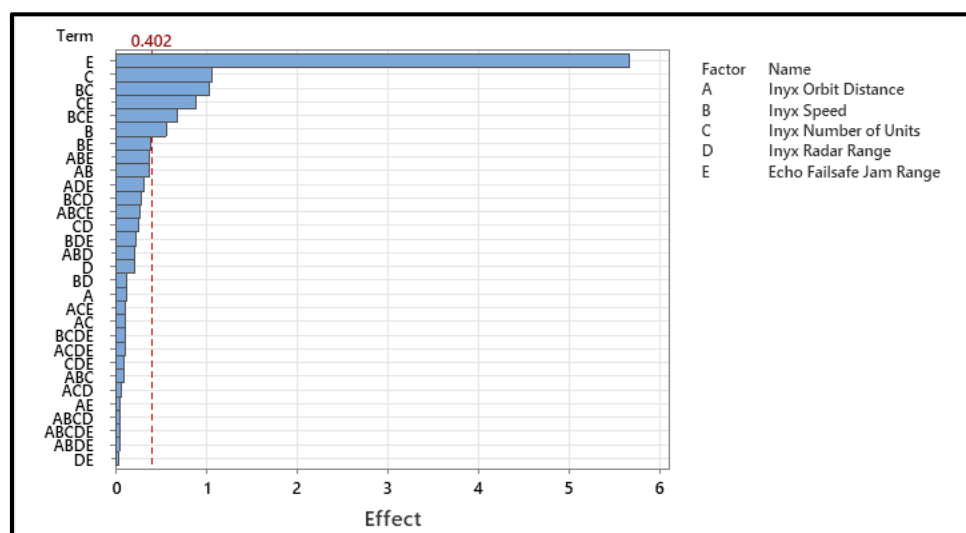
Table 24. Analysis Output Results, “Echo/Inyx” Alternative

Result Parameter	Value (unit)
Average Time for Hostile UxS to Enter Priority 1 Zone	318 seconds
Average Time for Hostile UxS to Enter Priority 2 Zone	223.03 seconds
Average Time for Hostile UxS to Enter Priority 3 Zone	295.43 seconds
Average Number of Hostile UxS Agents to Enter Priority 1 Zone	1.17 Agents
Average Number of Hostile UxS Agents to Enter Priority 2 Zone	1.76 Agents
Average Number of Hostile UxS Agents to Enter Priority 3 Zone	4 Agents
Average Time to HVU Intercept (When the HVU is intercepted)	617.25 seconds
Percent of Runs with No HVU Intercept	99.63%
Average Weighted Score Across All Runs (Higher is Better)	77.32

Based on the raw average data output, the impact of a C-UxS capability is significant. Using the Echo/Inyx C-UxS alternative, the HVU can avoid intercept 99.63% of the time, compared to 0% when no C-UxS alternative is used. While the number of agents entering the Priority 3 Zone is higher than the baseline scenario, this is due to the simulation being able to fully complete due to not having any HVU intercepts. Many of the parameters of the Echo/Inyx alternative achieve an effect in the Priority 3 Zone. Interpretation of the average weighted score leads to the conclusion that in the HVU self-

escort scenario, with emphasis placed on odds of HVU intercept as well as denial of entering range-based proximity rings around the HVU, the Echo/Inyx alternative is ten times more operationally effective compared to the baseline.

The findings from the Echo/Inyx full factorial regression show the significance of the Echo Failsafe Jam Range exerting the most significant impact on the weighted score results. As shown in Figure 26, this influences the outcome of the simulation by over five times that of other variables and variable combinations.

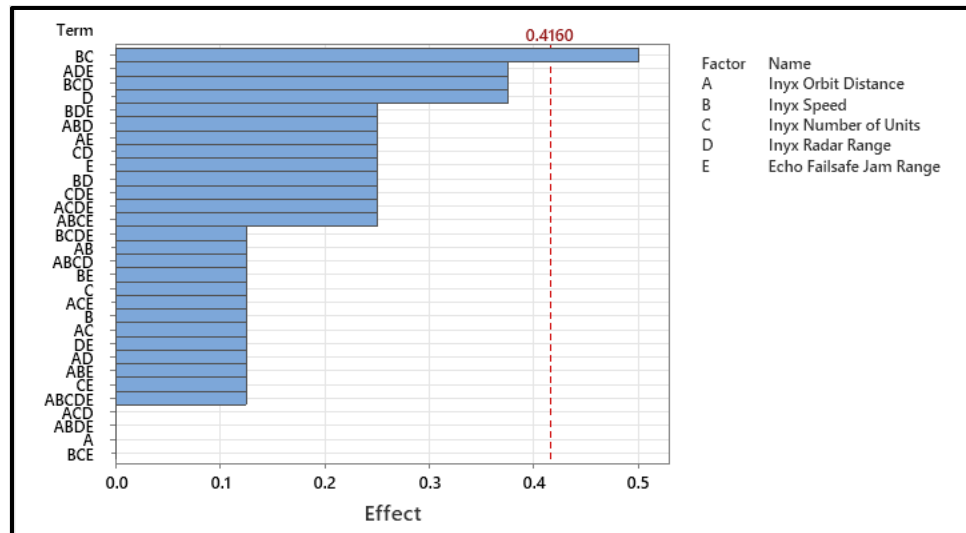


This figure shows the standardized effects for variables and variable combinations in the DOE that affect the calculated weighted score. The standardized effect is a t-statistic that tests the null hypothesis that the effect is zero. A vertical line on the figure indicates the variables with a standardized effect that exceeds 0.402, resulting in a five percent or less probability that these variables have no impact on the response. Individual variables that meet this criterion are Echo Failsafe Jam Range; Inyx Number of Units; and Inyx Speed. In order of magnitude of response, significant variables and variable combinations in the figure are Echo Failsafe Jam Range; Inyx Number of Units; a combination of Inyx Speed and Inyx Number of Units; a combination of Inyx Number of Units and Echo Failsafe Jam Range; a combination of all three variables that meet the criterion; and Inyx Speed.

Figure 26. Echo/Inyx Pareto Chart of Effects, Weighted Score Response

Despite other variables and combinations supplying relatively smaller effects on overall weighted score when compared to Echo Failsafe Jam Range, understanding the interplay of these variables is essential for a comprehensive analysis of the system's performance. Following the most significant variable, combinations of Inyx Speed,

Number of Inyx Units, and Echo Failsafe Jam Range supply the next greatest effect on the overall weighted score results. Figure 27 extends this to the percent of runs where the HVU is not intercepted by a threat, here shown as the probability of HVU survival, and shows how a combination of Inyx Speed and the Number of Inyx Units supplies the most significant effect on this response.



This figure shows the standardized effects for variables and variable combinations in the DOE that affect the probability of HVU non-intercept, defined as probability of HVU survival. The standardized effect is a t-statistic that tests the null hypothesis that the effect is zero. A vertical line on the figure indicates the variable combination with a standardized effect that exceeds 0.4160, resulting in a five percent or less probability that this variable combination has no impact on the response. Of the variables tested, only a combination of Inyx Speed and Inyx Number of Units meets this criterion.

Figure 27. Echo/Inyx Pareto Chart of Effects, Estimated Probability of HVU Survival Response

2. RamJammer

Table 25 supplies the average results for dependent variables for the RamJammer C-UxS alternative. The results are averaged across all 3,200 simulation runs in support of the analysis DOE.

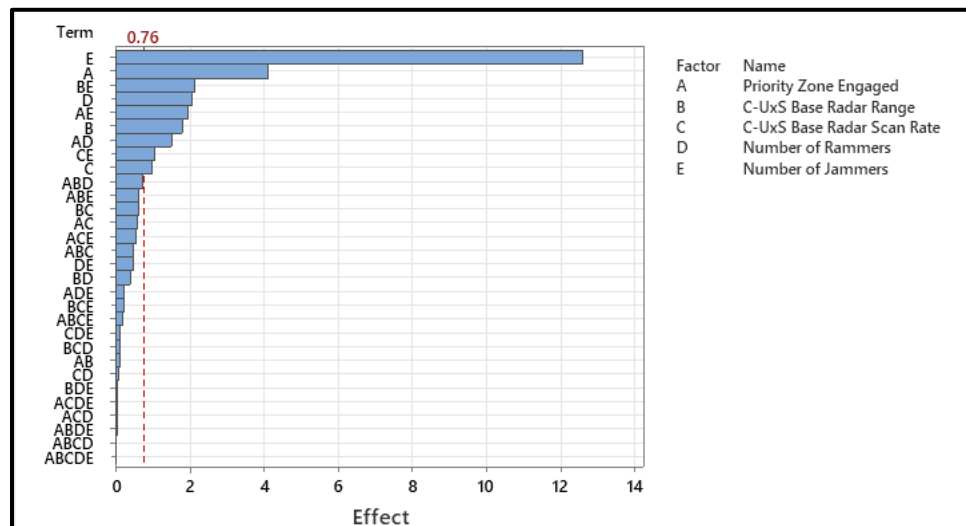
Table 25. Analysis Output Results, “RamJammer” Alternative

Result Parameter	Value (unit)
Average Time for Hostile UxS to Enter Priority 1 Zone	500.17 seconds
Average Time for Hostile UxS to Enter Priority 2 Zone	384.92 seconds
Average Time for Hostile UxS to Enter Priority 3 Zone	277.89 seconds
Average Number of Hostile UxS Agents to Enter Priority 1 Zone	1.98 Agents
Average Number of Hostile UxS Agents to Enter Priority 2 Zone	3.19 Agents
Average Number of Hostile UxS Agents to Enter Priority 3 Zone	3.64 Agents
Average Time to HVU Intercept (When the HVU is intercepted)	567.39 seconds
Percent of Runs with No HVU Intercept	35.34%
Average Weighted Score Across All Runs (Higher is Better)	29.87

RamJammer performs better than the baseline but struggles to meaningfully compete against the Echo/Inyx alternative. RamJammer results in more hostile agents entering all priority zones except for the Priority 3 Zone, only has 35.35% of runs with no HVU intercept compared to the 99.63% of Echo/Inyx and has a weighted score of only 29.87 compared to Echo/Inyx’s 77.32. Interpreting the average weighted score means that while the RamJammer alternative is approximately four times more operationally effective compared to the baseline, it is approximately two and a half times less operational effective compared to Echo/Inyx.

Like Echo/Inyx, the RamJammer system exhibits a single most significant variable, specifically the number of jammers deployed, greatly influencing overall weighted score. As clearly shown in Figure 28, the number of jammers has a profound impact on the system's effectiveness. This supports that the jammers are the most effective method for the RamJammer alternative to counter UxS threats. Beyond the number of jammers, another variable that affects the RamJammer system's effectiveness is the Priority Zone engaged with Rammers. Although its impact is approximately one-

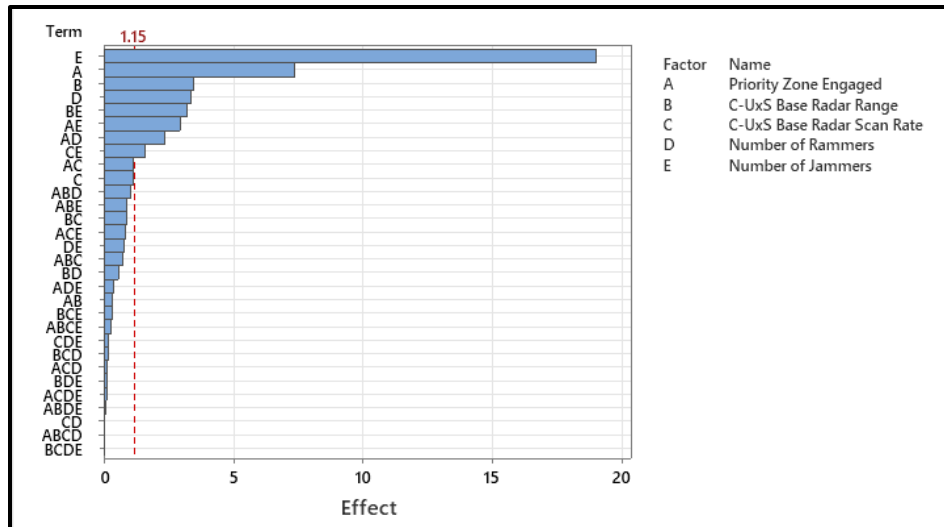
third as influential as the number of jammers, it is still significant when compared to other variables or combinations. All other variables and variable combinations are approximately 50% or less effective than this variable. The effects of all variables and combinations on the weighted score can be seen in Figure 28.



This figure shows the standardized effects for variables and variable combinations in the DOE that affect the calculated weighted score. The standardized effect is a t-statistic that tests the null hypothesis that the effect is zero. A vertical line on the figure indicates the variables with a standardized effect that exceeds 0.76, resulting in a five percent or less probability that these variables have no impact on the response. All five variables tested individually meet this criterion. In order of magnitude of response, significant variables and variable combinations in the figure are Number of Jammers; Priority Zone Engaged; a combination of C-UxS Base Radar Range and Number of Jammers; Number of Rammers; a combination of Priority Zone Engaged and Number of Jammers; C-UxS Base Radar Range; a combination of Priority Zone Engaged and Number of Rammers; a combination of C-UxS Base Radar Scan Rate and Number of Jammers; and C-UxS Base Radar Scan Rate.

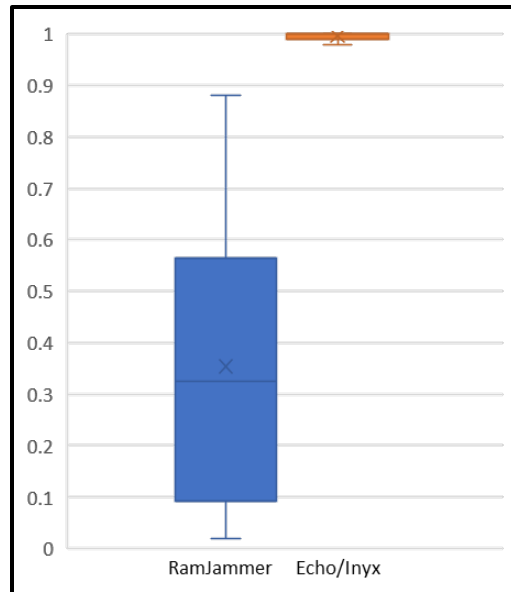
Figure 28. RamJammer Pareto Chart of Effects, Weighted Score Response

Unlike Echo/Inyx, RamJammer yields highly variable results for probability of HVU survival with a couple of experiments resulting in about 80 percent probability, and all other runs falling equally between zero and 60 percent probability. Due to this result, the effectiveness of variables on likelihood of HVU survival nearly mirrors the impact on overall weighted score, as captured in Figure 29. Figure 30 shows the distribution of the probability of HVU survival for both the RamJammer and Echo/Inyx alternatives.



This figure shows the standardized effects for variables and variable combinations in the DOE that affect the probability of HVU non-intercept, defined as the probability of HVU survival. The standardized effect is a t-statistic that tests the null hypothesis that the effect is zero. A vertical line on the figure indicates the variables with a standardized effect that exceeds 1.15, resulting in a five percent or less probability that these variables have no impact on the response. Individual variables that meet this criterion are Number of Jammers; Priority Zone Engaged; C-UxS Base Radar Range; and Number of Rammers. In order of magnitude of response, significant variables and variable combinations in the figure are Number of Jammers; Priority Zone Engaged; C-UxS Base Radar Range; Number of Rammers; a combination of C-UxS Base Radar Range and Number of Jammers; a combination of Priority Zone Engaged and Number of Jammers; a combination of Priority Zone Engaged and Number of Rammers; and a combination of C-UxS Base Radar Scan Rate and Number of Jammers.

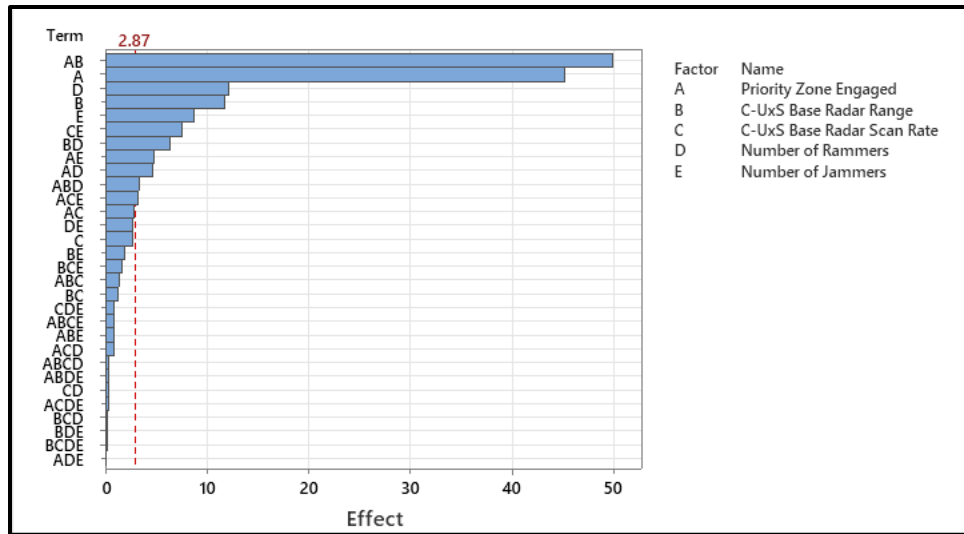
Figure 29. RamJammer Pareto Chart of Effects, Probability of HVU Survival Response



This figure shows the distribution of the probability of HVU survival for both the RamJammer and Echo/Inyx alternatives across all 32 combinations of factors and levels in the experiment. Probability of survival is consistently close to 100% for the Echo/Inyx alternative, which shows the utility in the simulation of a continuous EW capability. The wide variability of outcomes for the RamJammer alternative is attributable to reduced effectiveness of the kinetic capability in the simulation. Rammers account for half of the capability of the RamJammer alternative, and Number of Jammers has approximately five times greater of an effect on the probability of HVU survival than the Number of Rammers.

Figure 30. Probability of HVU Survival

Given the elevated likelihood of an HVU intercept for the RamJammer alternative, a second method of analysis is to assess the impact of the controlled variables on the time it takes for an HVU intercept to take place. When approaching analysis from this angle, Priority Zone Engaged in combination with the C-UxS Base Radar Range provide the most significant impact on the length of time the HVU can avoid intercept as seen in Figure 31. Priority Zone Engaged is not far behind in significance as an independent variable. Beyond these effects, Number of Rammers (i.e., kinetic effector) appears higher in significance when compared to other results. This shows the impact of including a kinetic capability for a defense in depth strategy to manage threats that penetrate through the initial layers of defense.



This figure shows the standardized effects for variables and variable combinations in the DOE that affect the average time to HVU intercept. The standardized effect is a t-statistic that tests the null hypothesis that the effect is zero. A vertical line on the figure indicates the variables with a standardized effect that exceeds 2.87, resulting in a five percent or less probability that these variables have no impact on the response. Of the tested variables, only C-UxS Base Radar Scan Rate does not individually meet this criterion. In order of magnitude of response, significant variables and variable combinations in the figure are a combination of Priority Zone Engaged and C-UxS Base Radar Range; Priority Zone Engaged; Number of Rammers; C-UxS Base Radar Range; Number of Jammers; a combination of C-UxS Base Radar Scan Rate and Number of Jammers; a combination of C-UxS Base Radar Range and Number of Rammers; a combination of Priority Zone Engaged and Number of Jammers; a combination of Priority Zone Engaged and Number of Rammers; a combination of Priority Zone Engaged, C-UxS Base Radar Range, and Number of Rammers; and a combination of Priority Zone Engaged, C-UxS Base Radar Scan Rate, and Number of Jammers.

Figure 31. RamJammer Pareto Chart of Effects, Average Time to HVU Intercept Response

C. DISCUSSION

This section supplies discussion for the results in this chapter. It reviews limitations and assumptions that apply to the analysis and highlights conclusions related to C-UxS alternative configuration and the utility of the weighted score.

1. Limitations and Assumptions

This analysis only addresses a subset of the potential problem space. Key limitations and assumptions that affect the analysis are listed here.

- The analysis is limited to material that is publicly releasable. The alternative C-UxS system compositions that are considered in the analysis are therefore based on publicly available information, and all data from this analysis is conceptual and for demonstration purposes. This results in an assumption that C-UxS mitigations, including kinetic and EW effectors, are effective 100 percent of the time. Use of controlled data will improve the relevance of any analysis supported by these tools. This project supplies tools that allow for input of controlled system performance data and other metrics, including sensor performance metrics, degraded system behavior modes, and potential response behaviors of the HVU.
- The MAST simulation that supports this analysis was executed on a government-supplied laptop computer. This resulted in limitations to the simulation run time, which affected the potential quality of the analysis. Future work should revisit options within the simulation software that may decrease model run times as updates to the software are developed.

2. Impact of Defense-In-Depth

The selection of the priority zone to engage a threat for a ship can have a profound impact on the effectiveness and timeliness of defense-in-depth responses. As shown in the RamJammer results, the choice of priority zone engaged influences the system's overall effectiveness, as allowing threats to enter higher priority zones will increase the density of threats near the HVU and reduce the time a C-UxS system must conduct a successful engagement. This results in a greater possibility of threats reaching the HVU. Engaging threats earlier—meaning, farther from the HVU—supports decreasing the threat density near the HVU. This increases the time available for kinetic effectors to supply a last line of defense.

These results align with expectations. For the scenario of defending HVUs from UxS swarms during restricted maneuvering, engaging earlier allows more time for defensive response, allowing more options from the C-UxS capabilities available. This

also stresses the importance of identifying potentially hostile UxS system early and far away from the HVU, as this gives the C-UxS system the most time to track and address the potential threat. Doing so helps to efficiently utilize available resources while enhancing the ship's survivability.

3. Effectiveness of Electronic and Kinetic Effectors

For likelihood of HVU survival, simulation results show distinct performance characteristics between the Echo/Inyx and RamJammer systems. In the case of Echo/Inyx, the outcomes consistently show an impressively high likelihood of HVU survival, ranging between 98% and 100%. This level of effectiveness suggests that the Echo/Inyx system excels in effectively countering potential threats and ensuring the HVU's safety in almost all tested scenarios. On the other hand, the RamJammer system shows greater variability in its simulation outcomes. While a few combinations display relatively strong results, yielding approximately 80% likelihood of HVU survival, most combinations show more diverse and less favorable results. The simulations show that the RamJammer system's effectiveness ranges widely, with some combinations resulting in HVU survival probabilities as low as 60% and even reaching near 0% in certain instances.

The contrasting performance profiles of the Echo/Inyx and RamJammer systems highlight the need for careful consideration when selecting the appropriate C-UxS solution for specific scenarios. In both scenarios, the EW solution employed supplies the greatest impact on survival rate and overall weighted scoring. The main difference is highlighted between Echo/Inyx's last line of defense (i.e., Echo Failsafe Jammer) supplying another layer of electronic warfare and resulting in a significant impact on simulation outcome, whereas RamJammer's last line of defense (i.e., kinetic Rammer capability) provided little effect in results.

4. Utility of Weighted Score for Alternative Comparison

The analysis implements a weighted score system to support comparison of alternatives in a realistic environment, accounting for scoring variables beyond just HVU intercept. All analysis presented here is in the context of the weights as defined in Table

20. If user priorities change, then any analysis using the tools presented here will need to implement different weighting factors to reflect the new priorities. This may result in different analysis outcomes.

As a summary, the baseline results in a score of 7.65, Echo/Inyx results in a score of 77.32, and RamJammer results in a score of 29.87. Using these scores, Echo/Inyx is significantly more effective as a C-UxS capability compared to RamJammer. In a complicated environment with many factors to consider, such as a restricted transit of an HVU, it can be challenging to find metrics that can sufficiently score alternatives in a way that allows for normalized comparison. The weighted scores of the two analyzed alternatives align with expected outcomes of the variables involved in calculating the weighted score. The Echo/Inyx alternative has greater success in keeping hostile UxS agents out of the Priority 1 Zone and Priority 2 Zone, which have higher weights, and has a significantly higher percentage of runs with no HVU intercept compared with the RamJammer alternative. In the context of the user priorities that define the weighting factors, the significantly higher weighted score functions as a single metric to communicate this increase in capabilities compared to other alternatives. Additionally, the weighted score aids in effectively comparing the impact of multiple variables on the operational performance of a C-UxS capability in the context of HVU self-escort, helping to identify variables that are significant in this specific mission set.

D. SUMMARY OF CHAPTER

This chapter presents a hypothetical case study application to an HVU transiting through a restricted maneuvering scenario and assessment of multiple C-UxS capabilities. Notional data supports a conceptual analysis of the relative effectiveness of C-UxS capabilities and capability compositions. A DOE is applied to alternatives developed in Chapter III and executed in MAST as discussed in Chapter IV. The resulting analysis shows how this application of MAST can effectively support analyses for C-UxS in HVU escort scenarios. The weighted scoring system discussed in Chapter IV is then applied to the result analysis and is shown as a useful single metric in comparing C-UxS alternative system capabilities.

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VI. CONCLUSIONS AND FUTURE WORK

This chapter supplies the conclusions to this project and discusses recommended areas for future research. It reviews the project's research objectives and addresses the extent to which this project fulfills the goals in the initial problem statement. Given the stated conclusions, the chapter closes by recommending areas for possible future investigation.

This project develops an analysis framework and modeling and simulation tool to explore defense of HVUs against UxSs. It does this by describing a systems architecture for C-UxS employment on an HVU, applying this systems architecture to a tailored application of MAST, and using a hypothetical case study to show how this application of MAST can support operationally relevant analyses.

Chapter I sets up the problem statement and discusses the statement of need in terms of gaps that this project fulfills and relevant stakeholders. The chapter connects the emerging threat of UxSs to the resource constraints implied by recent HVU escort guidance from the Chief of Naval Operations (Chief of Naval Operations 2020) and, given these resource constraints, discusses how this project applies recent technological developments to address the UxS threat. A literature review in Chapter II then sets up the project's baseline in terms of the state of maritime escort, the operational and technological status of UxSs and C-UxS systems, and potential applications for autonomy and AI. Chapter III then takes a mission engineering approach and describes the systems architecture for a C-UxS system integrated with an HVU. Escort of an HVU from an unprotected port to open water supplies an operationally relevant mission scenario both as the foundation for this architecture and for describing potential physical instantiations of the architecture. Chapter IV applies this systems architecture to a modeling and simulation application in support of capability-based analyses. It sets up a state-machine based method for C-UxS simulation, discusses how this method is applied in MAST, and executes verification of the tool. Chapter V then takes the method from Chapter IV and, using the alternatives described in Chapter III, applies a DOE to show a case study analysis of the relative effectiveness of the alternatives in an operational scenario.

A. CONCLUSIONS

This project supplies analysis tools and processes to support implementing a C-UxS capability in support of HVU self-escort. Using notional data, a hypothetical case study describes an HVU escort scenario and shows the relative benefit of the C-UxS self-escort capability. A DOE is applied to parameters for each alternative, supporting a Monte Carlo experiment for the impact of the parameters on a weighted score and the probability of HVU intercept. A weighted score implements weight assignments that reflect user priorities for avoiding intercept of the HVU and minimizing threat volume close to the HVU. If user priorities change, then any analysis using the tools presented here will need to implement different weighting factors to reflect the new priorities. This may result in different analysis outcomes.

When compared with a baseline scenario without a C-UxS capability and in the context of these user priorities, results from the experiment show that EW capabilities have the greatest effect on a C-UxS system's effectiveness. For both alternatives, variables related to EW capabilities have between five- and ten-times greater impact than other parameters on the weighted score. This impact carries over to comparisons between the alternatives, with the limited impact of kinetic capabilities resulting in an average probability of HVU intercept for the "Echo/Inyx" alternative approximately one third that of the "RamJammer" alternative. The correspondence between weighted score and the operational impact of the scenario, defined as HVU intercept, further demonstrates the utility of the weighted score as a single metric for distinguishing between alternatives.

B. RECOMMENDED FUTURE WORK

HVU escort scenarios, even when focused on only those that consider UxS threats, cover a wide range of potential conditions. As such, this project only addresses a small subset of the potential problem space. This section discusses examples of recommended areas for future research.

1. Incorporate Controlled and Proprietary Data

The products from this project, including the systems architecture and modeling and simulation tools, are presented using publicly available information. UxS and C-UxS capabilities are rapidly evolving areas, particularly given recent applications in the Russian War in Ukraine (Watling and Reynolds 2023), which means that even the most recent public information may be inaccurate or at best incomplete. Existing research by Hale and Van Bossuyt (2021) recommends areas of focus for C-UxS hardware and interoperability that supply potential areas of investigation using controlled data, including for, among other uses, spectrum analysis, improving probability of detection, and sensor emplacement. Use of controlled data will improve the relevance of any analysis supported by these tools. This project supplies tools that allow for input of controlled system performance data and other metrics, including sensor performance metrics, degraded system behavior modes, and potential response behaviors of the HVU.

2. HVU Escort in a Congested Environment

This project sets up a baseline architecture for implementing a C-UxS capability in support of HVU escort. One of the simplifying assumptions is that the mission scenario only includes the HVU, supporting systems, and potential threat systems. This leaves space for future work that can extend the architecture and simulation tool to other environments, including congested port environments. Congested maritime environments such as those in a port or harbor present unique challenges for HVU defense that may not occur in open water. Nearby civilian watercraft and ships from allied and partner nations open defense mechanisms to the risk of causing collateral damage, whether directly to systems or by interfering with spectrum communication requirements. Other congested environments may include maneuvering through restricted straights or through off shore energy platforms that may implement uncrewed patrol systems (Van Bossuyt et al. 2022). Future work is needed to explore how the congested physical and electro-magnetic environment affects the potential systems that may support C-UxS capability.

3. Terminal Effects and Damage Control

This project presents an analysis method that uses range to target to differentiate among alternative system compositions. Including lethality and survivability will improve the ability of the analysis to support operationally relevant trades in system-level tactics, techniques, and procedures. Future work should extend the method presented here to include gradations of terminal effects and associated operational impact, whether on the HVU or the threat UxS, and include capabilities for damage control on the HVU.

4. Application to Model-Based Systems Engineering Design Process

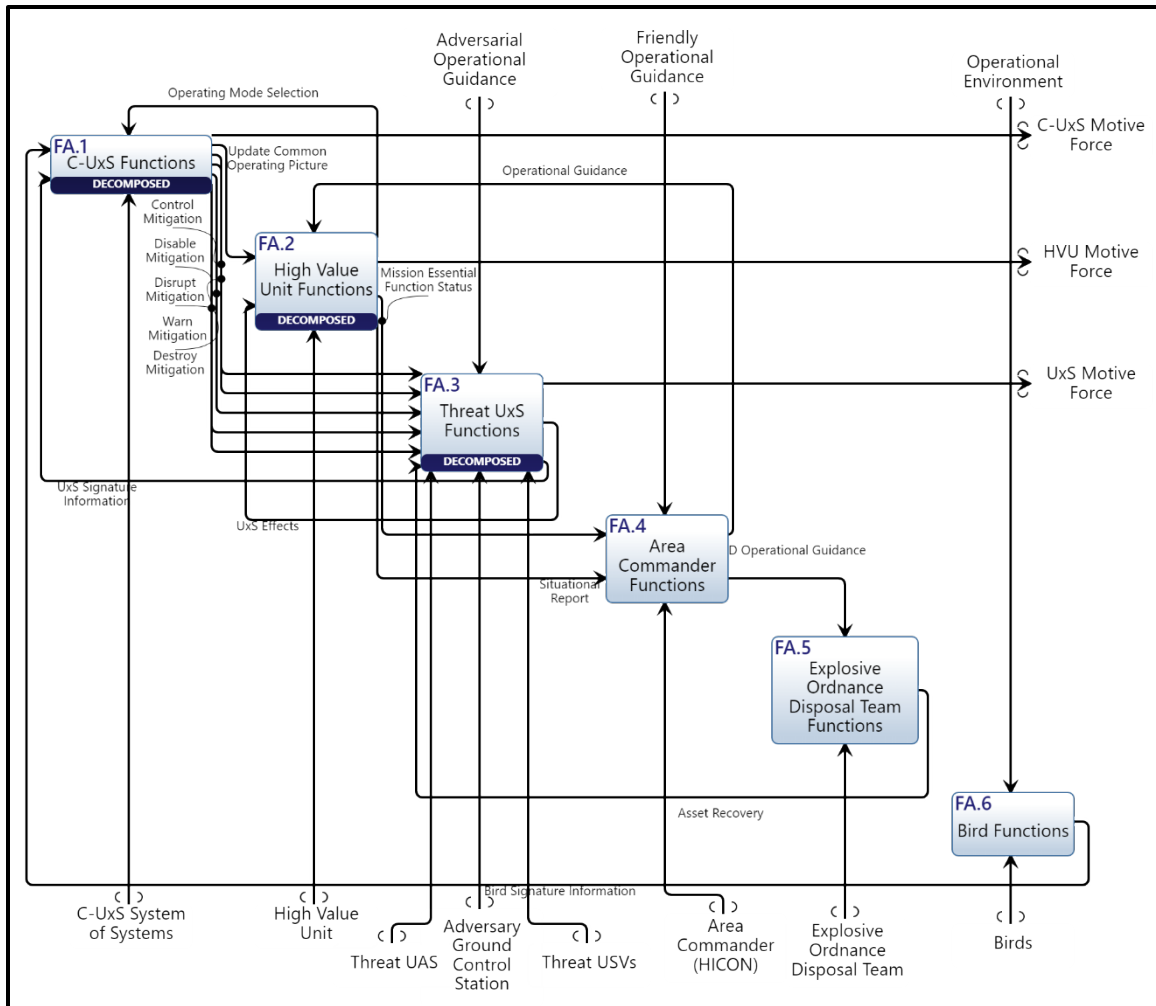
Existing research by Tan, Van Bossuyt, and Hale (2021) supplies a process for applying Model-Based Systems Engineering tools to understanding the effectiveness and limitations of counter unmanned aerial systems (C-UAS). Their process describes a systematic approach for collecting system information, determining threat definitions, assessing the state of the current system, and conducting evaluation and analysis to supply design recommendations for employing C-UAS systems (Tan, Van Bossuyt, and Hale 2021, 9). This creates an opportunity for applying modeling and simulation tools to support the required evaluation and analysis. Future work should apply the agent-based tools and scoring methods developed in this project to the analysis process described here.

5. Implementing Robust Communication Protocols

Dietz, Davis, and Hale (2023) discuss how implementation of an MLS protocol in a UAS swarm system can support asynchronous group key management and support robust response to EW attacks. Other work in this area is discussed in Britt, Leon, and Hale (2022). Future work should use the modeling and simulation tools developed for this project to implement agent-based methods for simulating an MLS protocol and associated UxS behaviors. This extension will support assessing cases where a threat UxS attempts to apply effects to the C-UxS system, for example by applying spoofing effects to one of the constituent UxSs.

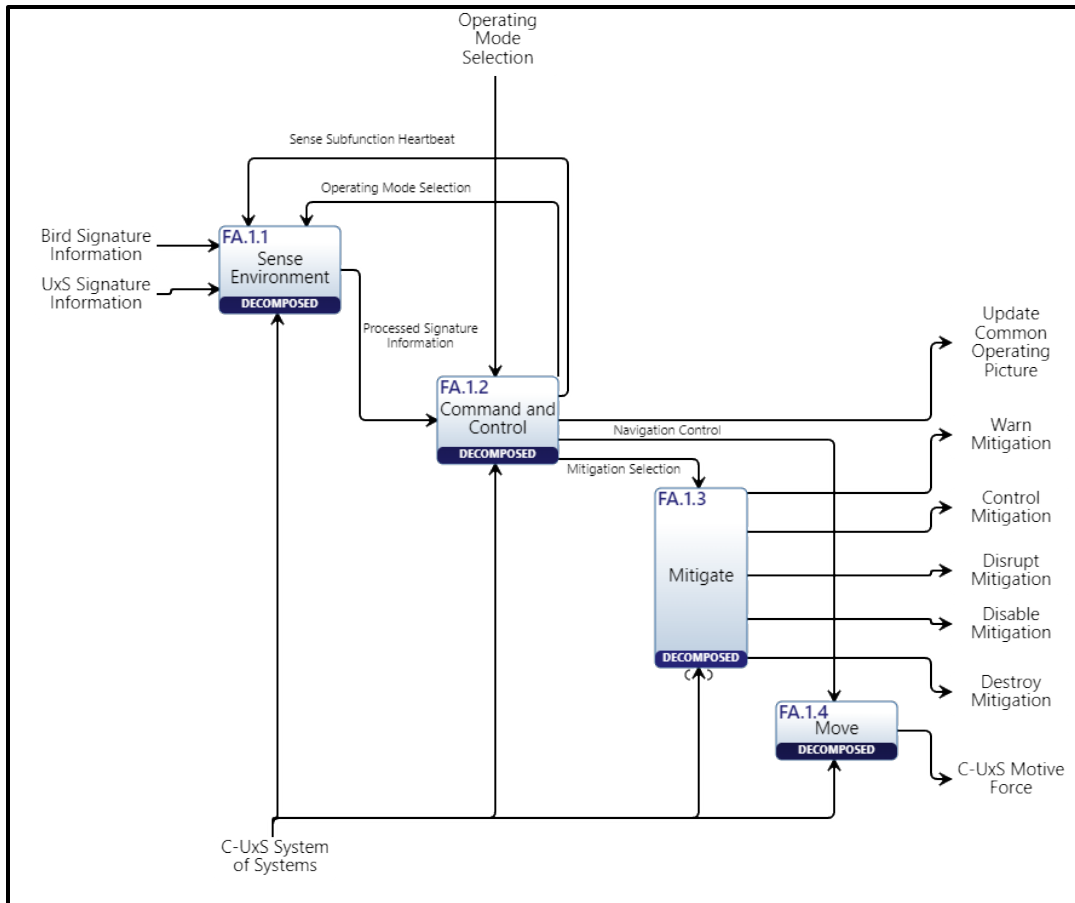
APPENDIX A. IDEF0 DIAGRAMS

This appendix includes IDEF0 diagrams (see Figure 32-Figure 41) for the HVU self-escort scenario described in Chapter 3. IDEF0 diagrams aid in setting the boundaries for the mission scenario and show relationships among the supporting hierarchical functional decompositions. In general, these illustrate how a C-UxS system achieves effect on a Threat UxS through a variety of possible mitigations. Signature information obtained from the Threat UxS or from noncombatants is received and processed by the C-UxS system to inform the choice of proper mitigation. Overall C2 for the mission scenario is provided through the Area Commander (block FA.4) which receives processed signature information from, and supplies operational guidance or action to, supporting assets. The HVU may also receive effect from the Threat UxS if the mitigations from the C-UxS system are unsuccessful.



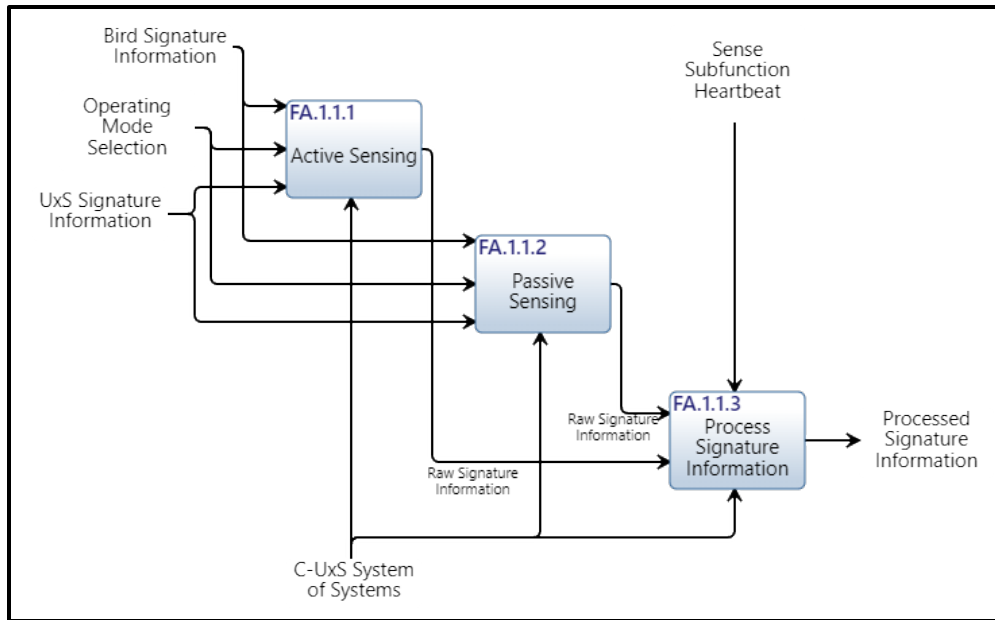
This IDEF0 diagram represents functional exchange as part of the overarching HVU self-escort mission scenario. The C-UxS system (block FA.1) achieves effect on the Threat UxS (block FA.3) through a variety of possible mitigations. Signature information obtained from the Threat UxS or from noncombatant assets such as birds (block FA.6) is received and processed by the C-UxS system to inform the choice of proper mitigation. Overall C2 for the mission scenario is provided through the HVU (block FA.2) and Area Commander (block FA.4) which receive processed signature information from, and supply operational guidance or action to, supporting assets. The HVU may also receive effect from the Threat UxS if the mitigations from the C-UxS system are unsuccessful.

Figure 32. HVU Self-Escort Operational Activity Model (OV-5b)



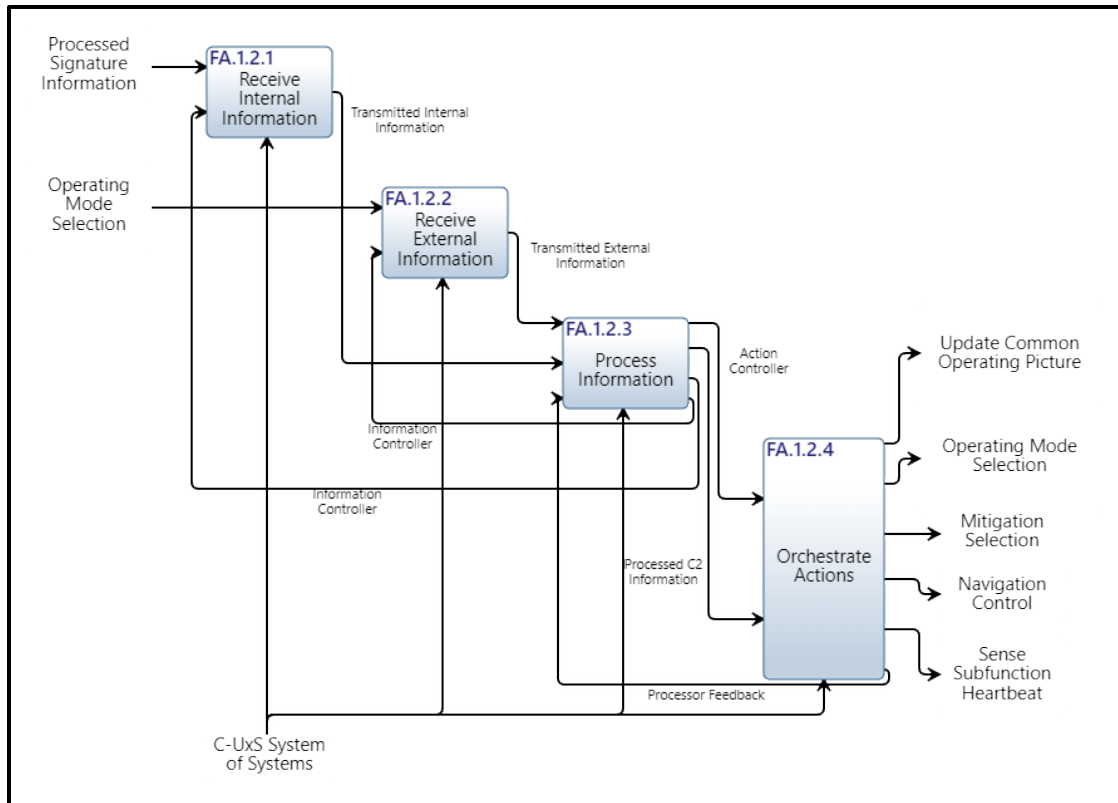
This IDEF0 diagram represents functional exchange internal to the C-UxS system as part of the HVU self-escort mission scenario. The C-UxS system performs functions to sense the environment (block FA.1.1), execute C2 (block FA.1.2), perform mitigations (block FA.1.3), and move in the environment (block FA.1.4). Signature information obtained from the Threat UxS or from noncombatant assets such as birds is received and processed by the C-UxS system to inform the choice of proper mitigation. The C-UxS system executes C2 over internal sense, mitigate, and move functions, receives guidance to update or change any operating modes, and supplies updates to an external common operating picture.

Figure 33. C-UxS Functions Operational Activity Model



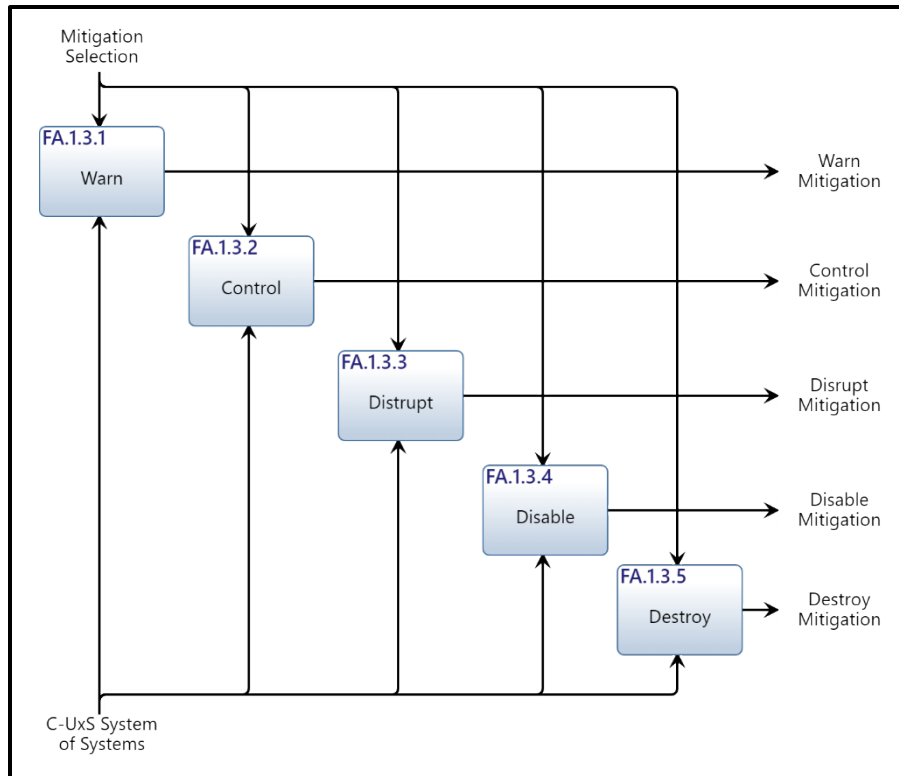
This IDEF0 diagram represents functional exchange in support of the sense subfunction of the C-UxS system. The C-UxS system executes functions for active sensing (block FA.1.1.1), passive sensing (block FA.1.1.2), and for processing signature information from the two preceding functions (block FA.1.1.3). Signature information obtained from the Threat UxS or from noncombatant assets such as birds is received through the active and passive sensing subfunctions and processed for further action. C2 function internal to the C-UxS system governs the operating mode of the sense subfunction and monitors execution through a function heartbeat.

Figure 34. C-UxS Sense Environment Operational Activity Model



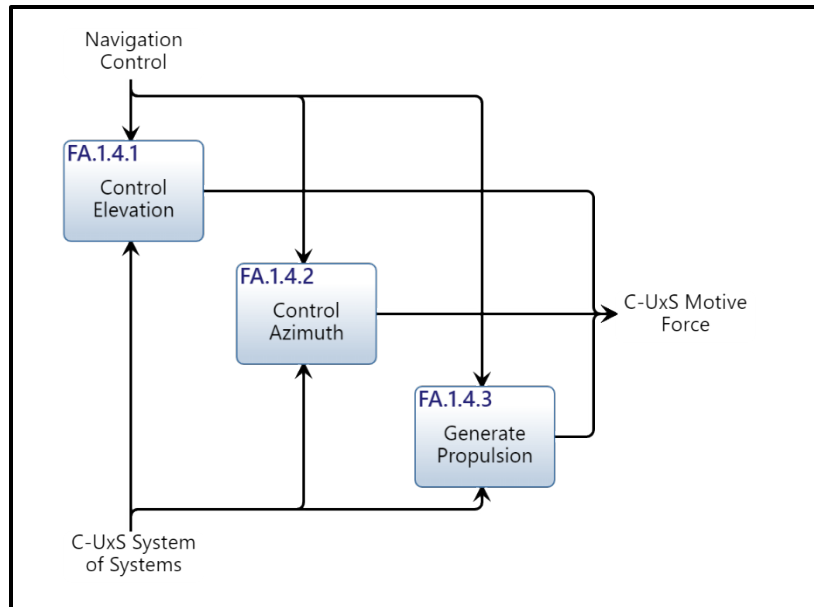
This IDEF0 diagram represents functional exchange in support of the C2 subfunction of the C-UxS system. The C-UxS system executes functions to receives internal information (block FA.1.2.1), receive external information (block FA.1.2.2), process information (block FA.1.2.3), and orchestrate internal and external actions (block FA.1.2.4). The C2 subfunction supports combining information from internal and external sources and transforming this information into updates to external activities and controls for internal functions.

Figure 35. C-UxS Command and Control Operational Activity Model



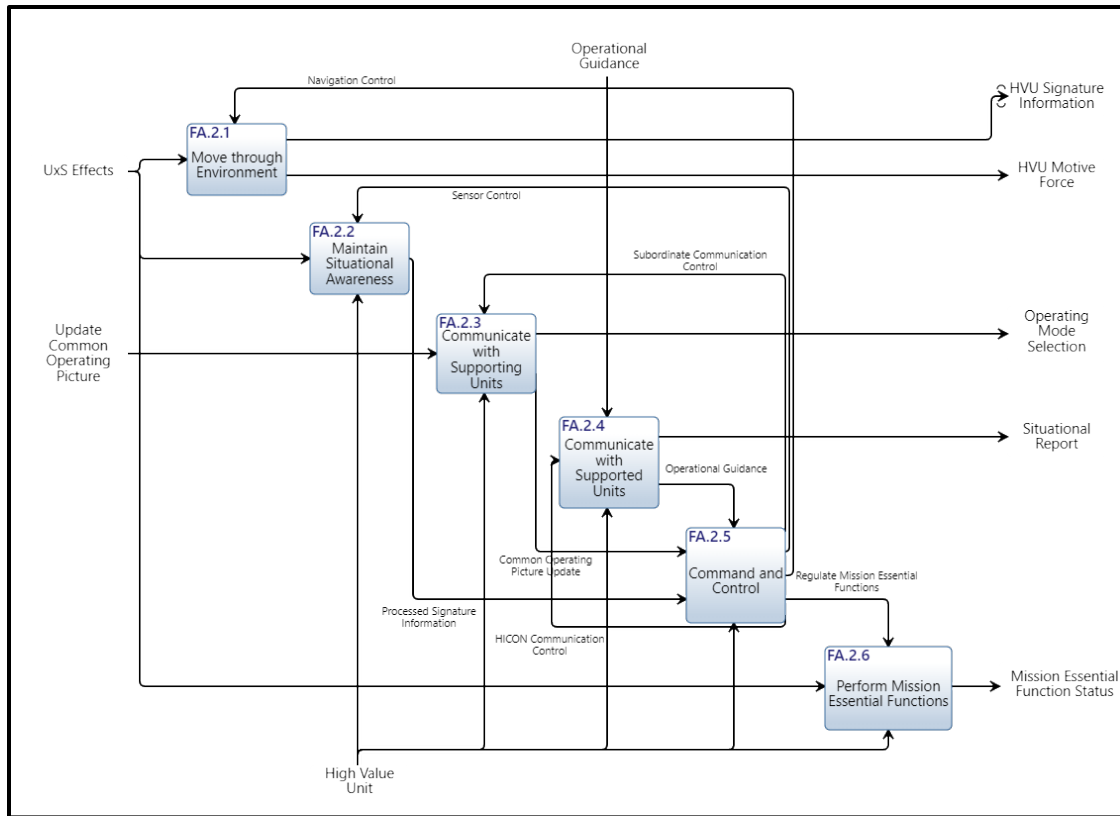
This IDEF0 diagram represents functional exchange in support of the mitigate subfunction of the C-UxS system. The C-UxS system executes functions to warn (block FA.1.3.1), control (block FA.1.3.2), disrupt (block FA.1.3.3), disable (block FA.1.3.4), and destroy (block FA.1.3.5) potential threat systems. Mitigation selection from the C2 subfunction determines which mitigation subfunction applies effect.

Figure 36. C-UxS Mitigate Operational Activity Model



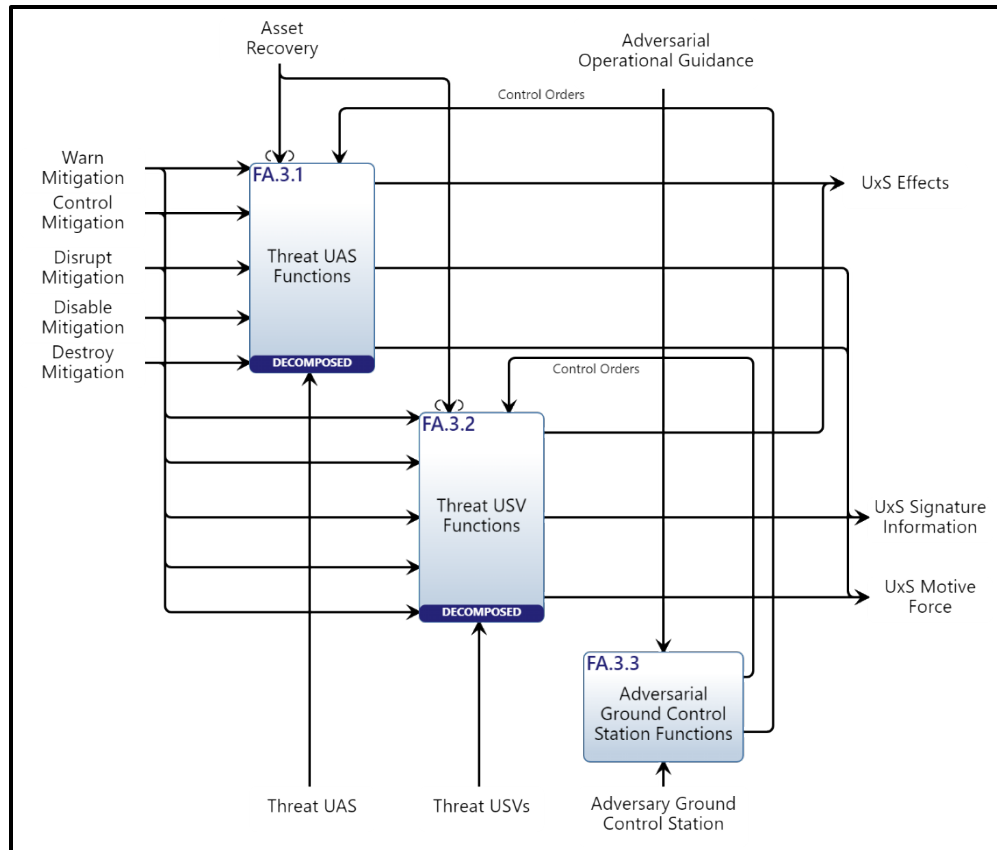
This IDEF0 diagram represents functional exchange in support of the move subfunction of the C-UxS system. The C-UxS system executes functions for controlling system elevation (block FA.1.4.1), controlling system azimuth (block FA.1.4.2), and generating propulsion (block FA.1.4.3). Navigation control from the C2 subfunction determines how each of the subfunctions support C-UxS motive force.

Figure 37. C-UxS Move Operational Activity Model



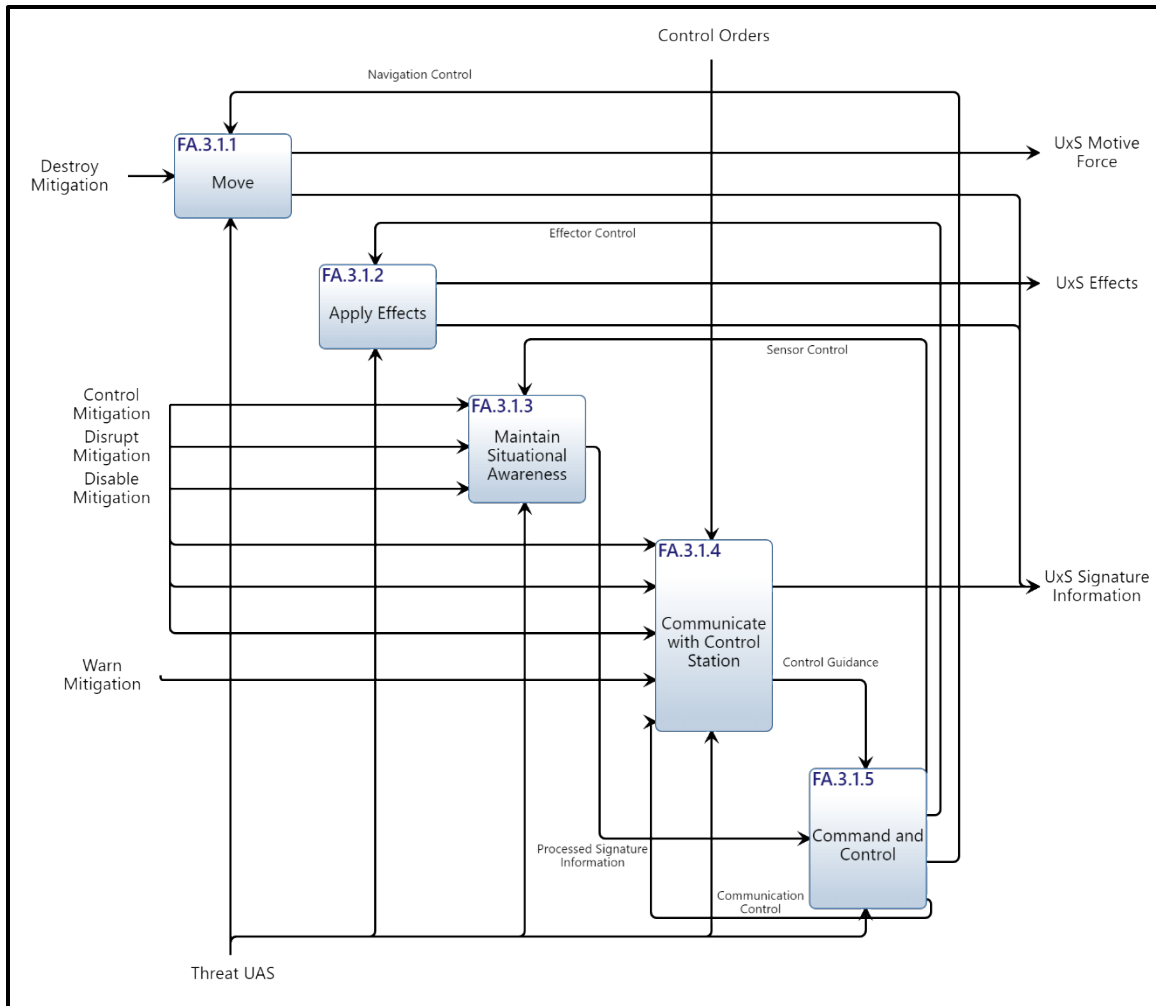
This IDEF0 diagram represents functional exchange internal to the HVU as part of the HVU self-escort mission scenario. The HVU performs functions to move through the environment (block FA.2.1), maintain situational awareness (block FA.2.2), communicate with supporting (block FA.2.3) and supported (block FA.2.4) units, and perform C2 (block FA.2.5). In addition to these subfunctions, the HVU performs mission essential functions (block FA.2.6) that are specific to its designation as an HVU. The HVU receives updates to the common operating picture and operational guidance from external sources and transforms these into operating mode selection for the supporting C-UxS system and situational reports for the supported area commander. The Threat UxS may achieve effect on the HVU through impact on function to move, communicate, and perform mission essential functions.

Figure 38. High Value Unit Functions Operational Activity Model



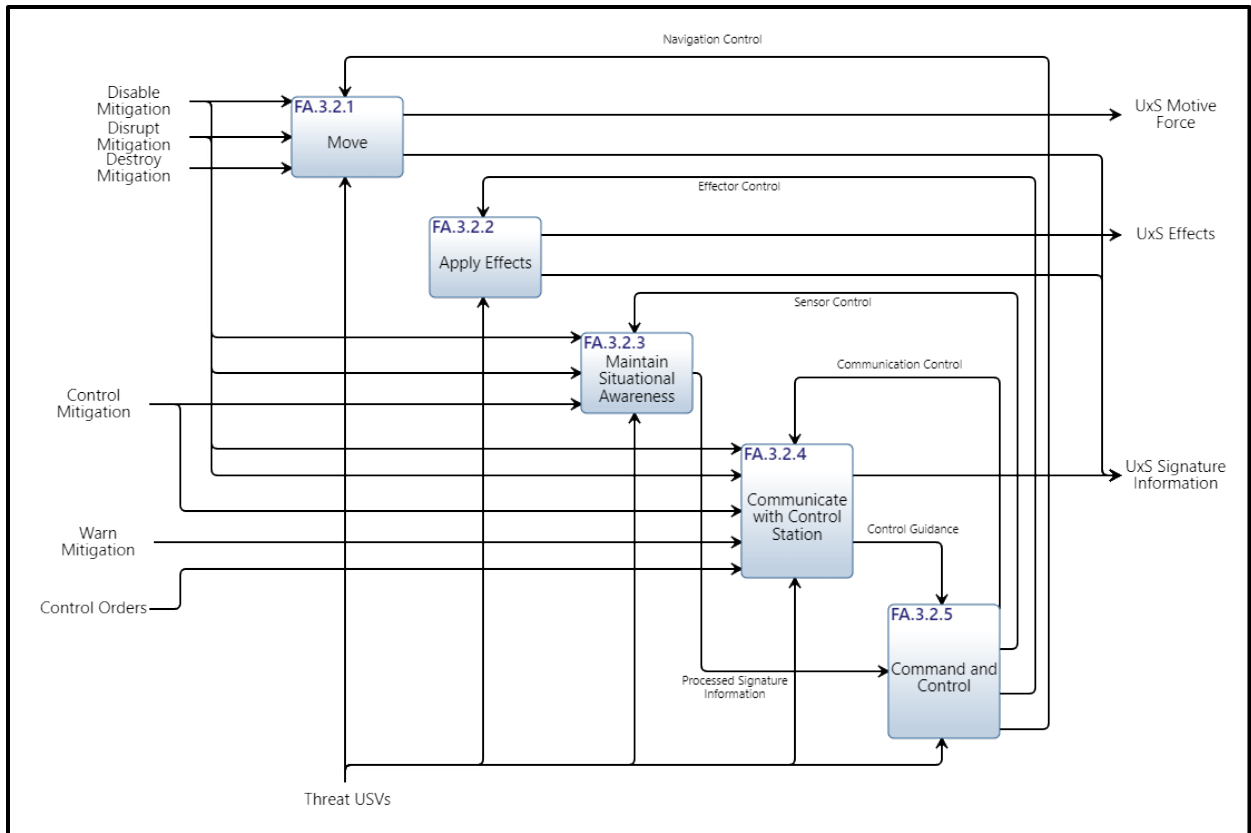
This IDEF0 diagram represents functional exchange internal to the Threat UxS as part of the HVU self-escort mission scenario. The Threat UxS is composed of functions for the Threat UAS (block FA.3.1), Threat USV (block FA.3.2) and adversarial GCS (block FA.3.3). The adversarial GCS supplies operating guidance to the Threat UAS and Threat USV, each which may apply effects to external systems. The Threat UAS and Threat USV move throughout the operating environment and emit signature information that may be received by the C-UxS system.

Figure 39. Threat UxS Functions Operational Activity Model



This IDEF0 diagram represents functional exchange internal to the threat UAS as part of the HVU self-escort mission scenario. The Threat UAS performs functions to move (block FA.3.1.1), apply effects (block FA.3.1.2), maintain situational awareness (block FA.3.1.3), communicate with the control station (block FA.3.1.4), and perform C2 (block FA.3.1.5). The Threat UAS senses the external operating environment and receives control orders from the GCS and transforms these inputs into potential effects on the HVU, motive force, and signature information. The C-UxS system may achieve effect on the threat UAS through impact on function to move and communicate.

Figure 40. Threat UAS Functions Operational Activity Model



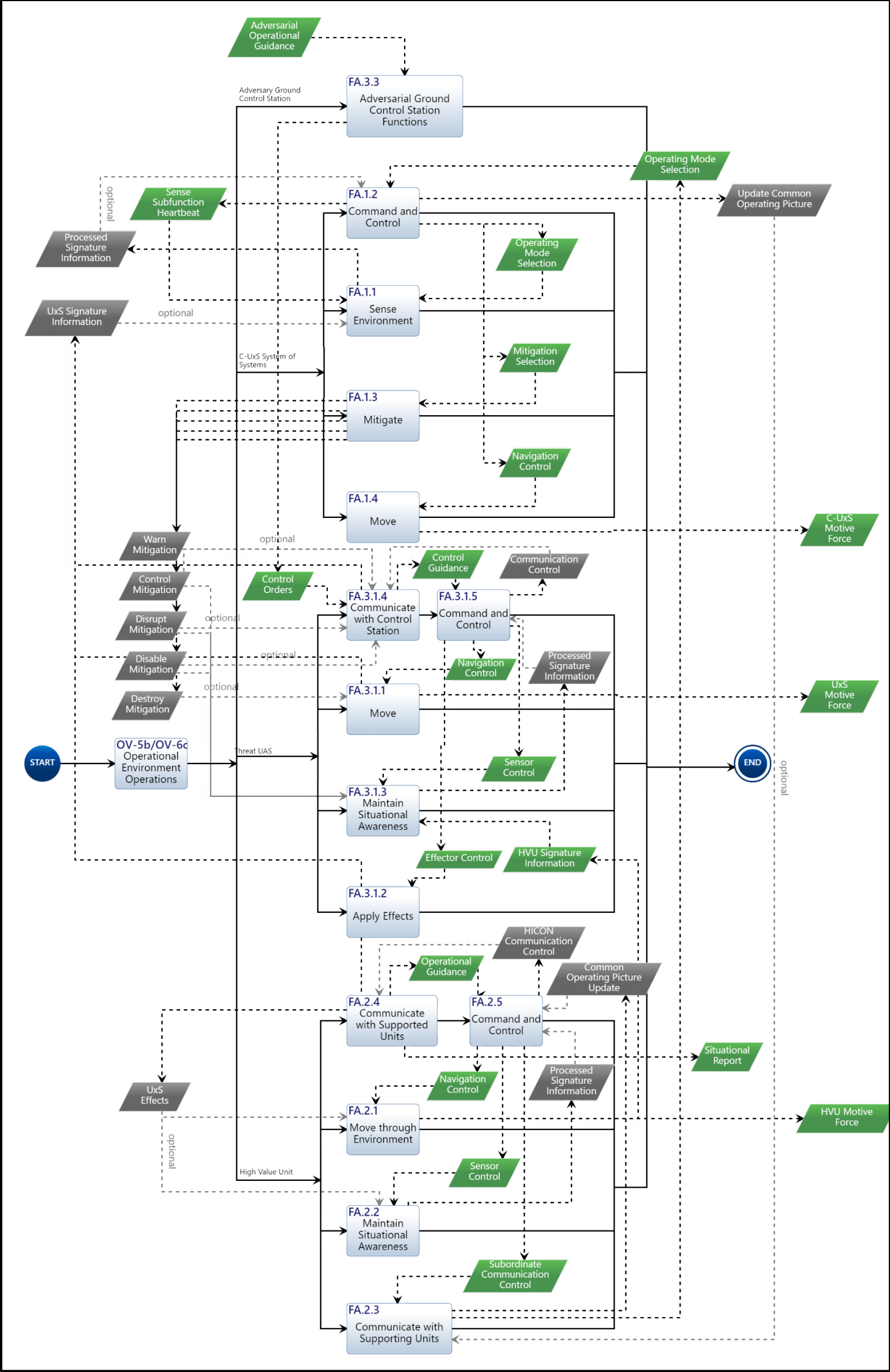
This IDEF0 diagram represents functional exchange internal to the threat USV as part of the HVU self-escort mission scenario. The Threat USV performs functions to move (block FA.3.2.1), apply effects (block FA.3.2.2), maintain situational awareness (block FA.3.2.3), communicate with the control station (block FA.3.2.4), and perform C2 (block FA.3.2.5). The Threat USV senses the external operating environment and receives control orders from the GCS and transforms these inputs into potential effects on the HVU, motive force, and signature information. The C-UxS system may achieve effect on the threat USV through impact on function to move and communicate.

Figure 41. Threat USV Functions Operational Activity Model

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APPENDIX B. ACTIVITY DIAGRAM

This appendix includes the activity diagram for the HVU encounter with a threat UAS. The activity diagram is displayed in Figure 42. An activity diagram applies timing and control logic to the IDEF0 to show process threads (Buede and Miller 2016, 87). This supplies the means to investigate the vignettes that are part of the scenario. This figure shows an activity diagram for the first vignette, the HVU encounter with a Threat UAS. This illustrates how the sequencing for the functional inputs and outputs, including types of signature information, operational guidance, and mitigation effects, enable functions that achieve operational effect. Operational functions, displayed as gray blocks, generate Input/Output blocks, respectively shown in green for mandatory triggers and in dark gray for optional indicators. The C-UxS SoS in the second swim lane deploys different forms of mitigation that align to functions assigned to the Threat UAS. Successful mitigation of these functions results in degraded UAS functionality.



An activity diagram applies timing and control logic to the IDEF0 to show process threads (Buede and Miller 2016, 87). This supplies the means to investigate the vignettes that are part of the scenario. This figure shows an activity diagram for the first vignette, the HVU encounter with Threat UAS. This illustrates how the sequencing for the functional inputs and outputs, including types of signature information, operational guidance, and mitigation effects, enable functions that achieve operational effect. Operational functions, displayed as gray blocks, generate Input/Output blocks, respectively shown in green for mandatory triggers and in dark gray for optional indicators. The C-UxS SoS in the second swim lane deploys different forms of mitigation that align to functions assigned to the Threat UAV. Successful mitigation of these functions results in degraded UAV functionality

Figure 42. HVU Self-Escort Activity Diagram (OV-5b/OV-6c)

APPENDIX C. ANALYSIS SCRIPTS

This appendix includes the Python scripts used for supporting simulation analysis from MAST outputs and calculating the weighted score. It supplies a step-by-step guide for how to set up MAST output to work with the scripts as well as how to use the scripts themselves. To illustrate this, the step-by-step guide examines how to conduct analysis of two values for the Number of Inyx agents in the hypothetical Echo/Inyx alternative examined in Chapter V.

A. SIMULATION OUTPUT SETUP

This section supplies the steps to configure the MAST simulation environment and the file structure to support analysis of a given alternative.

1. Create a folder titled for the alternative and, within this folder, create subfolders named for each variable under analysis. Separate subfolders under the variable folder are named for values for this. An example of this in Figure 43 supports the values one, five, and ten for the variable Number of Inyx associated with the Echo/Inyx (“Echo”) alternative.

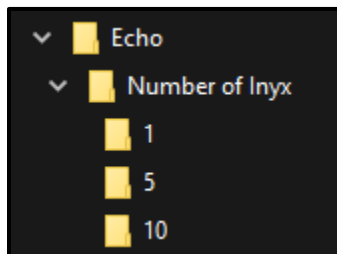


Figure 43. Folder Hierarchy

2. Given this folder hierarchy, the next step is to configure the MAST output. Using MAST, open the file for the simulation associated with the analysis and set the initial simulation parameters. An example of this in Figure 44 shows “Number of agents” set to two, supporting a value of two for the variable Number of Inyx.

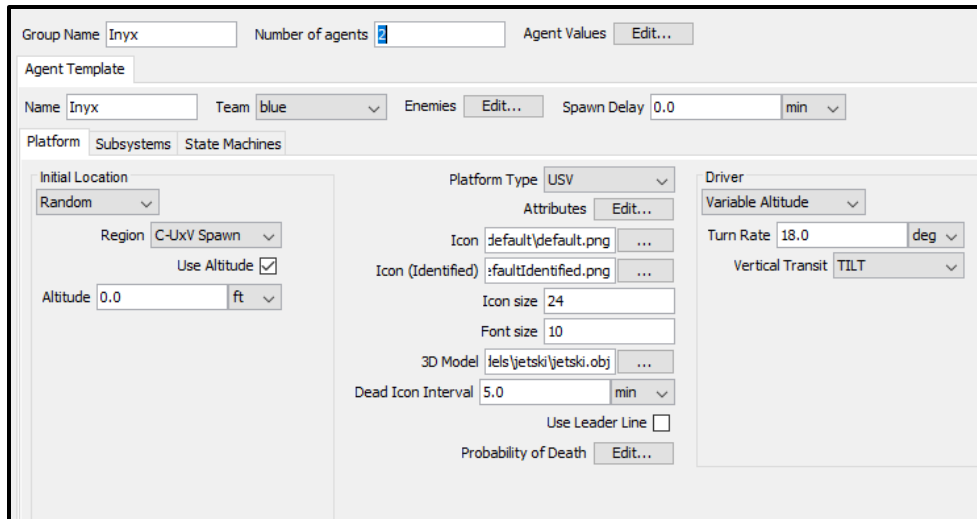


Figure 44. Changing Number of Inyx Agents

3. After configuring the desired simulation parameters, set the number of runs needed for the simulation in the Experiment window. Figure 45 shows this set to 100.

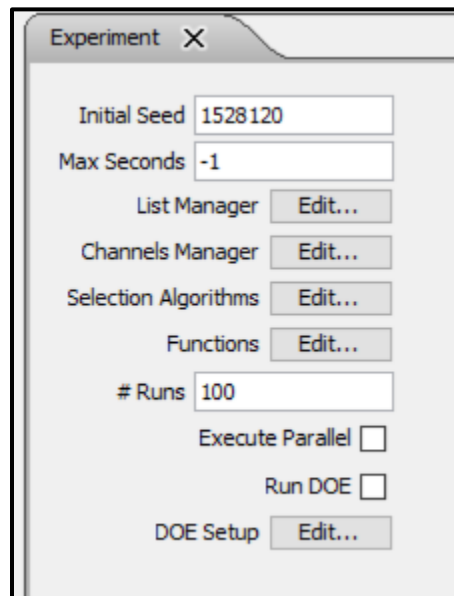


Figure 45. MAST Experiment Window

4. At the top of the MAST window, ensure that Detailed Log is enabled and that the Detailed Log window is turned on, as demonstrated in Figure 46 and Figure 47. This will ensure the simulation outputs the data needed for analysis.

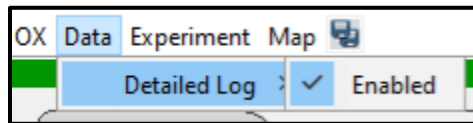


Figure 46. Detailed Log Enabled

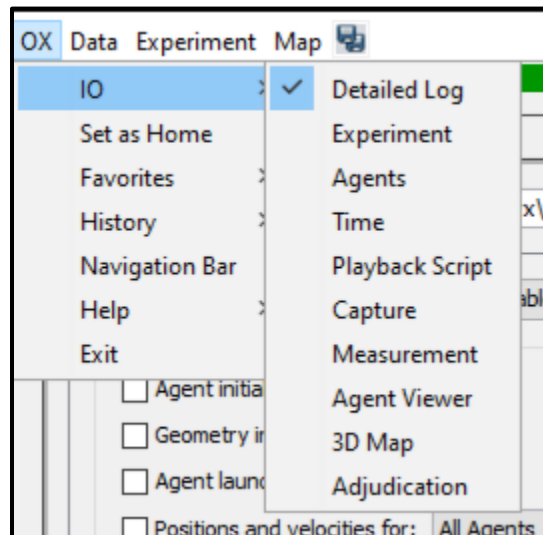


Figure 47. Detailed Log IO Window Enabled

5. Confirm that the right datapoints are captured in the log for post-simulation analysis. By default, MAST captures most available options, and this may result in output that interferes with the analysis. To do this, in the Detailed Log window ensure the only options selected are “Agent enters or leaves a geometry/crosses a geometry line” and “Agent death,” with all other options turned off. Finally, set the output directory to the folder associated with the variable and value combination for this simulation run. Figure 48 shows an example of this setting in the Detailed

Log window. The output folder here is configured to support setting the variable Number of Inyx equal to one.

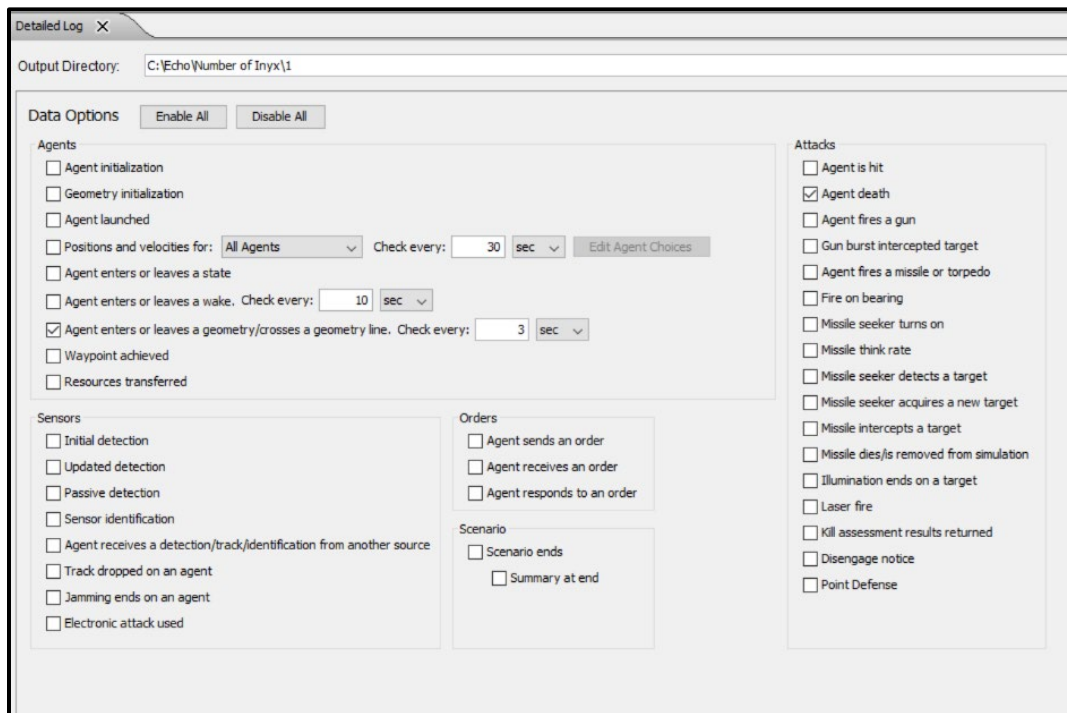


Figure 48. MAST Detailed Log Window

6. Execute the MAST simulation by clicking Run in the Experiment window. After all simulation runs are complete for the current parameter settings, follow the preceding steps to complete the simulation for the remainder of the desired parameter settings.

B. PYTHON SCRIPTS

The simulation process in Section A results in a set of nested folders filled with raw MAST output data logs. To conduct analysis on these MAST output data logs, this project supplies a set of Python scripts: HASDUUserInterface.py; HASDUparser.py; and HASDUAnalysis.py. These Python scripts will work in any integrated development environment (IDE) that is compatible with and can interpret code developed using Python version 3.11.4. The scripts use standard Python libraries such as tkinter and statistics. All

three scripts are designed to be run from within the same file system folder and, depending on the IDE, the same workspace. The scripts do not need to be in the same folder as the MAST output, as there is functionality for telling the scripts where the MAST output data is found.

1. Execution Steps

Open all three scripts in an IDE and run HASDUUserInterface.py. This will create a user interface window as shown in Figure 49. The user interface has input options for the scoring parameters described in Chapter IV. These are set by default to the values described in Chapter IV but can be changed by the user.

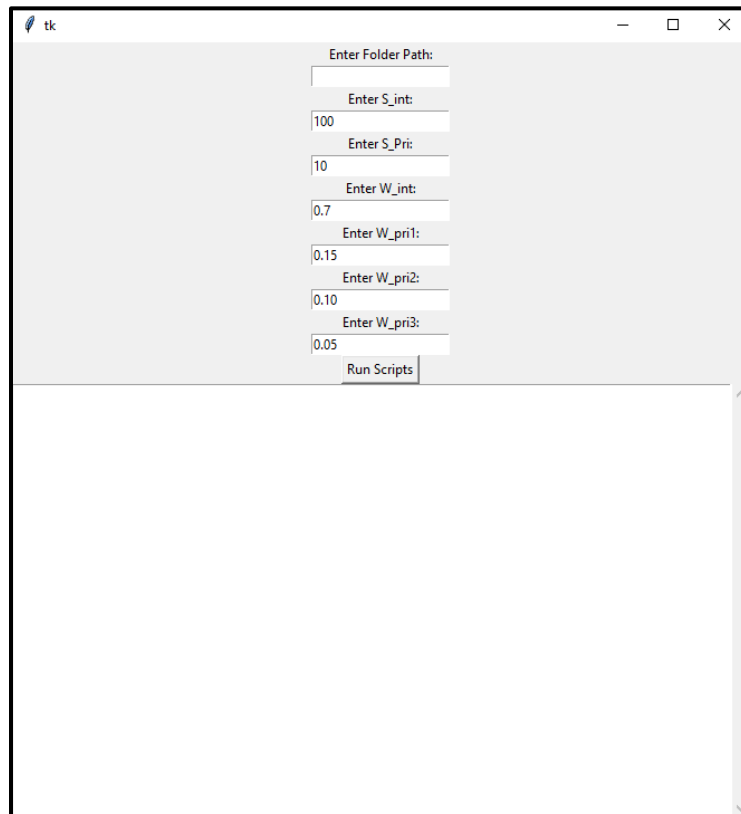


Figure 49. HASDUUserInterface.py Interface Window

In the Enter Folder Path field at the top of the window, enter the path to the first log folder and click Run Scripts. As discussed in Section A, log folders are associated

with individual variable and value combinations. This results in output at the bottom of the user interface window as shown in Figure 50. The output returns average values for simulation outputs across all simulation runs.

```
Total number of files is 25
File: C:\Echo\Number of Inyx\1

Average time to enter HVU/Priority1: 580.18s
Average time to enter HVU/Priority2: 441.03s
Average time to enter HVU/Priority3: 293.68s
Average number of agents entered HVU/Priority1: 7.0
Average number of agents entered HVU/Priority2: 7.48
Average number of agents entered HVU/Priority3: 7.92
Average time of HVU intercept action: 614.375s
Percent of Runs with no HVU intercept by hostile unit: 68.0%
Total number of unique agents with names starting with USV_ or UAS_: 8
Weighted score: 50.888854935913756
List for pasting into other applications:
1, 580.18, 441.03, 293.68, 7.0, 7.48, 7.92, 614.375, 68.0, 50.888854935913756
```

Figure 50. Example Analysis Output

A comma separated values list at the bottom of the output window supplies output for comparative analysis and includes all displayed values except for “Total number of unique agents with names starting with USV_ or UAS_.” This last value shows the threat set for the simulation and should be identical across all simulation runs for a given analysis. It is supplied here to provide the end user with a sanity check verification. These results can be recorded in a separate “.csv” file and saved for analysis in, e.g., Microsoft Excel or Minitab.

After the output data is saved, the analysis scripts are ready for the next value and variable combination. To do this, enter the next folder path and click on Run Scripts. This will populate the output for the new folder.

The scripts support bulk processing of multiple value and variable combinations. To do this, enter the path to the desired variable, e.g., “C:\Echo\Number of Inyx” and click Run Scripts. This will execute the scripts and generate output for each value subfolder within the set folder. It should also be noted the values may not output in sequential order. The end-user should verify that the output data is sorted as required for analysis.

2. Scripts

a. *HASDUUserInterface.py*

This code is intended to work with HASDUParser.py and HASDUAnalysis.py.
Both scripts must be in the same folder as this script for them to work
appropriately.

This code was developed with the help of OpenAI's GPT-4 LLM.

```
import os
import subprocess
from tkinter import Tk, Label, Button, Entry, StringVar, Text, Scrollbar,
END
```

```
class Application:
```

```
    def __init__(self, master):
```

```
        self.master = master
```

```
        self.folder_path = StringVar()
```

```
        self.S_int = StringVar(value = "100")
```

```
        self.S_Pri = StringVar(value = "10")
```

```
        self.W_int = StringVar(value = "0.7")
```

```
        self.W_pri1 = StringVar(value = "0.15")
```

```
        self.W_pri2 = StringVar(value = "0.10")
```

```
        self.W_pri3 = StringVar(value = "0.05")
```

```
        # User defines the folder location to be analyzed
```

```
        self.label = Label(master, text="Enter Folder Path:")
```

```
        self.label.pack()
```

```
        self.entry = Entry(master, textvariable=self.folder_path)
```

```
        self.entry.pack()
```

```
        # Enable user to define Intercept Scaling Factor
```

```
        self.S_int_label = Label(master, text="Enter S_int:")
```

```
        self.S_int_label.pack()
```

```
        self.S_int_entry = Entry(master, textvariable=self.S_int)
```

```
        self.S_int_entry.pack()
```

```
        # Enable user to define Priority Zone Scaling Factor
```

```
        self.S_Pri_label = Label(master, text="Enter S_Pri:")
```

```
        self.S_Pri_label.pack()
```

```
        self.S_Pri_entry = Entry(master, textvariable=self.S_Pri)
```

```

self.S_Pri_entry.pack()

# Enable user to define Intercept Weighting Factor
self.W_int_label = Label(master, text="Enter W_int:")
self.W_int_label.pack()

self.W_int_entry = Entry(master, textvariable=self.W_int)
self.W_int_entry.pack()

# Enable user to define Priority Zone 1 Weighting Factor
self.W_pri1_label = Label(master, text="Enter W_pri1:")
self.W_pri1_label.pack()

self.W_pri1_entry = Entry(master, textvariable=self.W_pri1)
self.W_pri1_entry.pack()

# Enable user to define Priority Zone 2 Weighting Factor
self.W_pri2_label = Label(master, text="Enter W_pri2:")
self.W_pri2_label.pack()

self.W_pri2_entry = Entry(master, textvariable=self.W_pri2)
self.W_pri2_entry.pack()

# Enable user to define Priority Zone 3 Weighting Factor
self.W_pri3_label = Label(master, text="Enter W_pri3:")
self.W_pri3_label.pack()

self.W_pri3_entry = Entry(master, textvariable=self.W_pri3)
self.W_pri3_entry.pack()

self.run_button = Button(master, text="Run Scripts",
command=self.run_scripts)
self.run_button.pack()

# Create a scrollbar
self.scrollbar = Scrollbar(master)
self.scrollbar.pack(side="right", fill="y")

# Create a Text widget with a scrollbar
self.output_text = Text(master, wrap="word",
yscrollcommand=self.scrollbar.set)
self.output_text.pack(side="left", fill="both", expand=True)

self.scrollbar.config(command=self.output_text.yview)

```

```

def run_scripts(self):
    # Get the values that the user defined
    parent_folder_path = self.folder_path.get()
    S_int = self.S_int.get()
    S_Pri = self.S_Pri.get()
    W_int = self.W_int.get()
    W_pri1 = self.W_pri1.get()
    W_pri2 = self.W_pri2.get()
    W_pri3 = self.W_pri3.get()

    last_lines = []

    # Ensure the folder path exists
    if not os.path.isdir(parent_folder_path):
        print(f"Folder path {parent_folder_path} doesn't exist.")
        return

    # Get all sub-folders
    subfolders = [f.path for f in os.scandir(parent_folder_path) if
f.is_dir()]
    print(f"Subfolders: {subfolders}")

    if not subfolders:
        # Script to be executed first
        folder_path = parent_folder_path
        script1 = "HASDUparser.py"

        print(f"Running {script1} with folder path {folder_path}...")
        subprocess.run(["python", script1, folder_path], check=True)

        # Script to be executed second and has output
        script2 = "HASDUAnalysis.py"
        print(f"Running {script2} with folder path {folder_path}...")

        # Execute the second script and capture output
        result = subprocess.run(["python", script2, folder_path,
S_int, S_Pri, W_int, W_pri1, W_pri2, W_pri3], text=True,
capture_output=True, check=True)

        # Add two newlines before the new output if the Text widget
        isn't empty
        if self.output_text.get(1.0, END).strip():

```

```

        self.output_text.insert(END, '\n\n')

    # Create label and display script2's output in the GUI
    self.output_text.insert(END, result.stdout)

for folder_path in subfolders:
    # Script to be executed first
    script1 = "HASDUParser.py"

    print(f"Running {script1} with folder path {folder_path}...")
    subprocess.run(["python", script1, folder_path], check=True)

    # Script to be executed second and has output
    script2 = "HASDUAnalysis.py"
    print(f"Running {script2} with folder path {folder_path}...")

    # Execute the second script and capture output
    result = subprocess.run(["python", script2, folder_path,
S_int, S_Pri, W_int, W_pri1, W_pri2, W_pri3], text=True,
capture_output=True, check=True)

    # Add two newlines before the new output if the Text widget
    isn't empty
    if self.output_text.get(1.0, END).strip():
        self.output_text.insert(END, '\n\n')

    # Create label and display script2's output in the GUI
    self.output_text.insert(END, result.stdout)

    # After all sub-folders have been processed, display all the last
    lines
    for line in last_lines:
        self.output_text.insert(END, '\n' + line)

root = Tk()
app = Application(root)
root.mainloop()

```

b. HASDUParser.py

This code is intended to work in tandem with HASDUAnalysis.py. After data has been parsed, the analysis script allows the end-user to understand the data.

This code was developed with the help of OpenAI's GPT-4 LLM.

```
import os
import re
import sys

def parse_text_file(file_path):
    pattern = re.compile(r"Time: (?P<time>[\d.]+)s, Agent (?P<action>[\w\s]+) a geometry, Agent Name: (?P<agent_name>[^,]+), Agent Lat: [\d.-]+, Agent Lon: [\d.-]+, Geometry Name: (?P<geometry_name>.+)"
    death_pattern = re.compile(r"Time: (?P<time>[\d.]+)s, Agent (?P<action>[\w\s]+), Agent Name: (?P<agent_name>[^,]+), Agent Lat: (?P<lat>[\d.-]+), Agent Lon: (?P<lon>[\d.-]+)")

    with open(file_path, 'r') as f:
        f.readline() # Skip the first line
        lines = f.readlines()

    data = []
    for line in lines:
        line = line.strip()
        match = pattern.match(line)
        death_match = death_pattern.match(line)
        if match:
            item = match.groupdict()
            item['geometry_name'] = item.get('geometry_name', '')
            data.append(item)
        elif death_match:
            death_data = death_match.groupdict()
            death_data['action'] = 'death'
            death_data['geometry_name'] = ''
            data.append(death_data)

            if "HVU" in death_data['agent_name']:
                break

    return data

def save_parsed_data_to_file(parsed_data, output_file):
```

```

with open(output_file, 'w') as f:
    for item in parsed_data:
        line = f"Time: {item['time']}, Action: {item['action']}, Agent
Name: {item['agent_name']}, Geometry Name: {item['geometry_name']}\n"
        f.write(line)

def main(folder_path):
    text_files = [f for f in os.listdir(folder_path) if f.endswith('.txt')
and not f.endswith('_parsed.txt')]

    for text_file in text_files:
        file_path = os.path.join(folder_path, text_file)
        parsed_data = parse_text_file(file_path)
        output_file = f"{os.path.splitext(text_file)[0]}_parsed.txt"
        save_parsed_data_to_file(parsed_data, os.path.join(folder_path,
output_file))

if __name__ == "__main__":
    folder_path = str(sys.argv[1])
    main(folder_path)

```

c. *HASDUAnalysis.py*

This file works in tandem with HASDUparser.py. Data must be parsed first and only data ending in "parsed.txt" will be analyzed by this code.
This code was developed with the help of OpenAI's GPT-4 LLM.

```
import os
import re
from statistics import mean
import sys
import math

def process_file(file_path):
    # Build dictionaries/lists for logging desired data
    enter_times = {"HVU/Priority1": [], "HVU/Priority2": [],
"HVU/Priority3": []}
    death_times = []
    death_geometries = []
    agent_count = {"HVU/Priority1": 0, "HVU/Priority2": 0,
"HVU/Priority3": 0}
    agents_entered = {"HVU/Priority1": set(), "HVU/Priority2": set(),
"HVU/Priority3": set()}
    agents_deaths = {"HVU/Priority1": 0, "HVU/Priority2": 0,
"HVU/Priority3": 0}
    last_agent_geometry = {}
    unique_agents = set()

    # This is where we analyze the files in bulk
    with open(file_path, "r") as file:
        # Initial focus on logging Time, Action, and Agent Names since
        these appear in every line
        for line in file:
            time_match = re.search(r"Time: (\d+)", line)
            action_match = re.search(r"Action: (\w+)", line)
            agent_match = re.search(r"Agent Name: (\w+)", line)

            # If a line has a time, an action, and an agent name, this is
            where we'll actually analyze it. Helps to avoid any potential empty lines
            if time_match and action_match and agent_match:
                time = int(time_match.group(1))
                action = action_match.group(1)
                agent_name = agent_match.group(1)
```

```

        # If a line has the term "death" in the action and "HVU"
in the agent name, we assume that is an HVU death based on output from
MAST and behavior from the parser.
        if action == "death" and "HVU" in agent_name:
            death_times.append(time) # Keeps track of how many
files result in an HVU death.
        if action == "death" and agent_name in
last_agent_geometry:
            death_geometries.append(last_agent_geometry[agent_name
])

            agents_deaths[geometry] += 1
        # Other primary action we care about is if an agent enters
a Priority zone. Specifically, we care about hostile UAS or USV, which
will always start with an agent name "UAS_" or "USV_".
        elif action == "enters" and (agent_name.startswith("USV_")
or agent_name.startswith("UAS_")):
            unique_agents.add(agent_name)
            geometry_match = re.search(r"Geometry Name:
(HVU\/Priority\d+)", line) # Looking at what geometry the agent entered
            if geometry_match:
                geometry = geometry_match.group(1)
                last_agent_geometry[agent_name] = geometry
                # We care most about how many individual agents
are able to gain entry and don't want an agent repeated multiple times.
The following if statement tracks when an agent enters a geometry and
doesn't count it again if it reenters the same geometry.
                if geometry in enter_times and agent_name not in
agents_entered[geometry]:
                    enter_times[geometry].append(time)
                    agent_count[geometry] += 1
                    agents_entered[geometry].add(agent_name)

            return enter_times, death_times, agent_count, unique_agents,
agents_deaths

def main():
    folder = sys.argv[1]
    all_enter_times = {"HVU/Priority1": [], "HVU/Priority2": [],
"HVU/Priority3": []}
    all_death_times = []
    total_agent_count = {"HVU/Priority1": 0, "HVU/Priority2": 0,
"HVU/Priority3": 0}
    agent_death_geometry_count = {"HVU/Priority1": 0, "HVU/Priority2": 0,
"HVU/Priority3": 0}

```

```

total_files = 0
files_with_no_death = 0
all_unique_agents = set()
avg_agent_track = []
priority_count = 0
avg_time_list = []

# "for" loop that compiles the data for analysis
for file in os.listdir(folder):
    # Only conduct analysis on runs that have already been parsed,
    identified by the parsed suffix
    if file.endswith("parsed.txt"):
        file_path = os.path.join(folder, file)
        enter_times, death_times, agent_count, unique_agents,
agents_deaths = process_file(file_path)

        for priority in enter_times:
            all_enter_times[priority].extend(enter_times[priority])

            # If a run doesn't have an HVU hit, then we add a count to
            track how many runs the HVU survives unscathed.
            if not death_times:
                files_with_no_death += 1

            all_death_times.extend(death_times)

            for priority in agent_count:
                total_agent_count[priority] += agent_count[priority]

            for priority in agents_deaths:
                agent_death_geometry_count[priority] +=
agents_deaths[priority]

            all_unique_agents.update(unique_agents)
            total_files += 1

    # Number of runs must be consistent among alternatives being analyzed.
    Number of runs is reported to end-user for verification.
    print(f"Total number of files is {total_files}")
    print(f"File: {folder}\n")

    # Average time for a hostile to first enter a given priority zone is
    reported to the end-user.
    for priority in all_enter_times:

```

```

        avg_time = mean(all_enter_times[priority]) if
all_enter_times[priority] else 0
        if avg_time != 0:
            avg_time = round(avg_time, 2)
        else:
            avg_time = 0
        print(f"Average time to enter {priority}: {avg_time}s")
        avg_time_list.append(avg_time)

    # Average number of hostile units able to enter a priority zone is
    reported to the end user.
    for priority in total_agent_count:
        avg_agent_count = total_agent_count[priority] / total_files if
total_files > 0 else 0
        avg_agent_count = round(avg_agent_count, 2)
        avg_agent_track.insert(priority_count, avg_agent_count)
        priority_count += 1
        print(f"Average number of agents entered {priority}:
{avg_agent_count}")

    # Calculate how long it takes for an HVU hit to occur on average and
    report to user as a data point for analysis.
    avg_death_time = mean(all_death_times) if all_death_times else None
    print(f"Average time of HVU intercept action: {avg_death_time}s")

    # Calculate a percentage of files with no HVU hit and report to end-
    user the percentage.
    percent_files_with_no_death = (files_with_no_death / total_files) *
100 if total_files > 0 else None
    percent_files_with_no_death = round(percent_files_with_no_death, 2)
    print(f"Percent of Runs with no HVU intercept by hostile unit:
{percent_files_with_no_death}%")

    # End-user must have a consistent number of hostile units in order to
    make score comparison useful. The next line prints the number of unique
    hostile agents to the end user.
    print(f"Total number of unique agents with names starting with USV_ or
UAS_: {len(all_unique_agents)}")

    # Calculate the weighted score. If the number of files analyzed is >0,
    a score is calculated. Otherwise, a weighted score is reported as 0.
    # With that in mind, if a weighted score of 0 is reported, verify that
    log files contain the required data and are being appropriately parsed by
    the analysis tool.

```

```

if total_files > 0:
    # Pull user-defined values from HASDUUserInterface.py
    S_int = float(sys.argv[2])
    S_pri = float(sys.argv[3])
    W_int = float(sys.argv[4])
    W_pri1 = float(sys.argv[5])
    W_pri2 = float(sys.argv[6])
    W_pri3 = float(sys.argv[7])

    death_score = (files_with_no_death / total_files) * S_int
    agent_score_1 = (len(all_unique_agents)/ avg_agent_track[0]) *
S_pri if avg_agent_track[0] >= 1 else len(all_unique_agents) * S_pri
    agent_score_2 = (len(all_unique_agents)/ avg_agent_track[1]) *
S_pri if avg_agent_track[1] >= 1 else len(all_unique_agents) * S_pri
    agent_score_3 = (len(all_unique_agents)/ avg_agent_track[2]) *
S_pri if avg_agent_track[2] >= 1 else len(all_unique_agents) * S_pri

    weighted_score = W_int * death_score + W_pri1 * agent_score_1 +
W_pri2 * agent_score_2 + W_pri3 * agent_score_3

else:
    weighted_score = 0

    # Below commented sections of code allow diagnosis of individual score
elements for troubleshooting purposes. For general use, only final
Weighted Score is reported to end user.
    # print(f"death_score: {death_score}")
    # print(f"agent_score_1 = {agent_score_1}")
    # print(f"agent_score_2 = {agent_score_2}")
    # print(f"agent_score_3 = {agent_score_3}")
    print(f"Weighted score: {weighted_score}")

    print(f"List for pasting into other applications:")
    print(f"{os.path.basename(sys.argv[1])}, {avg_time_list[0]},
{avg_time_list[1]}, {avg_time_list[2]}, {avg_agent_track[0]},
{avg_agent_track[1]}, {avg_agent_track[2]}, {avg_death_time},
{percent_files_with_no_death}, {weighted_score}")

if __name__ == "__main__":
    main()

```

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