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A STUDY OF HOW UNMANNED AERIAL VEHICLE SYSTEMS CAN IMPROVE OVER-THE-HORIZON TARGETING AND STRIKE MISSIONS

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Monterey, CA; Naval Postgraduate School

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NAVAL POSTGRADUATE SCHOOL

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SYSTEMS ENGINEERING CAPSTONE REPORT

A STUDY OF HOW UNMANNED AERIAL VEHICLE SYSTEMS CAN IMPROVE OVER-THE-HORIZON TARGETING AND STRIKE MISSIONS

by

Chadwick J. Boyd, Roderick E. Harris, Christopher L. Kleparek,
and Joshua W. Taylor

March 2020

Advisor: Bonnie W. Johnson

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This capstone project studied the mission utility of using unmanned aerial vehicle (UAV) systems to accomplish the over-the-horizon mission by modeling a variety of UAV capabilities and evaluating their contribution. An Excel probabilistic model of the mission was created to determine the optimized weapon loadout and swarm configuration, which assumed the electronic countermeasures (ECM) UAV to have the highest probability of enemy engagement due to its lead formation position and large radar signature. An ExtendSim simulation added a time element to the study. Both the model and simulation revealed that a maximum air-to-air and strike weapon loadout, which is four weapons for each role, yields the highest probability of success at the lowest probability of a UAV casualty. A maximum air-to-air and strike loadout was found to produce success and UAV casualty probabilities of 98 and 3 percent, respectively. A comparative cost analysis assessed the financial viability of substituting UAVs for manned platforms. The analysis found the unit and per-flight hour cost, for all UAV platforms except those that fulfill the ECM role, to be less than the cost for manned counterparts. However, the use of the ECM UAV eliminates the potential for a flight crewmember casualty.

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ABSTRACT

This capstone project studied the mission utility of using unmanned aerial vehicle (UAV) systems to accomplish the over-the-horizon mission by modeling a variety of UAV capabilities and evaluating their contribution. An Excel probabilistic model of the mission was created to determine the optimized weapon loadout and swarm configuration, which assumed the electronic countermeasures (ECM) UAV to have the highest probability of enemy engagement due to its lead formation position and large radar signature. An ExtendSim simulation added a time element to the study. Both the model and simulation revealed that a maximum air-to-air and strike weapon loadout, which is four weapons for each role, yields the highest probability of success at the lowest probability of a UAV casualty. A maximum air-to-air and strike loadout was found to produce success and UAV casualty probabilities of 98 and 3 percent, respectively. A comparative cost analysis assessed the financial viability of substituting UAVs for manned platforms. The analysis found the unit and per-flight hour cost, for all UAV platforms except those that fulfill the ECM role, to be less than the cost for manned counterparts. However, the use of the ECM UAV eliminates the potential for a flight crewmember casualty.

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LIST OF ACRONYMS AND ABBREVIATIONS

A/A	air-to-air
BREM	Battle Readiness Engagement Management
CONOPS	concept of operations
DoDAF	Department of Defense Architecture Framework
DOE	design of experiments
ECM	electronic countermeasures
M&S	modeling and simulation
NPS	Naval Postgraduate School
OTH	over-the-horizon
OTH-T	over-the-horizon targeting
OTH-S	over-the-horizon strike
OV	operational view
RCS	radar cross-section
SSM	swarm strike model
SSS	swarm strike simulation
SV	system view
UAV	unmanned aerial vehicle
VB	Visual Basic

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EXECUTIVE SUMMARY

Naval Air Warfare Center, Weapons Division, China Lake, is developing an automated decision aid for over-the-horizon targeting (OTH-T) and strikes (OTH-S), called the Battle Readiness Engagement Management (BREM) system. The BREM system, which is currently in the research and development phase, is envisioned as a decision aid to military decision makers by evaluating different OTH courses of action based on game theory and artificial intelligence. The BREM project has developed a prototype OTH targeting and strike game for evaluating a wide range of challenges, actions, and outcomes based on complex "real world" conflicts.

The BREM game's initial scope includes air-launched OTH smart weapons and similar adversarial threats. The primary area of interest of this project is to expand the BREM scope to include the utilization of unmanned aerial vehicles (UAVs). The unmanned platform has the potential to redefine the battlespace by augmenting many existing capabilities, such as carrying offensive missile payloads and electronic warfare pods, as well as providing OTH sensor surveillance and defensive capabilities. Operating multiple UAVs in a swarm allows for a mix of UAVs with specialized payloads, to further shape the battlespace.

Research began with developing a concept of operations (CONOPS). The CONOPS consists of the baselined interactions, strategies, and configurations for how a system of UAV systems can provide capabilities for OTH missions. With the incorporation BREM, the goal is to achieve the highest chance of mission success while using the fewest amount of resources. To do so, inputs such as the operation scenario, available resources, and threat data feed into a decision matrix. At this point, the decision matrix serves as the brains of the system, autonomously generating an optimized plan of attack. This plan will consist of the number of UAVs required for the mission, which type will be most effective, loadout configurations for each unit, and the strategy for executing the mission.

Establishing this functionality served as a launching point for architectural analysis. The DOD Architecture Framework (DoDAF) 2.02 was utilized as a guideline for capturing

the overall architecture. The UGN team was able to capture and illustrate many factors of the OTH mission: physical assets, the interaction of external systems, the flow of functionality, internal systems, internal communications, and functional allocation. The in-depth knowledge acquired from these DoDAF models fueled the development of modeling and simulation parameters.

The goal of the modeling and simulation effort was to quantify the effectiveness of various factors of an OTH strike mission. Modeling focused on two critical probabilities: the probability of striking the OTH target and the probability of a swarm UAV being hit. Both are driven by factors such as UAV selection, UAV performance, and enemy proficiency. Simulation enabled the UGN team to reinforce the data collected with modeling. The same performance parameters were used, but simulation provided a better representation of a live combat scenario (i.e., not targeting downed targets). Through modeling and simulation, the strike UAV was found to be the critical UAV platform for the successful engagement of the OTH target. In addition, loss of the strike UAV had the most detrimental impact on the success probability of the OTH strike mission.

This UGN team is convinced the results of the modeling and simulation effort can aid in developing further analyses to unlock new capabilities to be implemented in the OTH mission. An Excel application and ExtendSim model will be the near-term deliverables provided to support BREM development. This data provides a sufficient baseline, but the UGN Team recommends the swarm size analysis be repeated using real-world probabilities for UAV effectiveness and reliability.

I. INTRODUCTION

The over-the-horizon (OTH) mission is one of the most challenging engagements for modern weapons systems. The mission engagement is driven by the complexity of data transfer of target information due to the break in the line of sight from the horizon, as well as sensor error budgets from long mission execution times. The mission is further strained by the limits of weapons loadouts and adversarial counter-tactics. The complexities of the OTH mission area present a decision space that can benefit from automated decision aids to support human warfighting decision makers. Automated decision aids could support the selection of sensors for target data support and the selection of available weapons.

The Naval Air Warfare Center, Weapons Division, China Lake, is developing an automated decision aid for OTH missions, called the Battle Readiness Engagement Management (BREM) system (Nagy 2019). The BREM system, which is currently in the research and development phase, is envisioned as a decision aid to military decision makers by developing and evaluating different OTH courses of action. The BREM system incorporates game theory and machine learning to develop OTH courses of action and evaluate these options based on expected consequences and predicted adversarial responses (Johnson 2019). The BREM system will develop battle plans to determine when and how to use kinetic and non-kinetic weapons to support various OTH targeting and strike missions. The BREM program is using an incremental learning approach to ensure readiness in the successful execution and management of missions involving complex planning. This learning approach includes de-escalation tactics while also recommending the selection of available weapons, communications, and sensors that yield the highest likelihood of mission success. The BREM system is focused on leveraging the increased readiness provided by the system to reduce casualties and maximize results.

The BREM system's initial scope includes air-launched smart OTH weapons and similar adversarial threats. One area of interest is an expansion of the BREM system to include the contribution of unmanned aerial vehicles (UAVs) to the OTH mission. This capstone project studied the mission utility of adding UAVs to the OTH mission by modeling a variety of UAV capabilities in conjunction with the BREM system. The study looked at the use of different types of UAVs (missile payload, electronic countermeasure [ECM] pod, sensor, defensive, etc.) in different configurations and combinations (single UAVs to swarms of UAVs) using modeling and simulation to evaluate probabilities of mission success. The study supports the incorporation of UAVs as contributors to OTH mission operations into the BREM system decision space.

A recent NPS systems engineering student team developed an operational scenario and conceptual design architecture for the BREM system with a focus on weapons selection and determining salvo size and weapons trajectories (Fava et al. 2019). The student team compared the use of a future BREM system in an operational scenario to a purely human decision process. This showed how a BREM system may be incorporated into future OTH missions and how the automated decision-making capability could be leveraged across platforms to enable autonomous OTH multi-mission engagement.

This capstone project built upon the foundation laid by the previous NPS systems engineering student study (Fava et al. 2019) to model and analyze the contribution of UAVs to the OTH mission domain. The goal of this project is to provide an understanding of the operational utility of adding UAV capabilities to OTH missions. In addition, this capstone project aims to support the implementation of the UAV OTH decision space within the BREM gaming system. The capstone project team has conducted a systems engineering modeling and simulation analysis to capture the functions, architecture, data flow, event sequences, and concepts of operation used in various combinations and configurations of UAVs to assess the factors involved in improving OTH missions.

A. PROBLEM STATEMENT

The OTH mission presents a complex and stressing military decision domain for tactical decision makers. The complexity of this mission arises from incomplete and often inaccurate knowledge of the battlespace; the speed, kinematics, autonomy and destructive capabilities of modern strike weapons; unknown aspects of the adversary; unpredictable consequences of tactical decisions; adversarial means of obfuscation, countermeasures, and counterstrikes; and the general complexities of the operational environment including the beyond-line-of-sight distances. The complexities of the OTH mission area present a decision space that can benefit from automated decision aids to support human warfighting decision makers. The Navy is developing the BREM system as an automated OTH decision aid; however, BREM is not complete and currently lacks the consideration of naval UAV assets as contributors to the OTH mission space. This capstone study addresses this need by analyzing the potential contributions of UAVs to the OTH mission and supporting the implementation of adding this knowledge to the BREM decision aid system.

B. CAPSTONE PROJECT OBJECTIVES

The primary objective of this capstone project was to study the mission utility of adding UAVs to the OTH mission by modeling a variety of UAV capabilities in conjunction with the BREM game system. The study looked at the use of different types of UAVs (such as those with payload, ECM, sensor, and air-to-air defensive capabilities) in various configurations and combinations (single UAVs to swarms of UAVs) using modeling and simulation to evaluate probabilities of mission success. An additional objective of the study was to support the incorporation of UAVs into the BREM mission planning game system.

C. SCOPE, ASSUMPTIONS, AND CONSTRAINTS

The focus of this project was the application of a systems engineering analysis process to study the potential contribution of UAV capabilities for the OTH mission. Therefore, the scope of the project included:

- naval UAV assets
- OTH targeting and strike missions
- BREM as a decision aid under development
- modeling and simulation methods of performance assessments

The assumptions and constraints for this project were generated based upon the need for defining some of the mission parameter unknowns. These assumptions were used to reduce the complexity and bound mission parameters for the probabilistic analysis of systems performance. The assumptions are as follows:

- The OTH mission is not dependent on a single surface ship type for the OTH swarm mission execution
- OTH targets have a maximum return fire capability of four rounds.
- The performance of the return fire threats will be susceptible to electronic countermeasures ECM.
- The target tracking of the return fire threats is radar-based.
- The minimum UAV selection for the swarm engagement includes at least one strike UAV.

D. METHODOLOGY

The team developed a tailored system engineering analysis approach, as shown in Figure 1. As with a traditional "Vee" systems engineering process, definition and decomposition occurred as the project traversed down the left side, and testing and integration occurred as the project continued up the right side. This approach began with concept development, which included the development of a concept of operation (CONOPS). The CONOPS was then used to transition into the architectural analysis and the development of functional and architectural models based on the Department of Defense Architecture Framework (DoDAF). After completing the functional/architectural analysis, these models were used to create parameters for a mission execution simulation. After simulation development, the team evaluated the model evaluation and studied the analysis results.

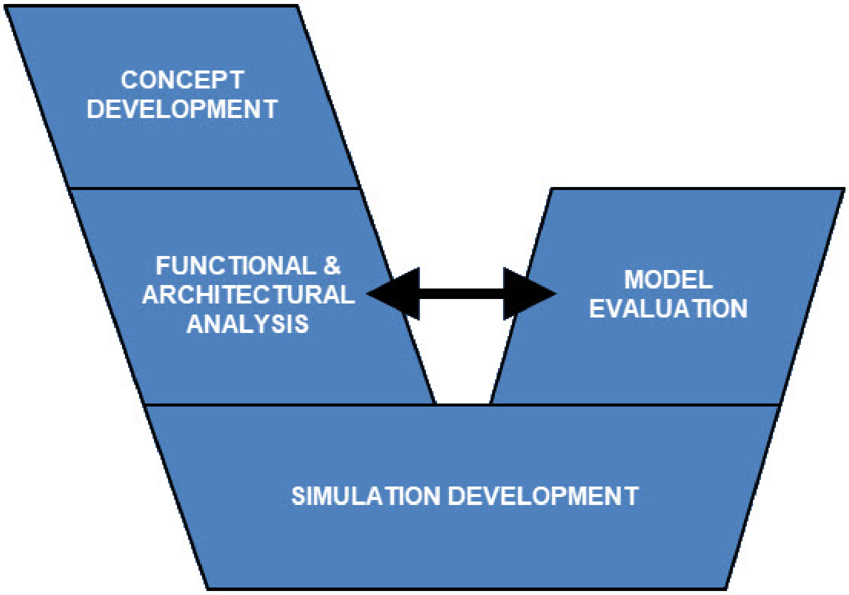

Figure 1. Modified Systems “V”

E. TEAM ORGANIZATION

Each team member had an identified set of roles and responsibilities that enabled the successful completion of the project. The fulfilled responsibilities are identified as follows:

Team Lead—Rod Harris

- Responsibilities: setup meeting agendas, kept meetings on track, kept workload distributed, kept team members accountable for attendance and deliverables

Lead Editor—Joshua Taylor

- Responsibilities: reviewed and submitted all deliverables, supported tracking, review, and accountability of deliverables

Systems Development Lead—Chris Kleparek

- Responsibilities: Ensured the systems engineering processes were being utilized, posted meeting minutes and actions to the Sakai team resource site, tracked-and-closed actions

Modeling and Simulation Lead—Chadwick Boyd

- Responsibilities: strategically organized architecture, modeling, and simulation solutions to ensure project objectives were achieved

Specialists, Analysts—All

- Responsibilities: remained accountable and diligent for completing tasking

F. CAPSTONE REPORT ORGANIZATION

The purpose of this report is to capture the analysis and results of the project execution. The report follows the systems engineering approach previously described. Chapter II presents the team's OTH UAV concept of operations (CONOPS). Chapter III contains the team's architectural analysis that describes the OTH UAV system of systems and functional architecture. Chapter IV describes the team's modeling and simulation analysis and performance analysis results. Chapter V reflects on the report's findings, identifies contributions, highlights potential benefits, and outlines future work to be undertaken by successive efforts.

Reflecting on Chapter I, the problem and scope of the project was defined and the underlying assumptions and constraints were identified to aid the reader in realizing the goal for this project. In addition, the team organization, project methodology, and report organization were introduced to provide the reader with a better understanding of the team element undertaking this project. Moving into Chapter II, the CONOPS, types of UAVs, operational scenarios, and battle strategies will be discussed to provide the foundation for the modeling and simulation effort.

II. CONCEPT OF OPERATIONS FOR UNMANNED AERIAL VEHICLES TO SUPPORT OVER-THE-HORIZON MISSIONS

The team developed a concept of operations (CONOPS) as a basis for developing a model and simulation (M&S) of UAV operations to support the OTH mission. The CONOPS details the operation of UAV systems of systems (SoS) in conjunction with the BREM decision aid system during an over-the-horizon targeting (OTH-T) and strike (OTH-S) mission. The CONOPS consists of the baselined interactions, strategies, and configurations for how a UAV SoS can provide capabilities for OTH missions. Establishing a CONOPS serves as a launching point for more in-depth content of the project: it provides the information necessary to develop architectural DoDAF models (Chapter III) and serves as the basis for parameter selection and M&S development (Chapter IV and V).

A. CONCEPT OF OPERATIONS DESCRIPTION

This CONOPS provides details of how UAVs could operate in conjunction with BREM decision aid system to improve OTH missions. Figure 2 illustrates this operational concept. Adding blue force UAVs as a SoS to the OTH mission can improve situational awareness, threat targeting, communication, countermeasures, and both defensive and offensive OTH actions. The role of the BREM system, as a decision aid, is to determine how a UAV SoS can best support the gathering of threat data and battle strategies (such as formations, loadout selection, resource management) to improve OTH missions. This CONOPS focuses on the successful utilization of blue force assets to neutralize a present threat, whether engaged in an offensive or defensive combat scenario.

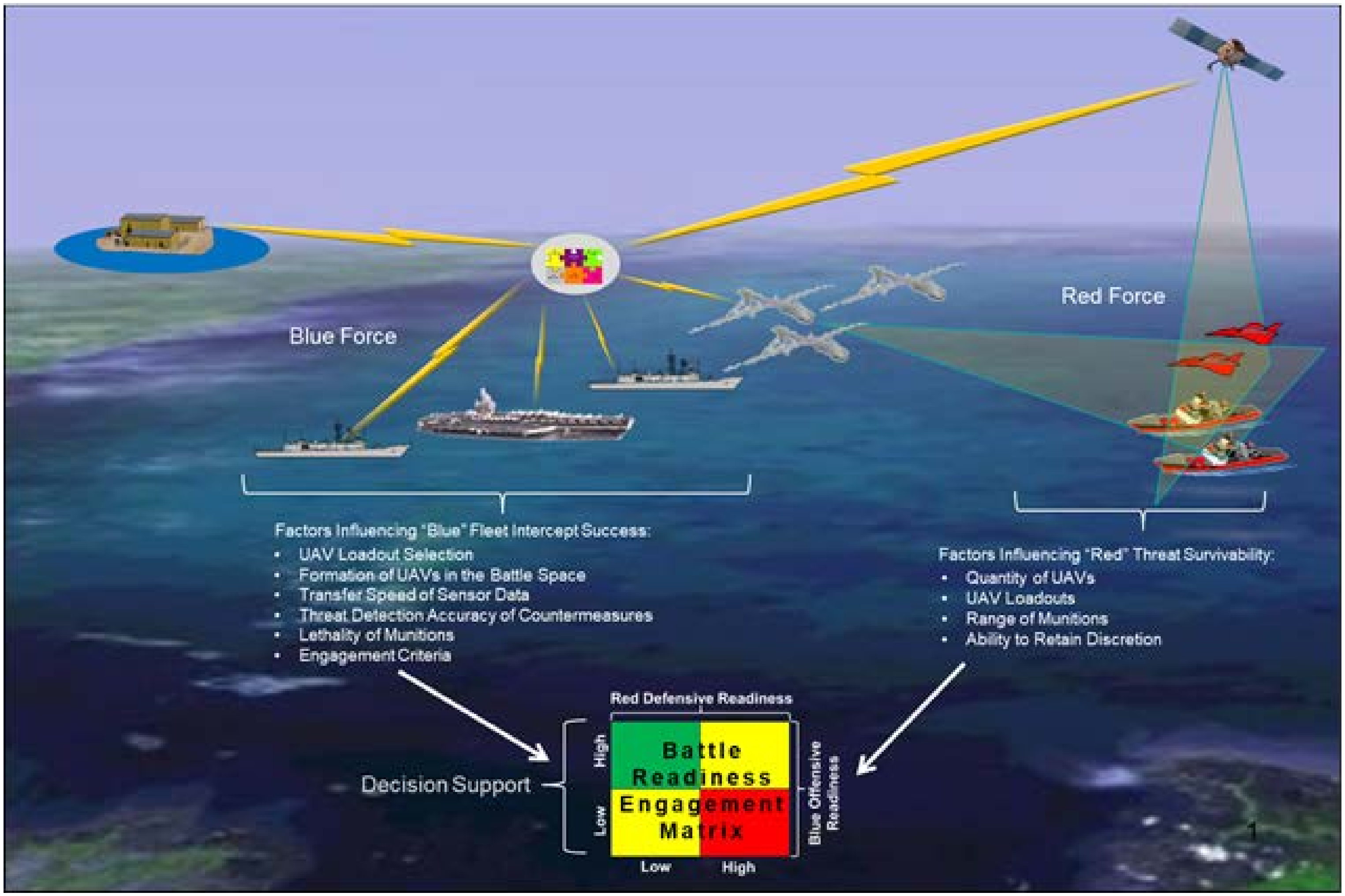

Figure 2. OV-1: Operational Concept for BREM and UAV SoS for OTH Missions

The CONOPS details the structure of the UAV system of systems (SoS) and its relationship to the BREM system. The CONOPS is based on information that is leveraged from Department of Defense weapon system experience and research detailing stochastic game theory, battle simulations, capabilities-based planning, and systems development. The CONOPS considers current capabilities for UAVs, radar, communications, and weapon systems.

As illustrated in Figure 2, the OTH mission domain includes blue force assets such as a naval strike group that can perform strike missions against a red force. The red force may defend itself with countermeasures and warfare strikes such as missile launches from ships and aircraft. The BREM system is shown in the figure as a colored cube representing this decision aid system that develops OTH courses of action (COA) and also evaluates the risk level of each COA—as green, yellow, or red. This CONOPS describes the use of the BREM system to determine how a UAV SoS could best support the blue force's OTH mission. The BREM tool would be used to deliver an estimation of the probability of success of COAs involving the engagement conditions of a given scenario. The engagement conditions include the following: types and quantity of blue force UAVs present, types and quantity of red force UAVs present, radar detection rates, ECM success rates, missile neutralization rates, and missile intercept rates.

The BREM is a tool used to illustrate this desired readiness condition. Mission success, represented as a green condition, is achievable through the informed use of available resources. Suggestions regarding resource allocation will aid decision makers in determining the actions required to maximize the probability of mission success while minimizing friendly casualties. Figure 3 depicts a high-level flow chart of BREM functionality. The system will take the mission scenario, analyze current resources and threat data (such as quantity, weaponry, vulnerabilities), and generate an optimal plan of attack. This plan will consist of the number of UAVs required for the mission, which type will be most effective, loadout configurations for each unit, and the strategy for executing the mission. This strategy will consist of communication, UAV coordination, reporting of sensor data, firing of weaponry, deployment of countermeasures, and all other functions required for mission success.

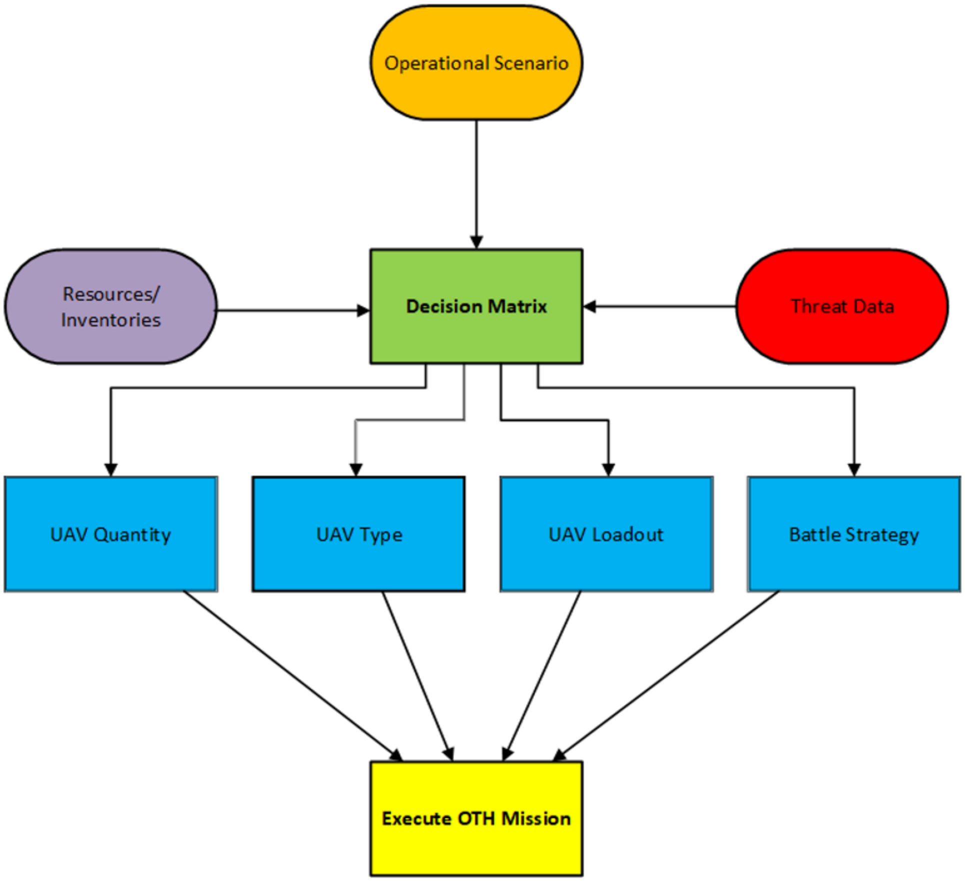

Figure 3. Operational Flow Chart

B. TYPES OF UNMANNED AERIAL VEHICLES

1. Sensor-Enabled Unmanned Aerial Vehicles

Sensor-enabled UAVs support the target and threat detection and tracking data needs for the blue force. This type of UAV supports the OTH-T mission. This information may then be used to support UAVs capable of electronic countermeasures (ECM), air-to-air (A/A) strikes, or air to ground target strikes. The sensor-enabled UAVs improve target and threat data fidelity and provide data used for battle state assessments.

2. Air-to-Air Defense Unmanned Aerial Vehicles

Equipped with antiballistic missiles, A/A defense UAVs are capable of countering incoming missiles. These UAVs are responsible for the completion of the inbound missile target OTH-S missions. The capability to combat incoming threats reduces the probability of damage to a UAV in the swarm and increases the likelihood of mission success.

3. Strike Unmanned Aerial Vehicles

Strike enabled UAVs are capable of engaging and neutralizing enemy targets. These UAVs support the offensive attack portion of the OTH mission. This type of UAV's probability of kill success contributes directly to the overall OTH mission success.

4. Electronic Countermeasures Unmanned Aerial Vehicles

UAVs equipped with ECM are capable of jamming the electronics of enemy threats, thereby reducing the red force's probability of successful attacks against the blue force. ECM UAVs target the red force's radar homing systems. Effective use of ECM UAVs will reduce the likelihood of damage to the blue forces and will increase the blue force's probability of OTH mission success.

C. OPERATIONAL SCENARIOS

1. Unmanned Aerial Vehicle Strike Mission

The OTH strike mission occurs when an OTH target is identified. During this event, the user-supplied target location and identification will be used by the BREM decision aid system to assess the number of assets to deploy to meet and predicted probability of success. In the event that a strike UAV is selected to support this mission, the strike UAV must acquire, track and engage the target. The engagement will be consummated with a missile deployment. Mission success will depend on the strike UAV probability of survival as well as the probability of a successful missile intercept by the red force.

2. Unmanned Aerial Vehicle Sensor Mission

The surveillance mission requires a percentage of radar coverage for a specified area based upon the user inputs. User-supplied radar capabilities are used by the BREM decision support system to generate the number of sensor-enabled UAVs required to maintain the desired domain coverage. The sensor-enabled UAV mission success will be dependent on the radar quality of sensor-enabled UAVs in support of the OTH target acquisition and track. The OTH target track data is sent to the OTH strike UAV to improve its probability of missile intercept success.

3. Unmanned Aerial Vehicle Missile Intercept Mission

The OTH missile intercept mission requires allocation of an intercept missile loadout based on the user assessment of the OTH target's return fire salvo size. This mission occurs during an inbound missile threat. During this event, the A/A UAVs must launch missiles to intercept the enemy missile. Significant factors influencing the success of this type of mission is the number of inbound missiles, the number of A/A UAVs, the velocity of an inbound missile, distance from an inbound missile, detection distance, target acquisition time, missile inventory, and missile intercept rate. The mission success will be assessed as a probability of intercepting inbound missiles.

4. Unmanned Aerial Vehicle Electronic Countermeasure Mission

The ECM mission requires a specific jamming energy output based on user input regarding the OTH target's return fire capability. The jamming performance factors include distance and angle to incoming threats, as well as, the ECM UAV position in relation to the target of the inbound threat. The ECM UAV mission success improves the UAV survivability by decrementing the intercept performance of inbound threat missiles.

5. Over-the-Horizon Unmanned Aerial Vehicle Target Mission

The OTH UAV target mission occurs when there is in inbound non-weaponized UAV threat. An example of this type of mission would be an enemy UAV equipped with cameras dedicated to retrieving intelligence. During this type of mission, strike UAVs must be employed to neutralize the enemy threat. Major factors influencing the success of this type of mission are the number of strike UAVs, enemy UAV velocity, missile kill-rate, missile inventory, missile velocity, and distance from an inbound missile.

6. Over-the-Horizon Unmanned Aerial Vehicle Swarm Mission

The UAV swarm mission relies on the efforts of each type of UAV in the SoS: sensor-enabled, air-to-air, strike, and ECM. The swarm mission simulates two opposing swarms of UAVs, and mission success is defined by the complete neutralization of the enemy UAVs. During this mission, blue force UAVs must defend their team from inbound missiles and attack the opposing force. This mission is composed of independent OTH Missile Intercept Missions and OTH UAV Target Missions. In addition, ECM UAVs are employed to help defend the blue force by reducing the blue force casualty rate during the engagement with the red force.

7. Communications

a. Ship-to-Ship Communications

The firing ship can receive data from support ships that include incoming threat data. The threat data covers the target states, such as position (altitude and range), velocity, and target type (such as maneuvering or sea skimming). The firing ship can also send and receive data about BREM states. The BREM data will be used to support weapons selection decisions.

b. Sensor-Enabled Unmanned Aerial Vehicle-to-Ship Communications

The firing ship can receive data from support sensors that include incoming threat data. The threat data covers the target states, such as position (altitude and range), velocity, and target type (such as maneuvering or sea skimming). Sensors will also communicate environmental data for mission support.

c. Ship-to-Unmanned Aerial Vehicle Communications

The firing ship can send data to the UAVs that include incoming threat data. The threat data covers the target states such as position (altitude and range), velocity, and target type (such as maneuvering or sea-skimming) as well as environmental data such as the presence of radar jamming.

d. Unmanned Aerial Vehicle-to-Ship Communications

The UAV released for intercept engagement will communicate the status of target acquisition, target tracking, and target kill to the firing ship.

e. UAV-to-UAV Communications

In a swarm UAV engagement, the UAVs will communicate the status of target acquisition and target track to the other UAVs. The UAVs may also transmit threat data required for target tracking.

D. MISSION BREAKDOWN

The BREM OTH scenario is a battle group mission. It includes the identification and tracking of an incoming threat or OTH target as well as the identification of the likely target. The nominal scenario starts with sensor support systems, shipboard or external, picking up a likely threat or OTH target. The threat/target information is delivered to the battle group, where the threat/target is identified as the OTH target. At this point, a target track is established using the available sensor. The sensors may be down-selected based on expected intercept complexity. The down select option allows the sensor resource to be reallocated to other tasks or shut down to prevent overuse. Once the track/position is established, target data is sent to the battle group. Based on the target data, the firing ship is selected from within the battle group. The firing ship then determines which UAV or UAV group to use for the intercept engagement. After UAVs are released, the continuation of UAV support with target state data is determined and supported if needed. The sensor systems continue to track the engagement. If the intercept/OTH mission fails, the scenario iterates until the threat is neutralized.

E. BATTLE STRATEGIES

Once the threat has been identified using a ship’s radar sensing system, the BREM program selects the optimal ship to launch the unique UAV or UAV swarm with the highest probability of destroying the target. Unique UAVs are on board each vessel with different weapon selections, flight characteristics, and missile inventory. It is up to the BREM program to leverage the ship’s position with the UAV information to defend against or attack the enemy. This program must also consider swarm engagement approaches and future engagements in the battle theater space. Table 1 lists types of BREM input and output, and scenario manager functions.

Table 1. BREM Input, Output, and Scenario Manager Functions

Input	Ship positioning (coordinates in the battle theater)
	UAV loadout (quantity for each variety on each ship, UAV weapon inventory)
	Remaining missions (number of probable future engagements
	Ship sensor data (number of threats, threat positions)
	UAV sensor data (number of threats, threat positions)
	Target (threat ID, trajectory, speed)
Output	UAV selection (ship selection, UAV team selection, weapon usages, lethality determination)
	Engagement decision (single UAV vs multiple, engagement success rate)
Scenario Manager Functions	User may select alternative UAVs to engage or create a new class of UAV
	Evaluate new engagement success rate under new theater space criteria

The engagement decision system utilizes three sets of decision factors (surface ship and UAV selection factors, event decision factors, and target decision factors) to develop the optimal battle strategy output.

Surface Ship and Unmanned Aerial Vehicle Selection Decision Factors

The position represents the coordinates of the ship in the battle theater. Each ship in the battle theater can launch its own set of UAVs teams at approaching threats and targets. The UAV loadout to be launched depends on the UAVs remaining on each ship. The multiple loadout values represent the remaining UAVs (of varying capabilities) available to execute battle tasks such as payload delivery, missile attacks, EW, and surveillance. The ship's UAV reserves are critical to ship and UAV selection. The remaining missions is another variable that is unique to each vessel.

The remaining missions are the expected number of future mission engagements based on the total number of missions allocated minus the number of missions executed. If a ship is likely to engage at least three more times in the theater space, there must be the appropriate resource allocation for each engagement. The resource allocation must account for missiles, UAVs, and UAV capabilities. The BREM program may require events such as payload drop-offs and ship-to-ship UAV transfers to maintain the optimal readiness condition. The fourth and final variable that is unique to each ship is the available sensor data. This sensor data is used to detect incoming threats and enemy UAVs. Due to each ship's unique positioning, each will encounter differing battle events.

1. Event Decision Factors

The target threat level represents the likelihood *(p)* of the threat to cause damage. This factor will be used in the UAV selection decision, and more specifically, the UAV quantity decision. Although the user of the BREM program may manipulate the target threat level, the default value will be set at 0.5. By increasing the threat level, the optimal position in the BREM will require a more significant swarm or attack force to neutralize the target. By decreasing the value below 0.5, non-violent approaches are preferred to reduce the likelihood of future casualties.

2. Target Decision Factors

Before selecting the appropriate means of engagement, the target attributes need to be identified and processed. Factors such as the position, trajectory, speed, and maneuverability of the target will be used to determine the optimal means of neutralization, counterattack, or surveillance approach. The ship and UAV selection are heavily dependent upon these factors. If an inbound threat is approaching a ship containing a UAV team or a non-weaponized UAV, the ship selection becomes critical to incepting the inbound threat. In this type of scenario, if a nearby UAV is in flight, it will be considered to intercept new threats.

Reflecting on Chapter II, the CONOPS, types of UAVS, operational scenarios, and battle strategies were discussed to provide the foundation for the modeling and simulation effort. Moving into Chapter III, the operational and system architecture will be defined to illustrate the relationships required between the swarm assets for mission execution.

III. ARCHITECTURAL ANALYSIS OF A SYSTEM OF UNMANNED AERIAL VEHICLE SYSTEMS IN SUPPORT OF THE OVER-THE-HORIZON MISSION

The capstone team performed an architectural analysis of the UAV SoS for the OTH mission. The team developed architectural views based on the Department of Defense Architectural Framework (DoDAF) to capture both operational and system views of the UAV SoS. This analysis was performed to aid in the refinement and maturation of the CONOPS, to inform the UAV SoS swarm size performance analysis, and support the UAV modeling and simulation.

A. DEVELOPMENT OF BREM SYSTEM ARCHITECTURE

The architectural analysis for the OTH mission focused on describing the UAV SoS functions and architecture. The analysis generated a system architecture for the proposed OTH mission using model-based system engineering (MBSE) tools. The identification of internal and external system interactions resulting from the architectural analysis supports the future BREM system as well as the team's M&S analysis.

With the understanding of how the system is expected to operate, who is involved, and what are the assumptions and parameters of the system as developed in the CONOPS, the architecture analysis took a top-MBSE approach. This approach utilized the DODAF 2.02 as a guideline for capturing the overall architecture. The team selected Innoslate's model-based systems engineering software Innoslate to develop the DoDAF viewpoints. Knowledge of the system and parameters generated were input into Innoslate, which was then used to generate various views of the system to show operational and system-level interactions.

Utilization of the Innoslate tool offered various ways to depict the interaction of systems and subsystems, both internal and external, involved in the execution of the OTH mission. The DODAF was used to model the core functions of the BREM system as well as the various interactions between internal and external systems required for swarm operation. The overarching DODAF views focused on for this architecture of the system were the operational and systems viewpoints. We chose these viewpoints to illustrate the system-to-system operation as well as the execution and exchange of information between assets. When examining the views, we recommend approaching them from the perspective of an external, high-level user as many of the finer system-related details have yet to be considered.

The following are specific viewpoints developed and brief reasoning for selection:

- OV-1: High-Level Operational Concept Graphic—Offers the high-level graphical depiction of the system's operational concept
- OV-5a Physical Context Hierarchy—Captures the physical assets of the OTH mission
- External Systems Diagram (IDEF0)—Captures the functional decomposition of the mission environment and the interaction between external systems required for the execution of the BREM swarm mission.
- OV-5b: Operational Activity Model and sub-assembly decompositions—Defines the relationship between the external systems and the OTH mission as well as the internal relationships captured in the IDEF0 format
- OV-6c: Event Trace Description—Captures the sequence of events required for the OTH mission
- SV-1: Systems Interface Description—Identifies the internal systems associated with the OTH mission
- SV-2: Communications Network Diagram—Captures the intra-swarm communications required for the execution of the OTH mission
- SV-4a Functional Hierarchy—Captures the functional allocations for the OTH mission

The knowledge gained during the development of the diagrams that support the system architecture and design will aid the modeling and simulation development.

B. OPERATIONAL ARCHITECTURE

The operational architecture view (OV) describes the operations of the system and the connections among the system and subsystems. The OV allows for evaluation of operational requirements, evaluation of interoperability issues, and system baseline. The decision was made to focus on the system analysis through the development of an OV-1, OV-5a Physical Context Diagram, OV-5b F1 External System Diagram and F2/F3 Sub-Functions decompositions, and the OV-6c Event Trace Diagram. These operational viewpoints are described in Table 2.

Table 2. DoDAF Operational Architecture for OTH Mission

DoDAF Operational Viewpoints Developed for the OTH UAV SoS	
OV-1: High-Level Operational Concept Graphic	Offers the high-level graphical depiction of the system’s operational concept (Note—this is located in Chapter II of this report)
OV-5a Physical Context Hierarchy	Captures the physical assets of the OTH mission
External Systems Diagram (IDEF0)	Captures the functional decomposition of the mission environment and the interaction between external systems required for the execution of the BREM swarm mission
OV-5b: Operational Activity Model and sub-assembly decompositions	Defines the relationship between the external systems and the OTH mission as well as the internal relationships captured in the IDEF0 format
OV-6c: Event Trace Description	Captures the flow of the functions performed by each UAV during the mission execution

1. OV-5a: Hierarchy Diagram—Physical Context Diagram

The hierarchy diagram outlines the decomposition of the physical assets allocated to the BREM swarm mission execution. The physical hierarchy includes the system decompositions, as shown in Figure 4. The battle group contains the UAV swarm that will be responsible for mission execution. The UAV decompositions capture the asset’s specific needs for each of the UAV configurations. The analysis used to develop this diagram reinforced that the system’s assets are captured and allocated to operational activities, which are represented in the system’s architecture views (SV).

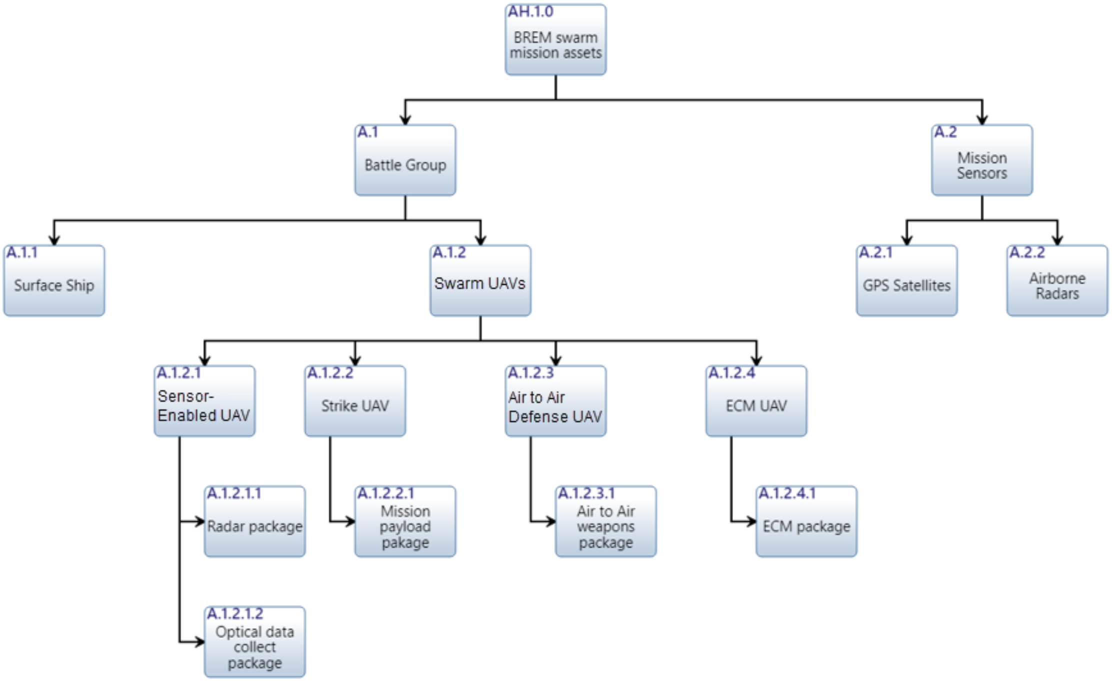

Figure 4. OV-5a: Physical Context Hierarchy

2. OV-5b: Operational Activity Diagrams

The operational activities models describe the interactions and relationships of the various system required to execute the OTH mission. These diagrams, shown in Figures 5 through 10, establish the functional architecture and identify the interactions between swarm assets and external conditions. As the team developed the architecture, each of the functional decomposition levels where labeled. The Level F-1 External System Diagram is the top of the systems architecture, the Level F-2 Execute Mission Diagram is a decomposition of the execute OTH mission function from the F-1 diagram, and Level F-3 Sub-Function decompositions of the OTH mission are captured in the remaining diagrams.

3. Level F-1 External System Diagram IDEF0

The External System Diagram (Level F-1) depicts the functions of the external systems as an SoS architecture. It also illustrates the data flow between each of the external systems. External systems include the OTH mission support systems that will not be decomposed as part of the swarm UAV architecture. The diagram aids in understanding the cooperative nature of the external systems and the architecture of the SoS utilized in the OTH mission execution.

The external systems captured in the external systems diagram include GPS satellites, airborne tracking radars, and surface ships. These systems provide functions such as; GPS target tracking, radar target tracking, mission parameters, and launching the swarm UAVs. These functions are required for the execution of the mission but cannot be accomplished by the swarm UAVs. In this architecture, the swarm UAVs are responsible for the execution of the OTH mission functions. These functions will be decomposed in the throughout architecture. The operational relationships for these systems are shown in Figure 5.

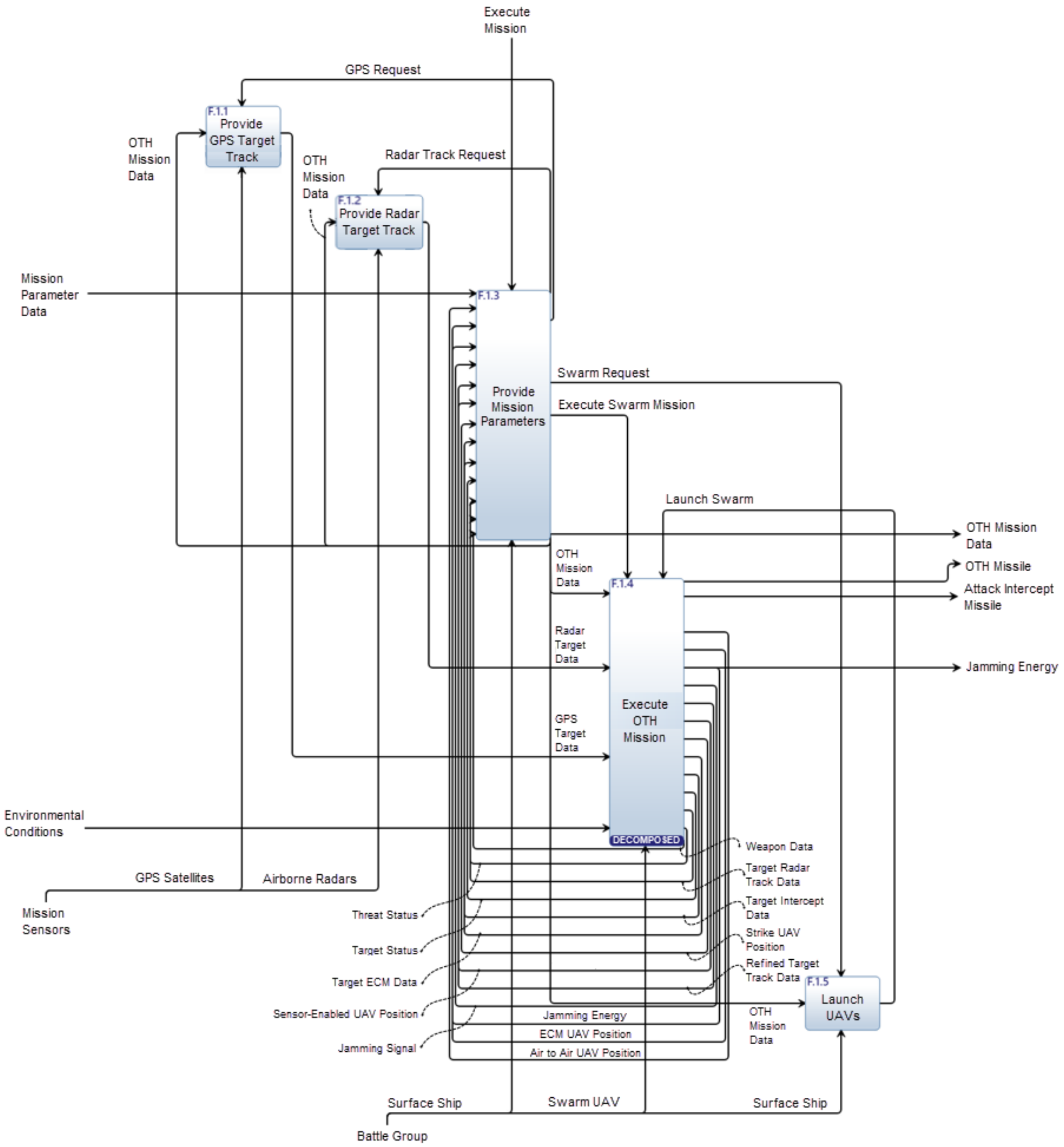

Figure 5. IDEF0: External System Diagram—External Mission Elements

4. Level F-2 IDEF0 Sub-function Execute Mission Diagram

The interactions between the swarm assets required for mission execution are shown in Figure 6.

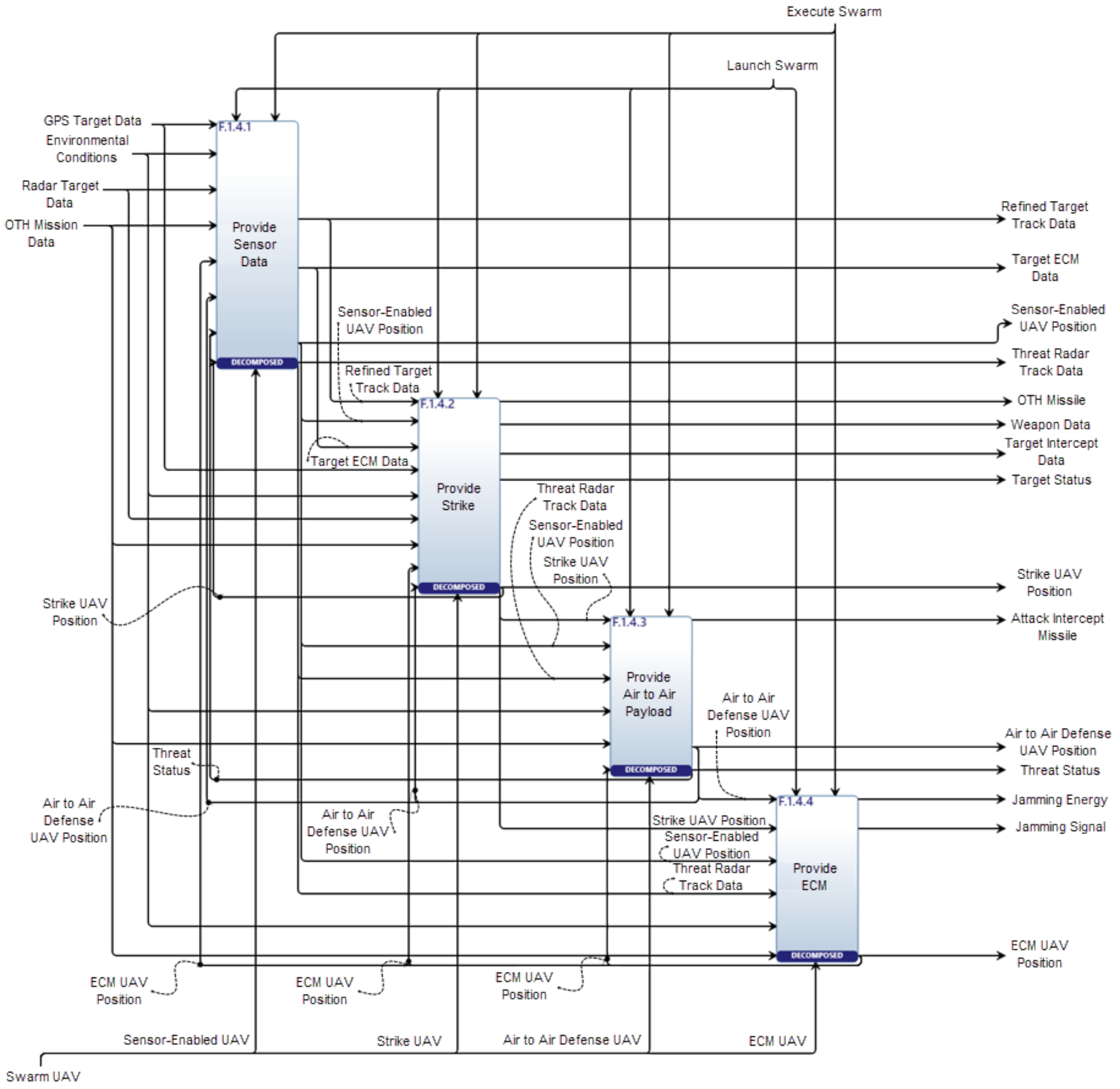

Figure 6. OV-5b: Execute Mission Context Diagram

5. Level F-3 IDEF0 Sub-function Decompositions

The BREM Swarm Execute Mission diagram was decomposed to its sub-functions to provide a better understanding of the UAV sub-systems. All of the UAV decompositions have a fly UAV function by necessity and for completeness, but the UAV functional decomposition focused on the unique UAV configuration functions needed to support the mission execution. This approach dictates the specifics for the command and control of the UAV concerning flight operations as they were combined into the single function by design. Note each UAV possesses a communications function responsible for receiving and transmitting data to elements external to the UAV. The communications function was also bundled to capture the need for an encrypted data link.

6. Level F-3 IDEF0 Sub-function of Sensor-Enabled Unmanned Aerial Vehicle

The decomposition of the sensor-enabled UAV operation describes the interfaces and functions that enable the mission execution to have radar sensor capability. The sub-functions include producing radar energy, detecting radar energy, identifying incoming threats, and determining target location. These functions describe the sensor-enabled UAV capability to produce refined target measurements as well as threat data that will be used by other UAVs in the swarm. They also identify the radar signals needed to support the sensor-enabled UAV functions within the swarm. See Figure 7 for a depiction of the interactions between sensor-enabled UAV's sub-functions.

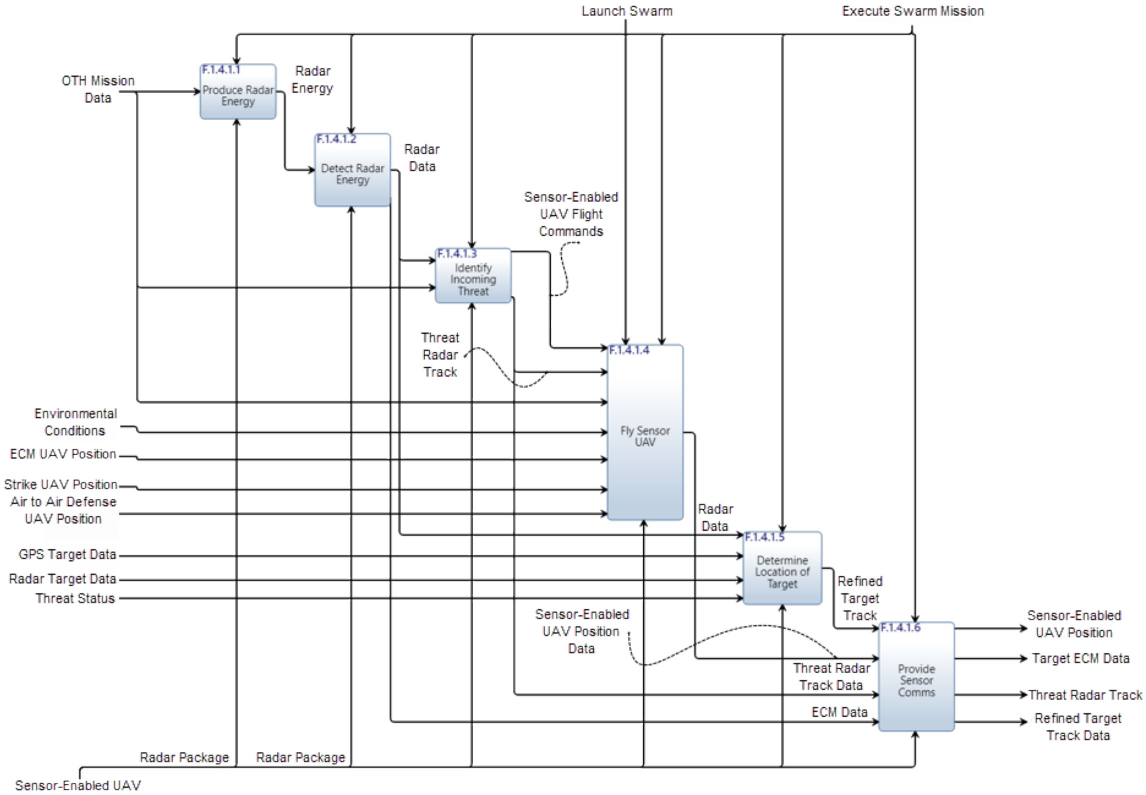

Figure 7. OV-5b for Sensor-Enabled UAV System Sub-functions IDEF0

7. Level F-3 IDEF0 Sub-function of Strike UAV

The decomposition of the strike UAV operation describes the interfaces and functions that enable the mission execution to have strike capability. The sub-functions are track target, identify target intercept, launch ordinance, and provide kill assessment. These functions describe the strike UAV capability needed to complete the OTH strike part of the mission. While the swarm is designed to increase the overall mission success, the strike UAV is solely responsible for the delivery of ordinance to the mission target. See Figure 8 for a depiction of the interactions between the strike UAV's sub-functions.

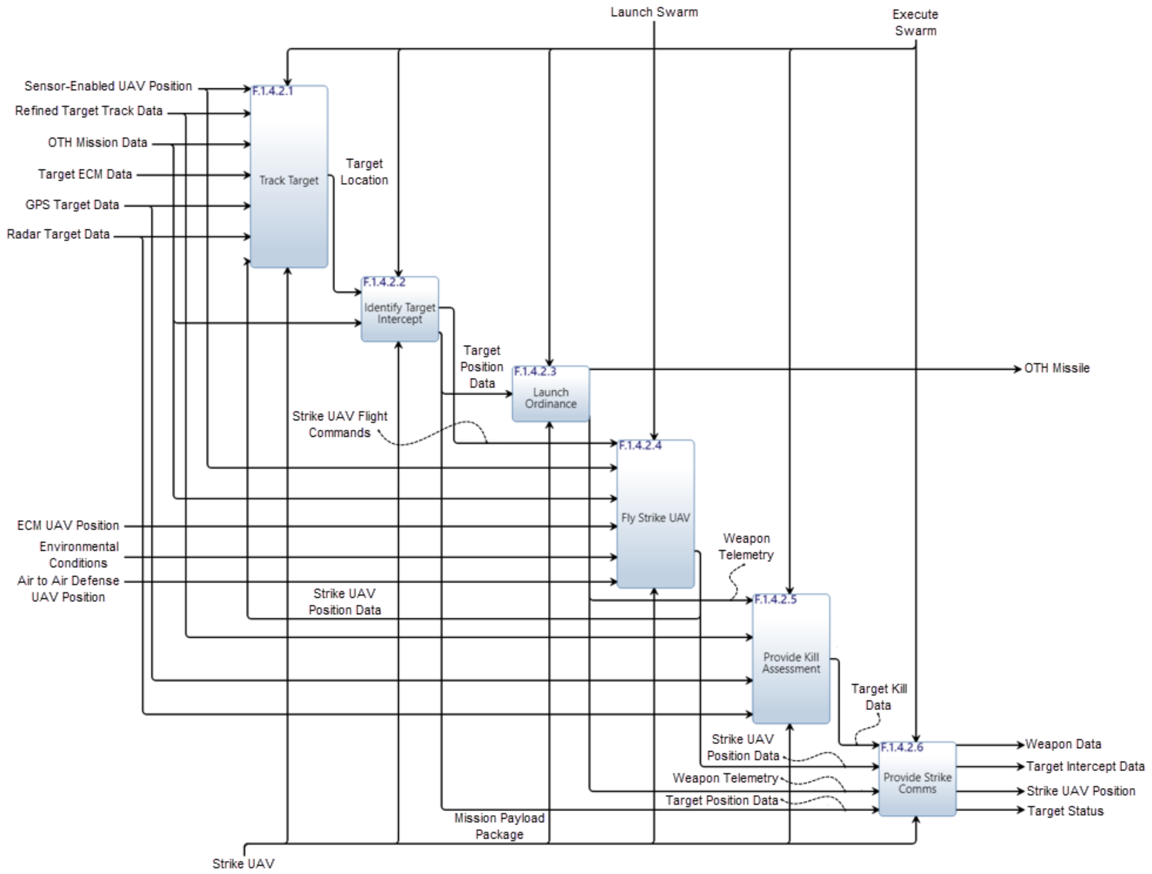

Figure 8. OV-5b for Strike UAV System Sub-functions IDEF0

8. Level F-3 IDEF0 Sub-function of Air-to-Air Defense Unmanned Aerial Vehicle

The decomposition of the air-to-air defense UAV operation describes the interfaces and functions that enable the mission execution to have an air-to-air defensive capability. The sub-functions are track inbound threat, identify threat intercept point, launch a missile, and assess threat status. These functions describe the air-to-air defense UAV capability needed to provide the swarm with an air-to-air intercept operation. By eliminating possible threats to the swarm, the overall mission success is improved. See Figure 9 for a depiction of the interactions between the air-to-air defense UAV's sub-functions.

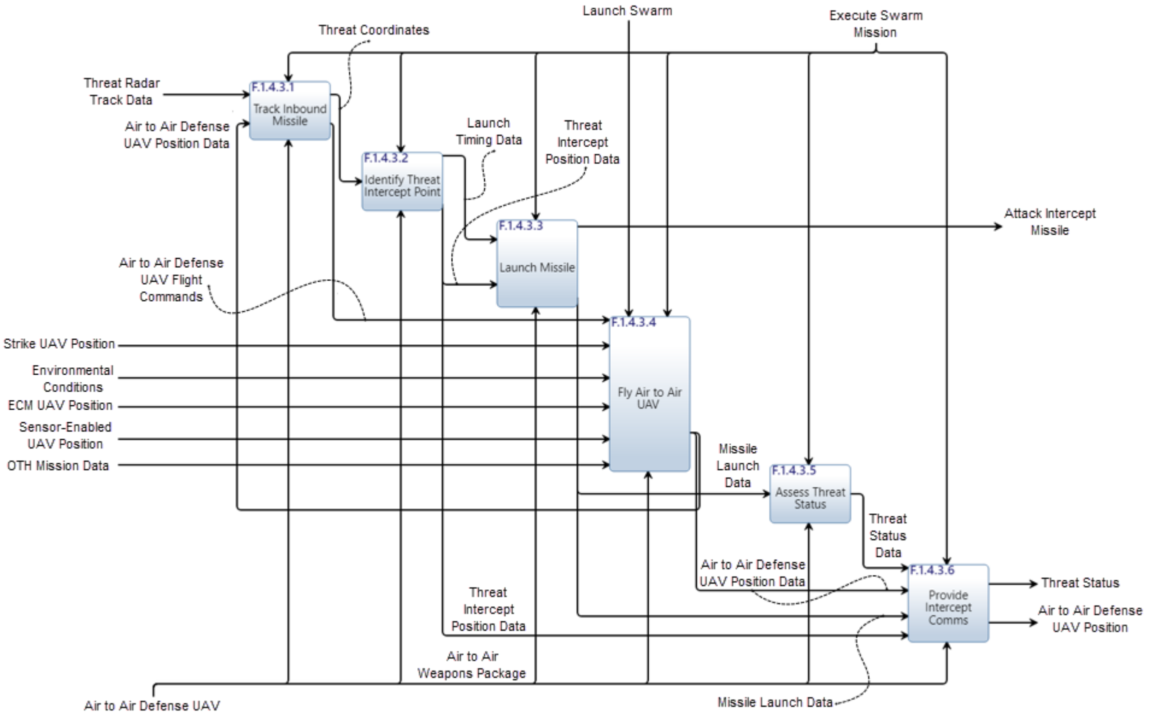

Figure 9. OV-5b for Air-to-Air Defense UAV System Sub-functions IDEF0

9. Level F-3 IDEF0 Sub-function of ECM UAV

The decomposition of the electronic countermeasure (ECM) UAV operation describes the interfaces and functions that enable the mission execution to have an ECM defensive capability. The sub-functions include calculating the jamming position and providing the jamming signal. These functions describe the ECM UAV capability needed to provide the swarm with a radar jamming operation. A jamming capability within the swarm can reduce the probability of success for an incoming threat. Decreasing the likelihood of success that a UAV in the swarm is damaged will help improve the probability of success for the overall mission. See Figure 10 for a depiction of the interactions between the ECM UAV's sub-functions.

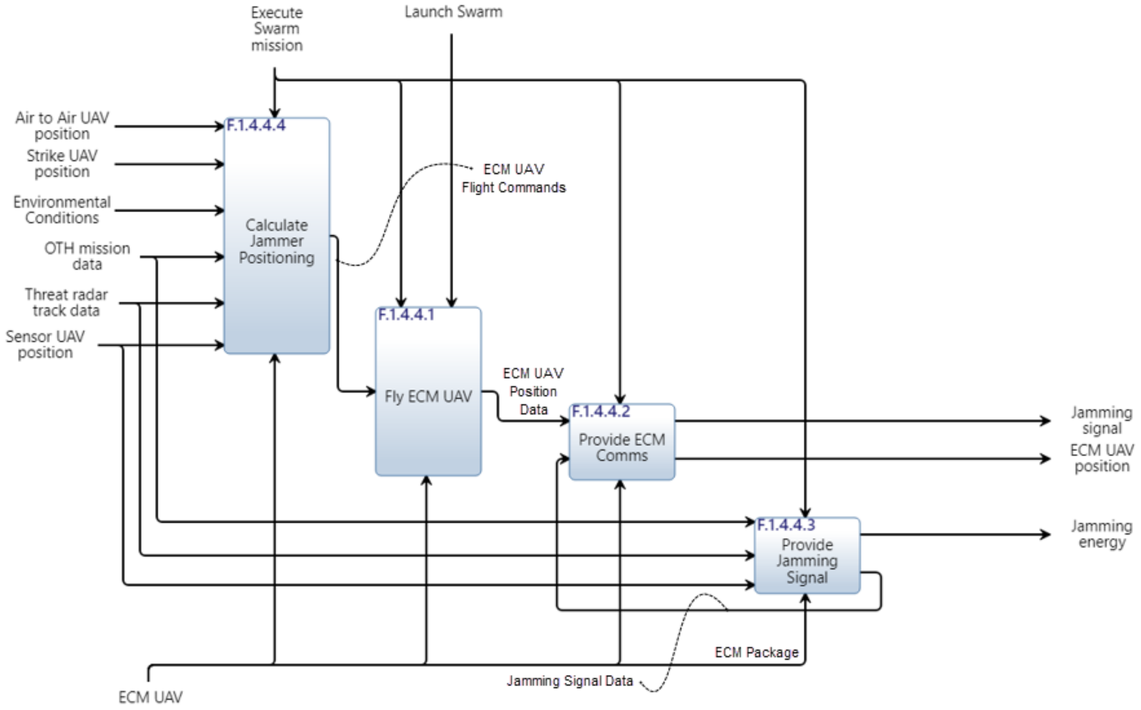

Figure 10. OV-5b for ECM UAV System Sub-functions IDEF0

The F-3 level of decompositions provides an understanding of the individual UAV capabilities supported through the UAV functional decompositions. This breakdown aided in identifying the sensor, strike, air-to-air, and ECM functions needed to develop the swarm capability. After several iterations of the decomposition, the UAV sub-functions can provide further fidelity in the development of the system architecture. They help define the swarm capabilities as needed to support the mission execution from a unique UAV mission package.

10. OV-6c: Event Trace Description

The OV-6c diagram traces the actions that occur in a given scenario or sequence of events. It provides a time-ordered examination of the resource flow for the swarm scenario as well as the tracing of actions in a critical sequence of events. The mission execution capability is modeled by the set of activities and their attributes. The event trace description captured focuses on the sequence of events completed by the swarm during the execution of the OTH strike mission. It establishes the inter-swarm events by describing the UAV to UAV interactions needed for the execution of the OTH mission. This event trace will be leveraged for the development of the modeling and simulation part of the project. The event trace diagram is shown in Figure 11.

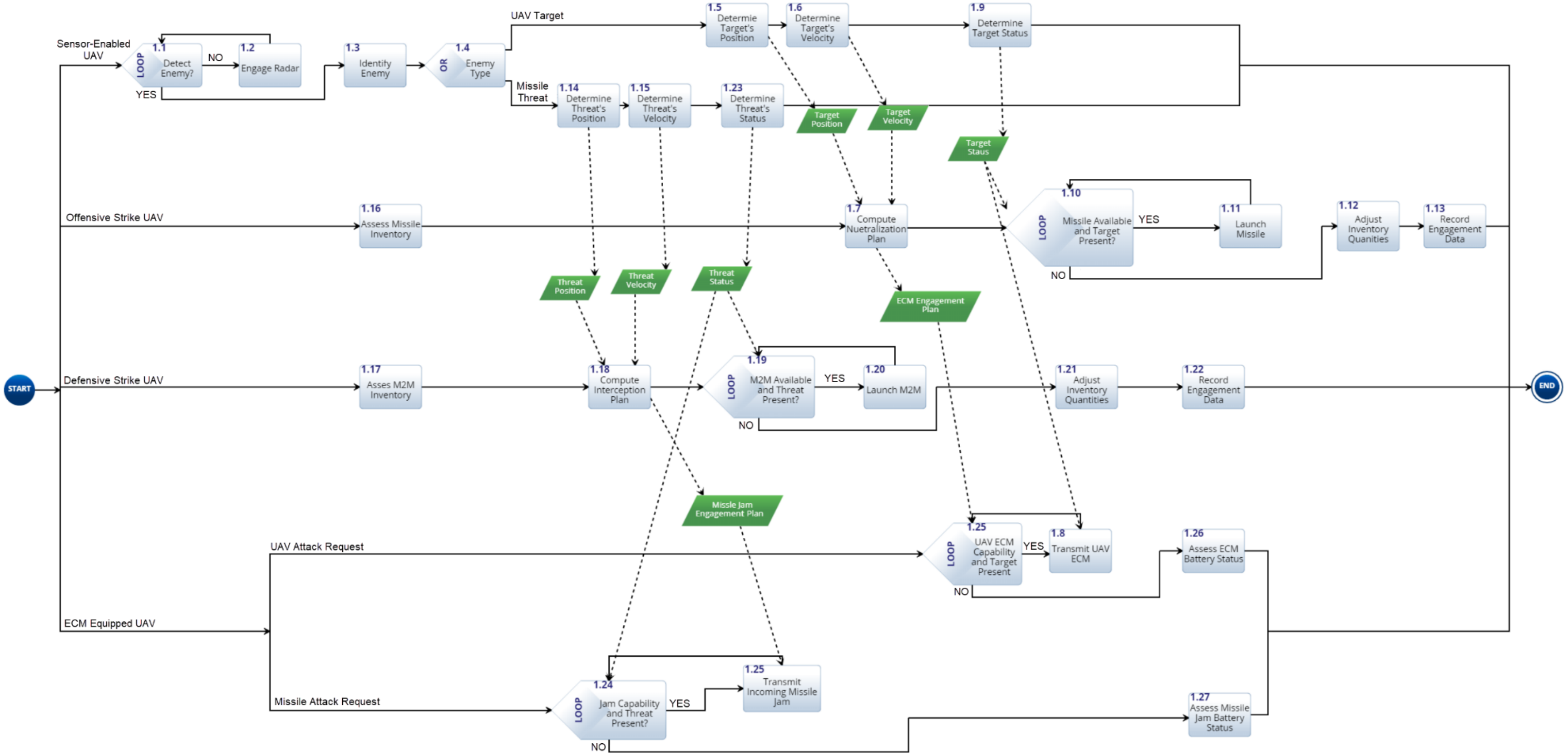

Figure 11. OV-6c Event Trace Description

C. SYSTEM ARCHITECTURE

Systems architecture view (SV) describes the system of concern and the connections among the system and subsystems in context with the operational view. The SV allows for evaluation of system operational requirements, evaluation of interoperability issues, and system baselining. As a group, we decided to showcase our system through the use of an SV-1, SV-2, and SV-4 diagram.

1. SV-1: Systems Interface Description

The SV-1 in Figure 12 visualizes the interconnections between the system and its subsystems. The SV-1 depicts the sharing of information between the battlegroup assets. Note the surface ship is acting as a vital node in the relay of this information. The surface ship collects data from GPS satellites, airborne radars, and the UAV swarm. In return, the surface ship relays collected information to each asset as needed. Together, each asset, including the surface ship, is more aware of potential threats in the battlespace than any one asset would be otherwise.

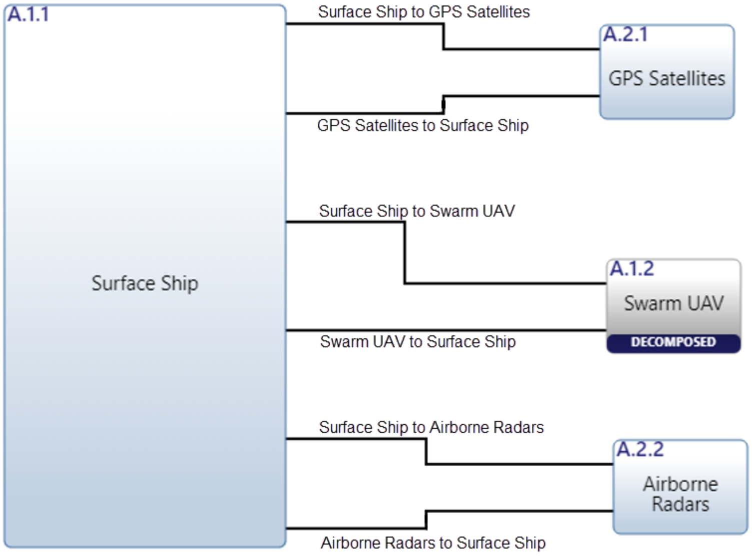

Figure 12. SV-1: Systems Interface Description

2. SV-2: Communications Network Diagram

The SV-2 depicted in Figure 13 details the lines of communication between the swarm assets. Note each UAV is connected to the other three UAVs through a secure data link, which allows information sharing to prevent UAV isolation should any UAV be lost to an incoming threat. The network design also allows information to be relayed between UAVs to maintain situational awareness even when assets are spread across the battlespace.

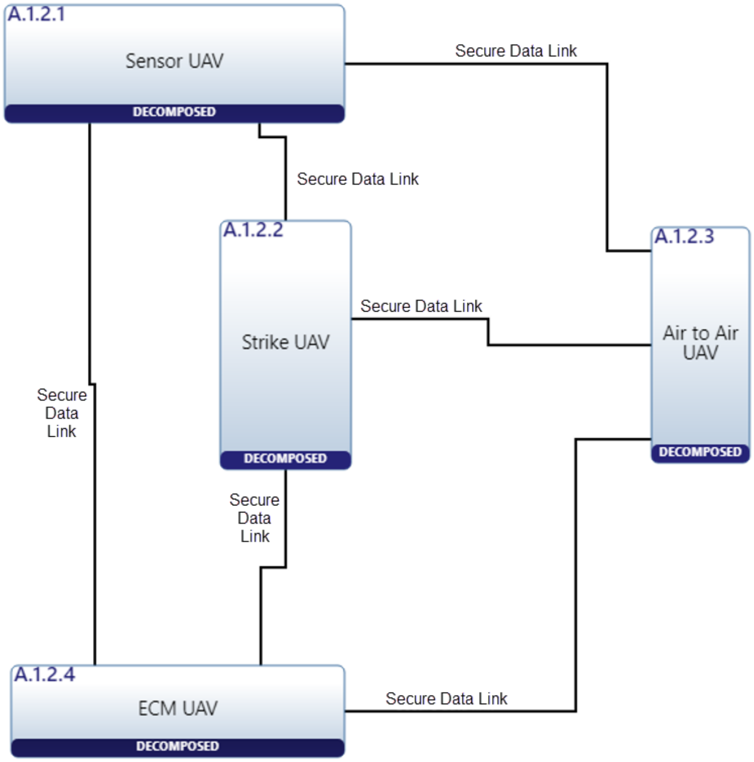

Figure 13. SV-2: Communications Network Diagram

3. SV-4: Functional Hierarchy

The SV-4a depicted in Figure 14 details the functional relationships required to support the over-the-horizon mission. Execution of the over-the-horizon mission is supported by the principle functions of the UAVs, which include providing sensor data, strike capability, air-to-air payload, and electronic countermeasures. Each principle function is decomposed to identify the required subfunctions.

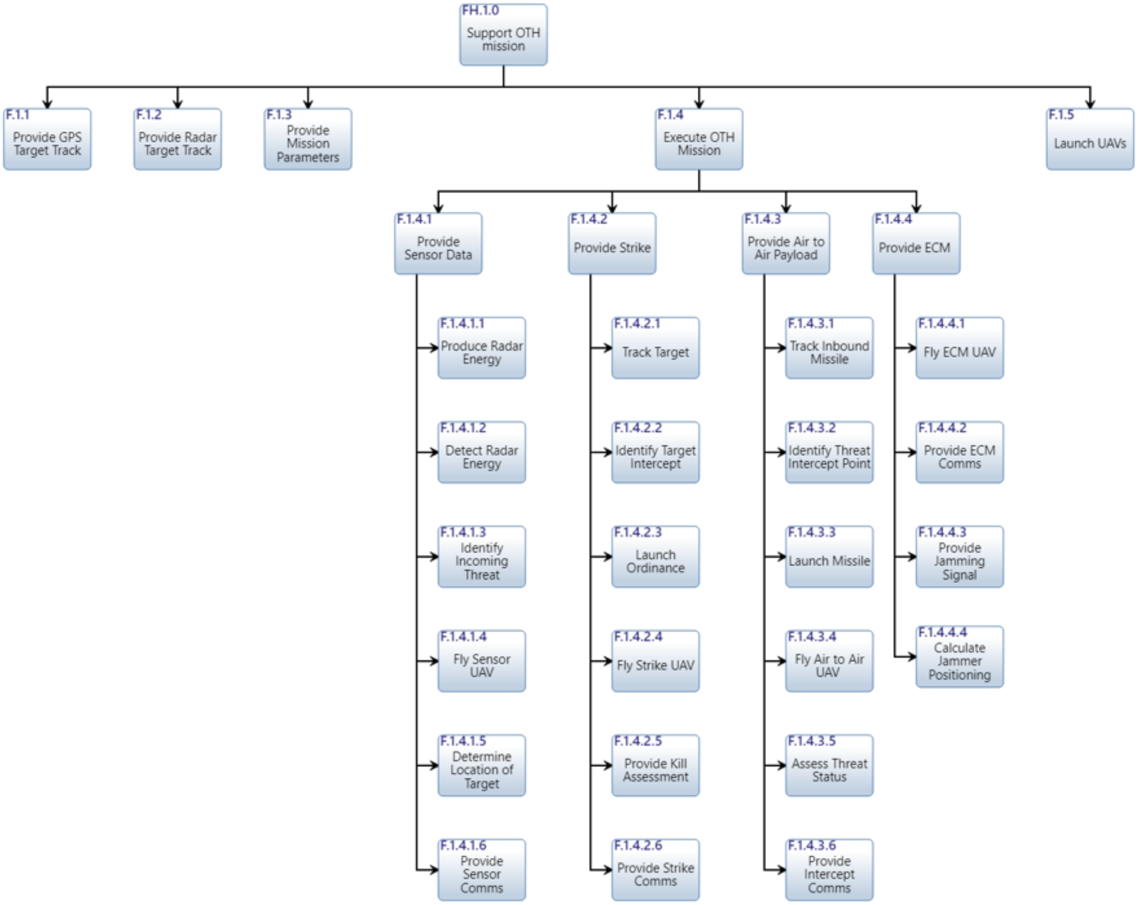

Figure 14. SV-4a: Functional Hierarchy

Reflecting on Chapter III, the operational and system architecture defined to illustrate the relationships required between the swarm assets for mission execution. Chapter IV will culminate the buildup of previous chapters with the modeling and simulation of the OTH mission execution by the UAV swarm.

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IV. MODELING, SIMULATION, AND, OTH MISSION ANALYSIS

This chapter describes the modeling and simulation (M&S) analysis of the system of UAV systems (referred to as the "swarm") for the OTH mission. It includes a look at cost factors for the utilization of UAVs in the execution of the OTH mission. The chapter contains an overview of the M&S effort and a description of the OTH mission analysis methods employed. The purpose of the model, as well as the model's limitations, will be discussed and followed by a review of the data derived from the model; a similar discourse will follow for simulation development. The execution of the OTH mission using UAVs will then be assessed from a cost-effectiveness standpoint with manned platforms.

A. PURPOSE OF THE MODELING, SIMULATION AND MISSION ANALYSIS

The goal of the M&S and mission analysis was to study the operational benefits of adding UAVs to the OTH mission. The M&S analysis assessed the individual UAV performance factors that are drivers for the OTH mission success. A blue force versus red force OTH mission scenario was modeled. The blue force was equipped with four different types of UAVs: sensor-enabled, air-to-air (A/A), electronic countermeasure (ECM), and strike. The red force consisted of a ship that could return fire with its own set of OTH weapons. The red force ship was the OTH target of the blue force. Mission success consisted of eliminating the red force ship. The performance values of the blue force's individual UAV types were varied, and different combinations and configurations of UAVs were modeled. The cost of the UAV mission implementation was assessed as well.

1. Modeling and Simulation Approach

The approach for the M&S effort is shown in Figure 15. A single scenario for the OTH target mission execution was captured. Then a probabilistic model called the swarm Strike Model (SSM) and the Swarm Strike Simulation (SSS) was developed to represent an instance of the scenario. The results from the SSM and the SSS were compared to establish confidence in the M&S effort. The performance data was then used to analyze the execution of the OTH scenario. This analysis was used to provide evidence for making recommendations about the use of UAV for OTH mission execution.

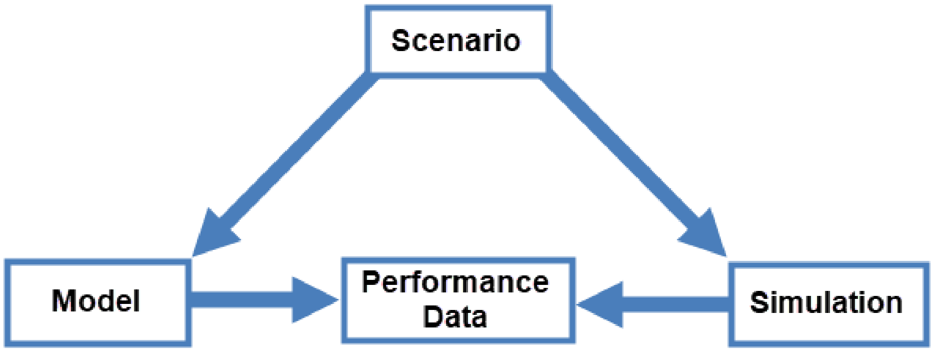


Figure 15. Modeling and Simulation Scenario

2. Modeling and Simulation Scenario

A mission scenario was chosen that represented a blue force OTH strike using a variety of UAV assets onto a red force ship, referred to as the “OTH target.” The red force was equipped with its own OTH weapons to fire at the blue force UAVs. Figure 16 is an illustration of the scenario.

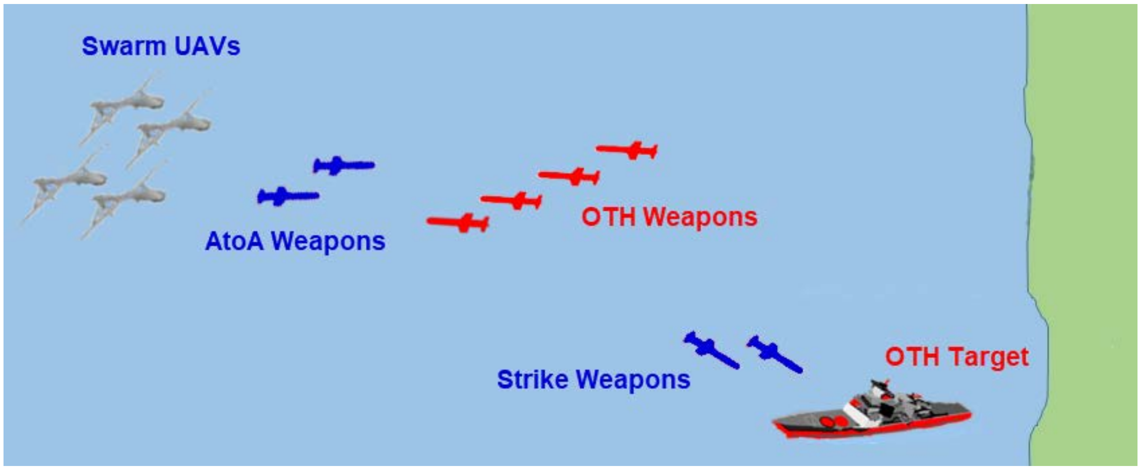


Figure 16. UAV Swarm Engagement Scenario

The M&S efforts leveraged the UAV types described in the CONOPs and the UAV functional descriptions in the DoDAF architectures. In the mission scenario, the red force “OTH target” can fire on the swarm UAVs during the execution of the OTH-S mission. The scenario outcomes capture the OTH target kill as well as the number of swarm UAVs lost to hostile fire. Successful swarm engagement is defined by the elimination of the OTH target while minimizing swarm UAVs lost to hostile fire. Two critical probabilities were leveraged to evaluate the OTH-S mission success: the probability of striking the OTH target and the probability of a swarm UAV being hit. These two probabilities were central to the series of experiments executed to determine the impact of swarm configurations and UAV performance parameters on engagement success.

The scenario shown in Figure 16 was used to develop the M&S capability. The scenario captures the engagement of the swarm by hostile OTH weapons, as shown in the middle of Figure 16. The inbound threats may be intercepted by the A/A UAV’s weapon loadout. The remaining OTH weapons, if any, may be defeated by the jamming energy of the ECM UAV when the ECM UAV is included in the swarm configuration. Any OTH weapons that survive intercept and jamming attempts will have the opportunity to kill a swarm UAV. If the Strike UAV survives the OTH weapons engagement, the UAV will release the strike weapons on the OTH target, as shown in the lower right of Figure 16. The strike weapons will be aided by the sensor-enabled UAV when present in the swarm. Elimination of the OTH target is considered a mission success. Note the scenario detailed above assumes the OTH target environment does not include any factors inhibiting swarm performance.

3. Modeling, Simulation, and Data Analysis Tools

The SSM used for assessing the OTH mission was developed in Excel. This model uses several of the built-in Excel functions including the random number generator and the Binomial Inverse Function, which returns the inverse of the Cumulative Binomial Distribution for a given number of independent trials. These functions allow for probabilistic evaluation of the OTH engagements. The SSM also used the Visual Basic (VB) software in Excel to automate the generation and collection of the swarm configuration data. The SSM’s VB script runs every allowable swarm configuration and captures the probabilities affecting mission success for each run.

Confidence in the SSM was increased upon comparing the results from the SSM to those obtained from the SSS. The SSS created for this purpose, which was developed in ExtendSim, captures a time-based execution of the OTH mission scenario. The ExtendSim functions for normal distribution time delays, random number generation, and probabilistic branch selection were used to produce the metrics required for comparable assessment of the OTH scenario.

The M&S effort used both the Excel and Minitab statistical analysis tools to assess data generated. Excel was used to calculate the variance and confidence intervals for the data produced by the SSM. The statistical tools in Minitab were used to generate the design of experiments for the UAV performance parameter analyses. Minitab was also used to generate the main effects analysis using the data from the design of experiments (DOE) executions. The role of each tool in the M&S effort is summarized by the flowchart shown in Figure 17.

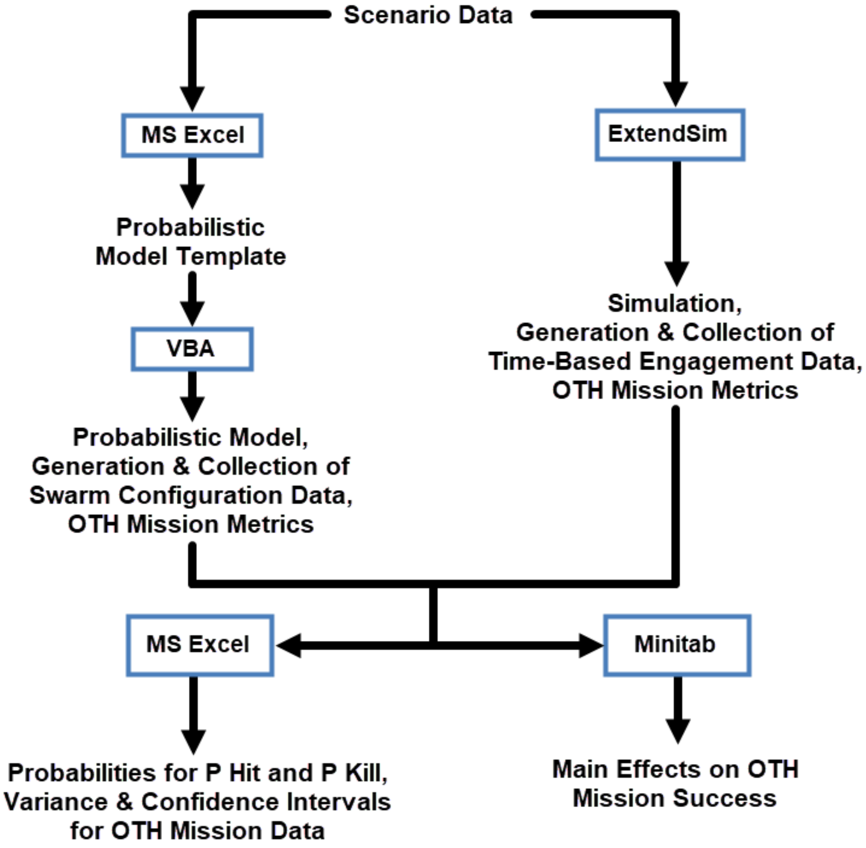


Figure 17. Modeling and Simulation Flowchart

4. Assumptions and Constraints

Several assumptions were made at the onset of the project. For instance, the scenario assumes a single hit to a swarm UAV, the OTH target, or OTH weapon will result in a kill of the targeted asset. In addition, the OTH target position is assumed known prior to swarm launch and will not loiter outside the effective range of the swarm. Note the current SSM and SSS builds neglect adverse effects in the OTH target environment, such as severe weather and geographical influences. Swarm UAV reliability is also neglected.

Both SSM and SSS are constrained to a single OTH target engagement per scenario execution. The OTH weapon performance, percent of kills per engagement, is defined in terms of threat probability of kill (threat P_k) in both the SSM and SSS. Threat P_k in the M&S was held constant at 70 percent throughout scenario execution. The SSM was constrained to having a maximum of five of each UAV type in the mission. This was done to manage the complexity of the SSM in relation to its capability for assessing swarm sizes. One functional constraint is that the SSM does nothing to prevent the OTH weapons from targeting the same UAV multiple times. The SSS was developed to have a single configuration of each UAV in the swarm during the scenario execution. This was done to manage the complexity of the SSS and focus on the assessment of the UAV specific performance factors.

5. Modeling and Simulation Capabilities

The M&S effort developed both the SSM and the SSS as a means to provide more fidelity in the OTH mission analysis. A full comparison of the SSM versus the SSS capabilities is shown in Table 3.

Table 3. M&S Capability Comparison

Capability	Modeling	Simulation
UAV performance factors	Included	Included
Swarm UAV configurations	Variable	1 each
OTH target	Single	Single
OTH target weapons loadout	Variable	Set to 4
OTH weapons targeting order	Based on RCS	Based on RCS
OTH weapons targeting fidelity	Low	Medium
OTH weapon performance	Set to 70%	Set to 70%

The low assessment for the SSM targeting fidelity reflects a limitation inherent to the model that allows the continued targeting of a downed UAV. The model’s targeting fidelity is further reduced by the instantaneous assessment of all engagements, which negates the effects of volley timing and follow-on target selection. The SSS targeting fidelity was assessed as medium due to the inclusion of a timing component. The timing component allowed for the downing of the A/A or ECM UAV at mission onset. The loss of these UAVs decreased the swarm’s defensive capabilities and the OTH weapons were able to target another UAV with a greater kill probability. The SSS targeting fidelity was not assessed as high due to the complexity preventing multiple swarm configurations to be readily assessed. As such, only one UAV of each type was represented in the swarm configuration for the simulation effort.

B. DESCRIPTION OF THE MODEL

1. Model Parameters

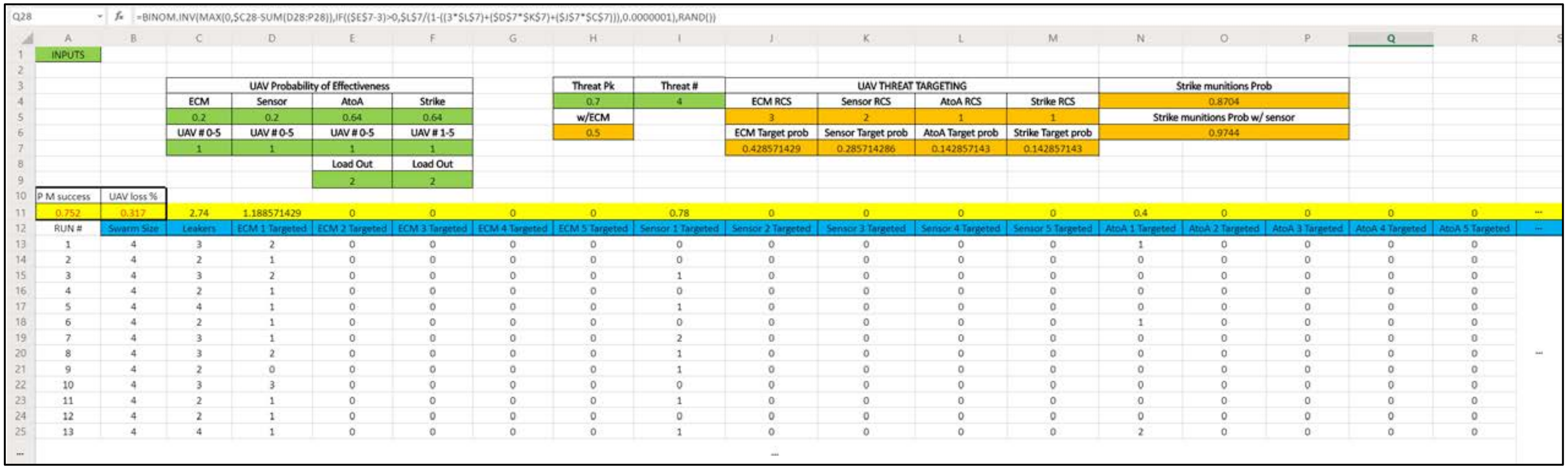
Weapon performance values are integral to the UAV performance analysis and drive the target kill assessment. The success of a weapon's engagement is quantified by the probability of target intercept, the probability of target elimination upon intercept, and the overall weapon reliability. Factors affecting the performance of assets assigned to the Strike and A/A UAVs are accounted for in their respective success probabilities. Factors affecting the probability of effectiveness for the sensor-enabled and ECM UAVs are accounted for in each UAV's net contribution to the swarm. The sensor-enabled UAV's probability of effectiveness reflects the UAV's ability to enhance the intercept of A/A UAV's intercept of OTH weapons as well as the Strike UAV's probability of OTH target hit. Likewise, the EMC UAV's probability of effectiveness reflects the UAV's ability to degrade the performance of inbound OTH weapons. The M&S efforts did not account for factors affecting UAV reliability, thereby allowing for an engagement success value of 1. Known reliability events could be integrated by multiplying the engagement probabilities by the reliability value of the swarm UAV.

Using the CONOPs and system architecture developed for the OTH mission as a foundation, the team developed the SSM for the swarm OTH engagement scenario. The SSM allows for the assessment of swarm size and selection of UAV assets as well as analysis of individual UAV performance. These metrics are captured in the SSM and expressed in terms of probability of relative success.

There are several probability factors included in the SSM, such as the probabilities for targeting order for OTH weapons. The UAV targeting probabilities are based on assumptions developed from a radar cross-section (RCS) analysis of the UAVs. An inbound OTH weapon is expected to target the ECM UAV with the sensor-enabled UAV being the next likely target. The remaining OTH weapons would give the A/A and strike

UAVs equal priority. The ECM UAV is thought to be the priority target for the OTH weapons as the UAV's escort jamming capability is most effective with the UAV in front of the swarm. The ECM UAV is likely the first UAV targeted by the OTH weapons due to its jamming signal transmission and lead formation position. The sensor-enabled UAV's employment of radar to enhance the OTH firing solution also generates considerable radar signature thereby placing the UAV next OTH weapon's targeting order. The A/A and strike UAVs have a similar configuration and asset loadout, which allows the UAVs to share the lowest position in the targeting order.

The probability that a hostile force would target and eliminate a swarm UAV is dependent on the engagement values and performance of the OTH weapons. Successful engagement of the A/A weapons reduces the number of inbound threats. Likewise, the employment of the ECM UAV function minimizes the probability that a hostile threat will be successful in killing a swarm UAV. Once the probability of a successful OTH weapon engagement has been evaluated, and the fallout of the intercept attempt realized, the number of UAV casualties per scenario execution is used to determine the probability of the UAV hit (P_{Hit}) metric. Next, the SSM predicts the success of the OTH target kill using the remaining strike UAVs weapons available. The OTH target kill success is used in the calculation of the probability of success ($P_{Success}$) metric. An excerpt from the SSM is shown in Figure 18.



```
Q28   fx  =BINOM.INV(MAX(0,$C28-SUM(D28:P28)),IF(($E$7-3)>0,$L$7/(1-((3*$L$7)+($D$7*$K$7)+($J$7*$C$7))),0.0000001),RAND())
```

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	INPUTS																		
2																			
3			UAV Probability of Effectiveness					Threat Pk	Threat #	UAV THREAT TARGETING				Strike munitions Prob					
4			ECM	Sensor	AtoA	Strike		0.7	4	ECM RCS	Sensor RCS	AtoA RCS	Strike RCS	0.8704					
5			0.2	0.2	0.64	0.64		w/ECM		3	2	1	1	Strike munitions Prob w/ sensor					
6			UAV # 0-5	UAV # 0-5	UAV # 0-5	UAV # 1-5		0.5		ECM Target prob	Sensor Target prob	AtoA Target prob	Strike Target prob	0.9744					
7			1	1	1	1				0.428571429	0.285714286	0.142857143	0.142857143						
8					Load Out	Load Out													
9					2	2													
10	P M success	UAV loss %																	
11	0.752	0.317	2.74	1.188571429	0	0	0	0	0.78	0	0	0	0	0.4	0	0	0	0	...
12	RUN #	Swarm Size	Leakers	ECM 1 Targeted	ECM 2 Targeted	ECM 3 Targeted	ECM 4 Targeted	ECM 5 Targeted	Sensor 1 Targeted	Sensor 2 Targeted	Sensor 3 Targeted	Sensor 4 Targeted	Sensor 5 Targeted	AtoA 1 Targeted	AtoA 2 Targeted	AtoA 3 Targeted	AtoA 4 Targeted	AtoA 5 Targeted	...
13	1	4	3	2	0	0	0	0	0	0	0	0	0	1	0	0	0	0	
14	2	4	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
15	3	4	3	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	
16	4	4	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
17	5	4	4	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	
18	6	4	2	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	
19	7	4	3	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	
20	8	4	3	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	...
21	9	4	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	
22	10	4	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
23	11	4	2	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	
24	12	4	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
25	13	4	4	1	0	0	0	0	1	0	0	0	0	2	0	0	0	0	
...										...									

Figure 18. Swarm Strike Model Excerpt

The orange boxes shown in Figure 18 highlight the calculated values used in the execution of the scenario. These values are not altered by direct input; however, several values are linked to input values and may vary as a result. The targeting probability values, shown below the probability cells, are mathematically defined by RCS in the targeting process.

The UAV performance inputs and OTH weapons performance parameters are shown in Table 4. These values are also shown in the light green boxes of Figure 18. In addition to these values, the table captures the allowable range for the SSM inputs.

Table 4. Swarm Strike Model Input Parameters

UAV Probability of Effectiveness				
	ECM	Sensor	A/A	Strike
Range	0.01-0.99	0.01-0.99	0.01-0.99	0.01-0.99
	Swarm Configuration			
	ECM	Sensor	A/A	Strike
Range	0-5	0-5	0-5	1-5
	UAV Weapons		OTH Weapons	
	Strike Loadout	A/A Loadout	Threat Pk	Threat Load-out
Range	0-4	0-4	0.7	0-4

The range values shown in Table 4 were used to calculate asset-specific probabilities. While the full range shown in Table 4 is allowed in the SSM execution, the probability of effectiveness for a given platform is bounded by operational effectiveness parameters as well as reliability factors. These bounds were defined by the performance assessments conducted on each UAV platform. The number of weapons a UAV may carry is not mathematically restrained in the SSM; the values shown reflect the range considered for the scenario assessment. Once the SSM functionality was confirmed, a study of the output variance was conducted to assess the consistency of the results.

The data in Table 5 shows the variance in the SSM outputs for $P_{Success}$ and P_{Hit}.

Table 5. Swarm Strike Model Output Variance

Model	**100 runs**		**200 runs**		**350 runs**		**500 runs**	
Sample	$P_{Success}$	P_{Hit}	$P_{Success}$	P_{Hit}	$P_{Success}$	P_{Hit}	$P_{Success}$	P_{Hit}
1	0.740	0.335	0.750	0.318	0.746	0.304	0.704	0.319
2	0.720	0.315	0.720	0.315	0.717	0.319	0.738	0.313
3	0.720	0.300	0.760	0.286	0.703	0.331	0.740	0.322
4	0.730	0.290	0.725	0.324	0.731	0.305	0.726	0.324
5	0.740	0.293	0.700	0.300	0.766	0.320	0.714	0.321
6	0.770	0.308	0.770	0.311	0.723	0.339	0.720	0.326
7	0.820	0.305	0.720	0.311	0.723	0.354	0.746	0.328
8	0.700	0.343	0.745	0.336	0.709	0.325	0.748	0.313
9	0.720	0.310	0.715	0.326	0.743	0.327	0.744	0.309
10	0.710	0.328	0.740	0.300	0.706	0.317	0.736	0.319
11	0.740	0.300	0.760	0.314	0.726	0.335	0.734	0.316
12	0.720	0.288	0.720	0.331	0.686	0.338	0.718	0.318
13	0.840	0.303	0.740	0.331	0.746	0.315	0.728	0.319
14	0.740	0.323	0.760	0.320	0.737	0.323	0.732	0.331
15	0.780	0.333	0.740	0.305	0.726	0.326	0.706	0.319
16	0.680	0.328	0.775	0.290	0.729	0.317	0.738	0.317
17	0.730	0.315	0.695	0.323	0.751	0.312	0.692	0.309
18	0.700	0.298	0.725	0.296	0.706	0.328	0.744	0.328
19	0.780	0.295	0.780	0.301	0.737	0.320	0.750	0.317
20	0.740	0.310	0.715	0.319	0.731	0.329	0.756	0.314
Variance	1.58E-03	2.57E-04	6.04E-04	1.98E-04	3.66E-04	1.38E-04	2.91E-04	3.71E-05
Mean	0.741	0.311	0.738	0.313	0.727	0.324	0.731	0.319
95% CI +/-	0.019	0.007	0.012	0.007	0.009	0.005	0.008	0.003
99% CI +/-	0.025	0.010	0.016	0.009	0.012	0.008	0.011	0.004

The number of model trials was gradually increased from 100 to 500 runs per engagement. All inputs for the SSM were held constant during the increase of trial runs. A selection of 20 samples was collected at the higher trial count for statistical analysis. As shown in Table 5, the observed variance decreases as the number of trial runs increases per engagement. The variances were then used to calculate the 95 and 99 percent confidence intervals. The benefit of adding additional trial runs on $P_{Success}$ output decreases significantly from 350 to 500 runs. Based on the minimal difference in obtained data and the increased time required to run the SSM, a run size of 350 was selected for the remaining analyses.

2. Model Runs for UAV Performance Factors

The SSM established six UAV performance factors. The ECM and sensor performance, as well as loadout, A/A, and strike weapon performance, were assigned values of estimated effectiveness on a scale from zero to one; a value of zero represents no effect and a value of one would be completely effective. For instance, an effective range of 0.20 to 0.50 was estimated for the ECM UAV while the sensor UAV was assigned an effective range of 0.20 to 0.50. Using the six UAV performance factor inputs to the SSM, a 2-level factorial design of experiments (DOE), with a 1/8 fraction and a single center point per cube, was developed. The performance modeling inputs and outputs for the DOE are captured in Table 6.

Table 6. UAV Performance Modeling DOE

P_{ECM}	P_{Sensor}	$P_{A/A}$	P_{Strike}	Strike Loadout	A/A Loadout	$P_{Success}$	P_{Hit}
0.20	0.50	0.64	0.64	4	1	0.723	0.391
0.20	0.50	0.64	0.84	1	4	0.831	0.182
0.20	0.20	0.84	0.64	4	4	0.946	0.086
0.20	0.20	0.84	0.84	1	1	0.697	0.351
0.50	0.20	0.64	0.64	1	4	0.760	0.091
0.50	0.20	0.64	0.84	4	1	0.849	0.208
0.35	0.35	0.74	0.74	3	3	0.931	0.152
0.50	0.50	0.84	0.64	1	1	0.809	0.170
0.50	0.50	0.84	0.84	4	4	0.983	0.029

Referring to Table 6, the ECM P-value relates to the degradation in the performance of an inbound OTH weapon as caused by the ECM UAV. On the offensive, the sensor performance (Sensor P) value represents the enhancement of the strike weapon's performance afforded by the sensor-enabled UAV. The A/A and strike performance (Strike P) values represent the probability of hit for each weapon in the A/A and strike UAV loadout. The strike and A/A loadout values capture the total number of weapons in the swarm as equipped by the respective UAV platform.

The swarm configuration was maintained at one UAV of each configuration to ensure that multiple UAVs of the same platform did not weigh the performance parameters. The OTH weapons loadout was set to four to present a stressing engagement for the swarm. The results of the DOE were evaluated in Minitab. The main effects for the probability of OTH hit ($P_{Success}$) and the probability of UAV hit (P_{Hit}) are captured in Figures 19 and 20.

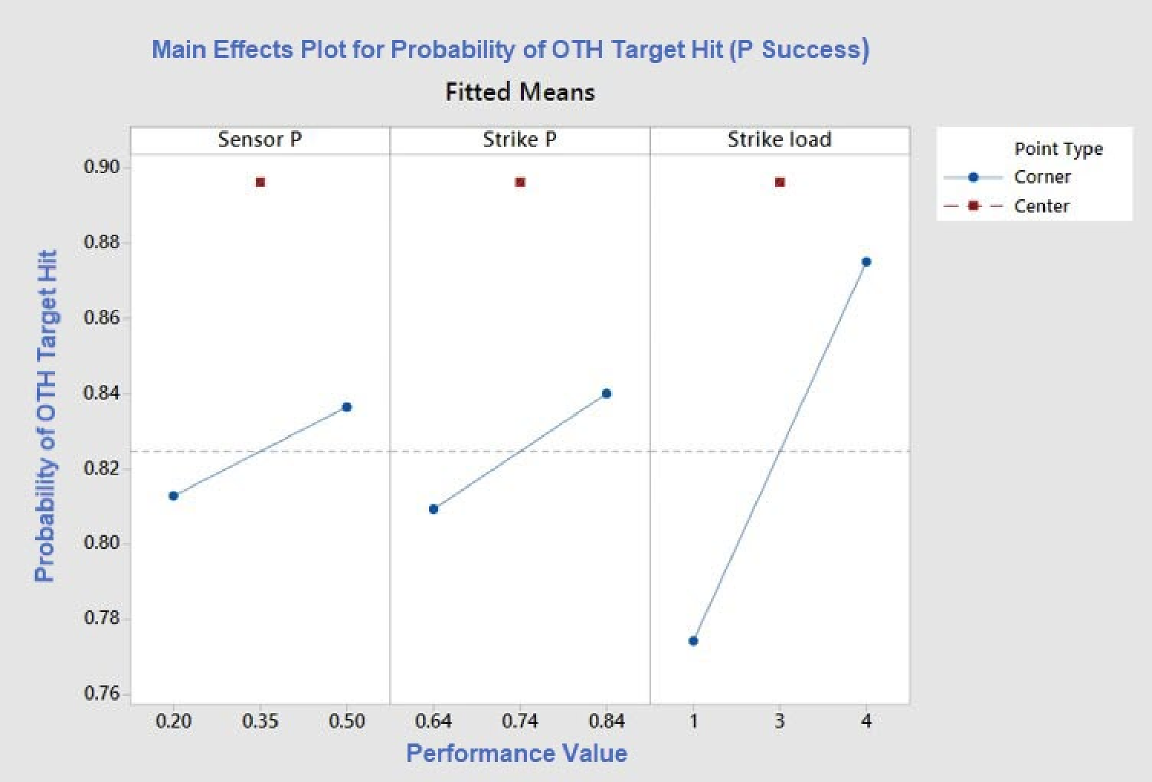


Figure 19. Engagement Probability of Success Main Effects

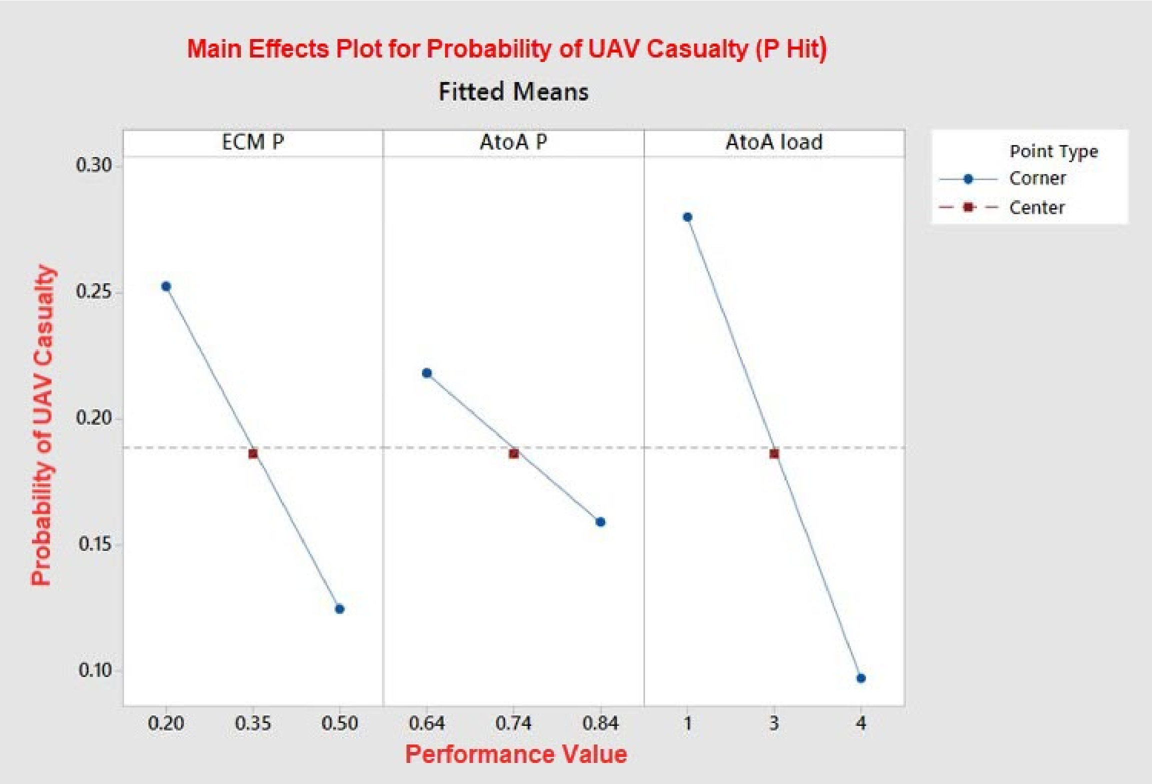


Figure 20. Engagement Probability of Hit Main Effects

The slope of the line in the main effects plots captures the impacts of the UAV performance factors on the engagement criteria. The plots show that increasing the strike loadout has the most significant impact on the probability of OTH hit. While increasing the A/A loadout has the most significant impact on the probability that a UAV is hit. The overall engagement was evaluated, and the SSM is predicting that UAV survivability is driving $P_{Success}$ for the OTH engagement.

3. Model Runs for Swarm Configurations

Utilizing the swarm configuration capability of the SSM, a two-level factorial DOE with a 1/8 fraction and a single center point per cube, for the swarm size was developed in the Minitab software tool. The model inputs and outputs for the swarm size DOE, shown in Table 7, cover the analysis of a mission where the OTH target has a loadout of four weapons.

Table 7. Swarm Size and Configuration Modeling Design of Experiments
with a Red Force with a Return Fire Capability of Four Weapons

ECM UAV	Sensor UAV	A/A UAV	Strike UAV	$P_{Success}$	P_{Hit}
5	5	0	1	0.914	0.173
0	0	5	5	1.000	0.003
0	0	0	1	0.006	0.994
0	5	0	5	1.000	0.246
5	0	0	5	0.997	0.180
5	5	5	5	1.000	0.001
5	0	5	1	0.803	0.002
0	5	5	1	0.963	0.004

The data shown in Table 8 has the inputs and outputs for the analysis of a mission where the OTH target has no return fire capability.

Table 8. Swarm Size and Configuration Modeling Design of Experiments
with a Red Force with No Return Fire Capability

ECM UAV	Sensor UAV	A/A UAV	Strike UAV	$P_{Success}$
5	5	0	1	0.969
0	0	5	5	1.000
0	0	0	1	0.834
0	5	0	5	1.000
5	0	0	5	1.000
5	5	5	5	1.000
5	0	5	1	0.883
0	5	5	1	0.963

The combination of each of the UAV configuration numbers equates to the total swarm size for the engagement. The performance inputs remained constant at 0.2 for the ECM and sensor, while the A/A and strike weapons performance values were set to 0.64. The A/A and strike loadouts were set to two each. The swarm size was evaluated for an OTH weapons loadout of zero, or non-stressing, and loadout of four, a highly stressing engagement. The results of the DOE were evaluated in Minitab. The following three figures capture the main effects for the probability of OTH hit ($P_{Success}$) based on the red force OTH loadouts of zero (shown in Figure 21) and four (shown in Figure 22) as well as the probability of UAV hit (P_{Hit}) for an OTH loadout of four (shown in Figure 23).

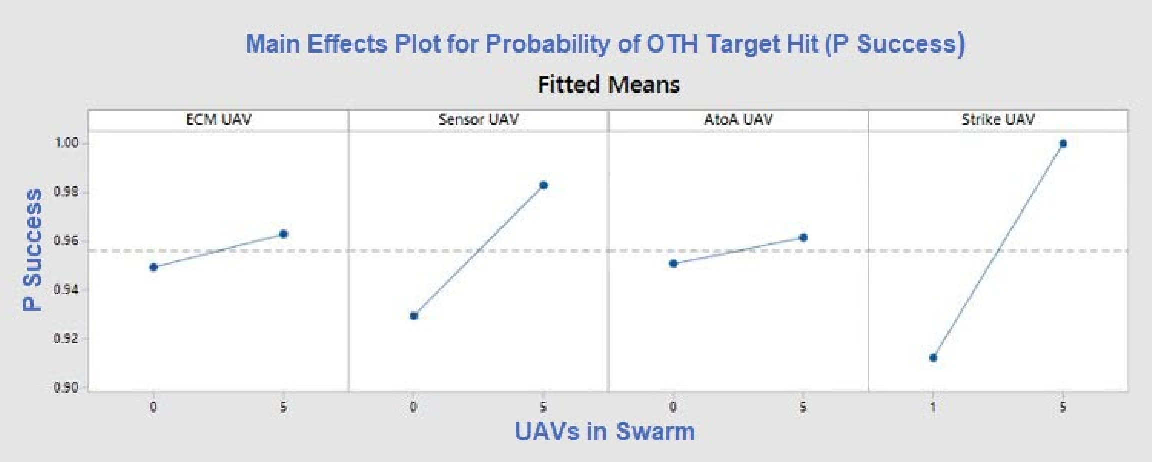


Figure 21. Probability of Success Main Effects for Red Force with No Return Fire Capability

The main effects plots for the modeling parameters show the strike UAV is the performance driver for the scenario in which the red force has no return fire capability. The A/A and ECM UAVs have a negligible impact in this scenario since there are no OTH weapons to act upon.

The main effects plot in Figure 22 shows all UAV configurations are significant in the scenario where the red force can return fire using four weapons. As seen in Figure 22, increasing the number of strike UAVs has the most significant positive impact on mission success. A swarm consisting of five strike UAVs provide additional opportunities for engagement of the OTH target. However, a UAV swarm consisting solely of strike UAVs is more susceptible to casualties and is not ideal.

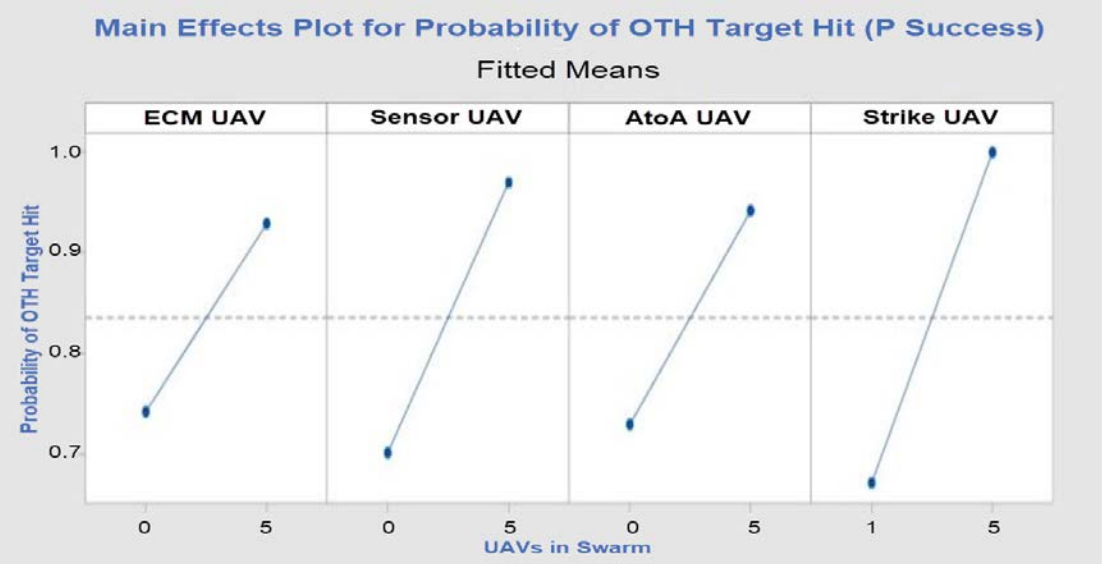


Figure 22. Probability of Success Main Effects for Red Force with Four Return Fire Weapons

The main effects plots in Figure 23 show that the UAV hit (P_{Hit}) performance driver for the four fire OTH engagement is the A/A UAV. The sensor and strike UAVs have an equivalent impact on P_{Hit} due to the constant OTH weapons having an increasing number of targets. However, increasing the number of A/A UAVs has the most significant positive impact on the P_{Hit} criteria for mission execution.

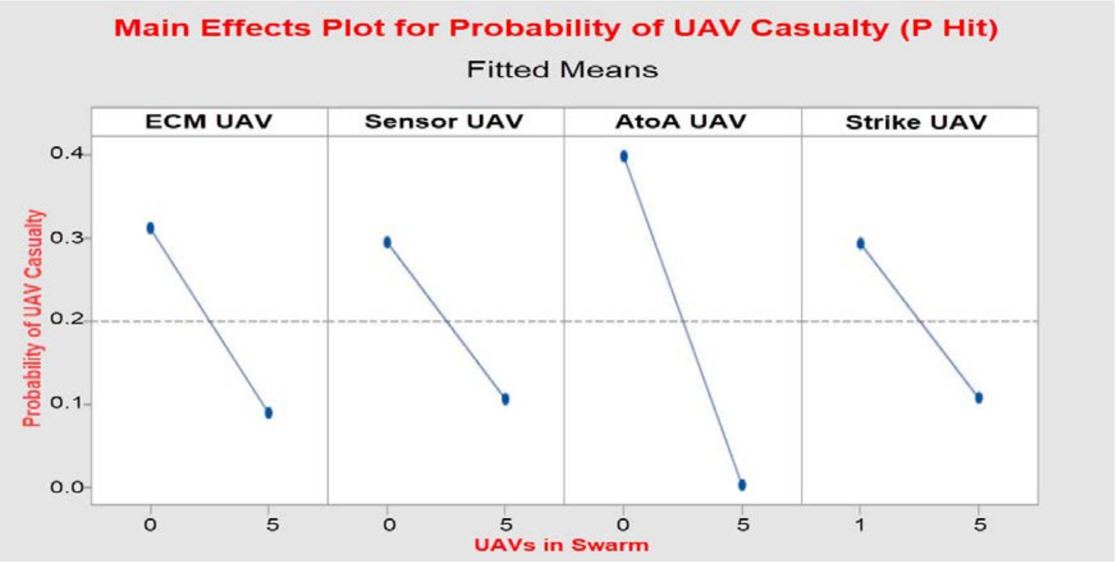


Figure 23. Probability of Hit Main Effects against Red Force with a Return Fire Capability of Four Weapons

4. Lookup Table Model of Swarm Configurations

The SSM was also used to produce a table of swarm configurations as a lookup table for the execution of a set of OTH engagements, as shown in Table 9. This table was developed by evaluating the OTH return fire capability shown in the threat column. The swarm configurations were chosen by maximizing the probability of OTH hit ($P_{Success}$) while minimizing the values of UAV hit (% UAV loss) and reducing the UAVs committed to each engagement to ensure the highest number of missions could be completed.

Table 9. Swarm Configuration for OTH Engagement

Threat No.	ECM No.	Sensor No.	A/A No.	Strike No.	$P_{Success}$	P_{Hit}	Swarm Size
0	0	1	0	1	0.986	0.000	2
1	1	1	1	1	0.963	0.014	4
2	0	1	1	2	0.971	0.119	4
2	1	1	2	1	0.963	0.021	5
3	0	1	2	2	0.974	0.081	5
3	1	1	1	2	0.974	0.175	5
4	0	1	2	2	0.969	0.170	5
4	1	1	1	2	0.966	0.260	5

The data in Table 9 represents the recommended swarm sizes for deployment against OTH targets that have a known return fire capability. For an OTH target without return fire capability, the SSM is predicting that a swarm configuration of one sensor and one strike UAV will have a 98% probability of target kill. The prediction for the stressing scenario includes two swarm configurations with good probabilities for the scenario metrics of $P_{Success}$ and P_{Hit}. The determining factor in using one swarm configuration over another is made when planning the likelihood of follow on missions. Choosing to deploy a swarm consisting of a single A/A UAV allows an additional OTH mission to be accomplished using an A/A UAV in the swarm.

C. SIMULATION ANALYSIS

The SSS executes the single OTH target engagement with the same mission performance parameter outputs as the SSM. The UAV performance simulation the SSS for the OTH engagement was developed to increase the fidelity of the performance data analysis. The OTH engagement in the SSS was developed in two parts. The first part captures the incoming fire of the OTH weapons. The second part evaluated the engagement of the OTH target based on the surviving swarm UAVs. The SSS includes functionality that disables the targeting and capabilities of UAVs that have been hit by the OTH salvo.

The SSS is shown in Figure 24 was used to conduct an additional assessment of the UAV performance factors. This data was used to build confidence in the modeling results as well as provide further evaluation of the scenario success drivers based on UAV performance factors.

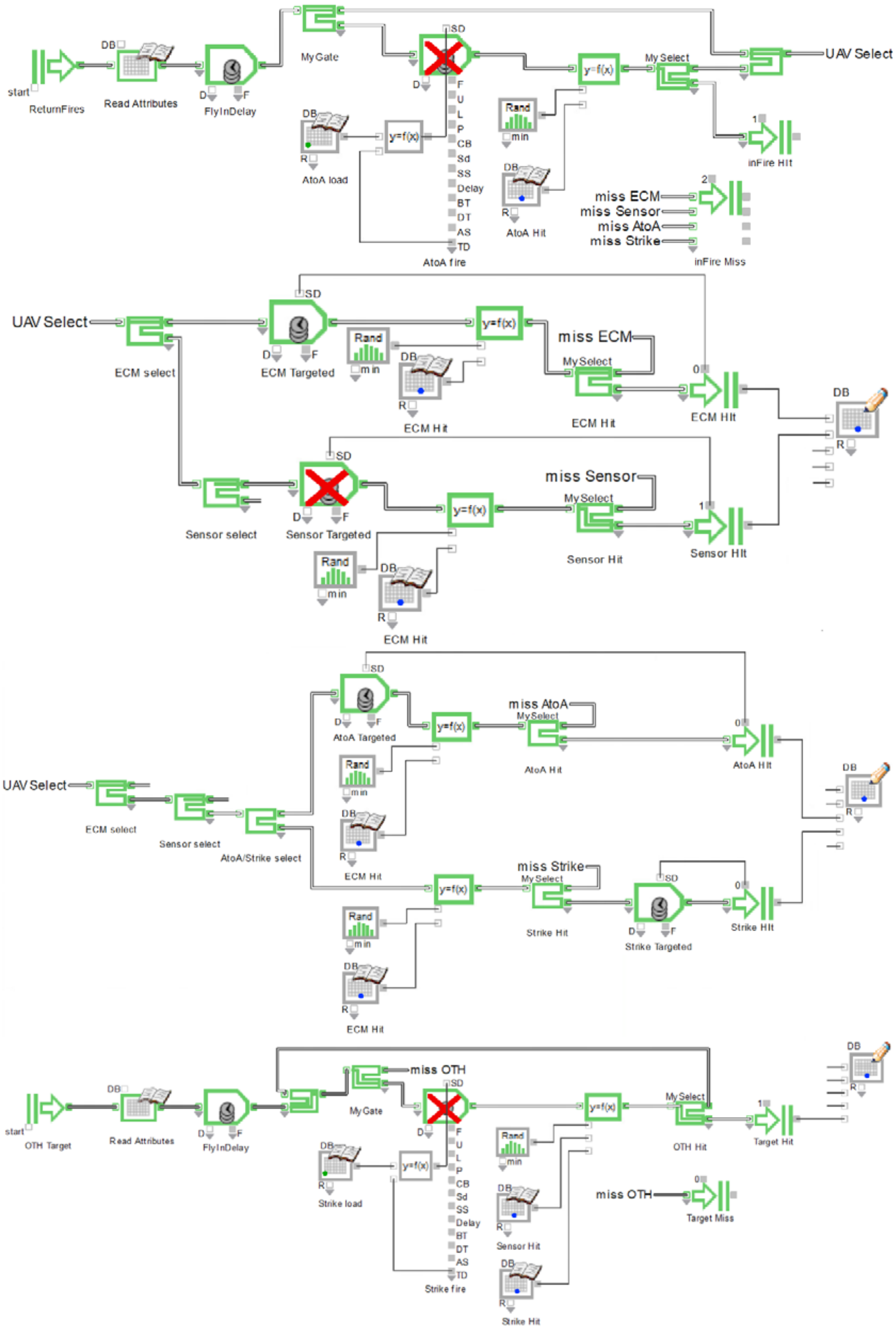


Figure 24. Swarm Strike Simulation

When the SSS functionality matured, 20 runs of data were collected using the same performance parameters as the model data from Table 5. This data is shown in Table 10. The variance from the SSS for the $P_{Success}$ is smaller than the SSM which shows that the simulation has a more repeatable assessment of $P_{Success}$. The variance from the SSS for the P_{Hit} is larger than the SSM which shows that the model has a more repeatable assessment of P_{Hit}. The P_{Hit} variation could be due to the higher fidelity implementation of the UAV targeting in the SSS.

Table 10. Swarm Strike Simulation Output Variance

Simulation	**350 runs**	
Sample	$P_{Success}$	P_{Hit}
1	0.711	0.333
2	0.683	0.368
3	0.674	0.356
4	0.683	0.368
5	0.694	0.359
6	0.674	0.356
7	0.689	0.354
8	0.680	0.353
9	0.686	0.379
10	0.666	0.345
11	0.697	0.371
12	0.677	0.346
13	0.674	0.334
14	0.709	0.379
15	0.671	0.356
16	0.689	0.364
17	0.703	0.341
18	0.686	0.359
19	0.674	0.342
20	0.697	0.351
Variance	1.620E-04	1.761E-04
Mean	0.686	0.356
95% CI +/-	0.006	0.006
99% CI +/-	0.008	0.008

The run data from the variance assessment was used to compare the mission performance outcomes ($P_{Success}$ and P_{Hit}) averages using the Excel t-test function with unequal variances. The t-test data in Table 11 shows that the SSM and SSS are producing different results for the mission outcomes. This was expected, as the refinement provided by the SSS should have a significant impact on the mission outcome.

Table 11. Swarm Strike Simulation UAV Performance DOE

P Success t-Test: Two-Sample Assuming Unequal Variances		
SSM/SSS 90% confidence		
	SSM	*SSS*
Mean	0.727	0.686
Variance	3.660E-04	1.620E-04
Observations	20	20
Hypothesized Mean Difference	0.000	
df	33	
t Stat	8.003	
P(T ≤ t) one-tail	1.5566E-09	
t Critical one-tail	1.308	
P(T ≤ t) two-tail	3.1133E-09	
t Critical two-tail	1.692	
P Hit t-Test: Two-Sample Assuming Unequal Variances		
SSM/SSS 90% confidence		
	SSM	*SSS*
Mean	0.324	0.356
Variance	1.376E-04	1.761E-04
Observations	20	20
Hypothesized Mean Difference	0.000	
df	37	
t Stat	-7.983	
P(T ≤ t) one-tail	7.2422E-10	
t Critical one-tail	1.305	
P(T ≤ t) two-tail	1.4484E-09	
t Critical two-tail	1.687	

Now that the SSS fidelity has been assessed, the OTH mission can be analyzed. This was done through the execution of the performance DOE parameters from the modeling assessment shown in Table 6. The DOE parameters were run through the SSS with 350 executions per row. Table 12 shows both the DOE inputs and outputs for the UAV performance in the SSS.

Table 12. Swarm Strike Simulation UAV Performance DOE

P_{ECM}	P_{Sensor}	$P_{A/A}$	P_{Strike}	A/A Loadout	Strike Loadout	$P_{Success}$	P_{Hit}
0.20	0.50	0.64	0.64	1	4	0.651	0.414
0.20	0.50	0.64	0.84	4	1	0.800	0.193
0.20	0.20	0.84	0.64	4	4	0.951	0.089
0.20	0.20	0.84	0.84	1	1	0.606	0.419
0.50	0.20	0.64	0.64	4	1	0.774	0.087
0.50	0.20	0.64	0.84	1	4	0.837	0.192
0.35	0.35	0.74	0.74	3	3	0.897	0.156
0.50	0.50	0.84	0.64	1	1	0.797	0.181
0.50	0.50	0.84	0.84	4	4	0.980	0.036

The performance results from the SSS reinforce the performance analysis from the SSM. This increases the confidence that the analysis and findings from the modeling effort are useful. The DOE analysis from Minitab produced the same main effects results that were observed in the modeling analysis. These effects are shown in Figures 25 and 26.

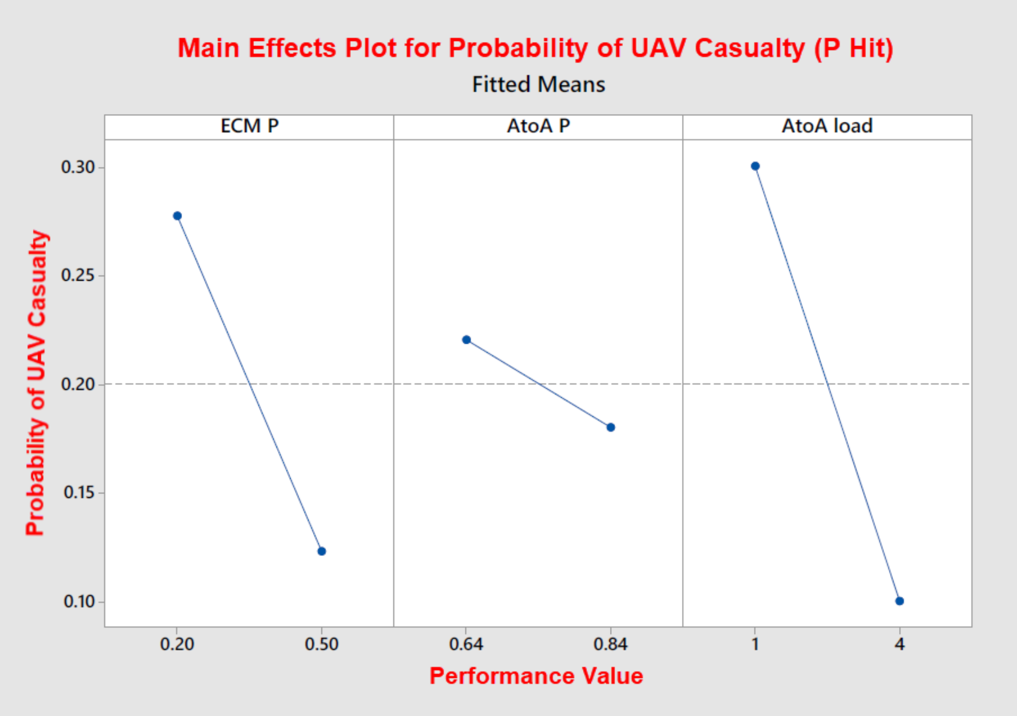


Figure 25. Swarm Strike Simulation Probability of Hit Main Effects Plot

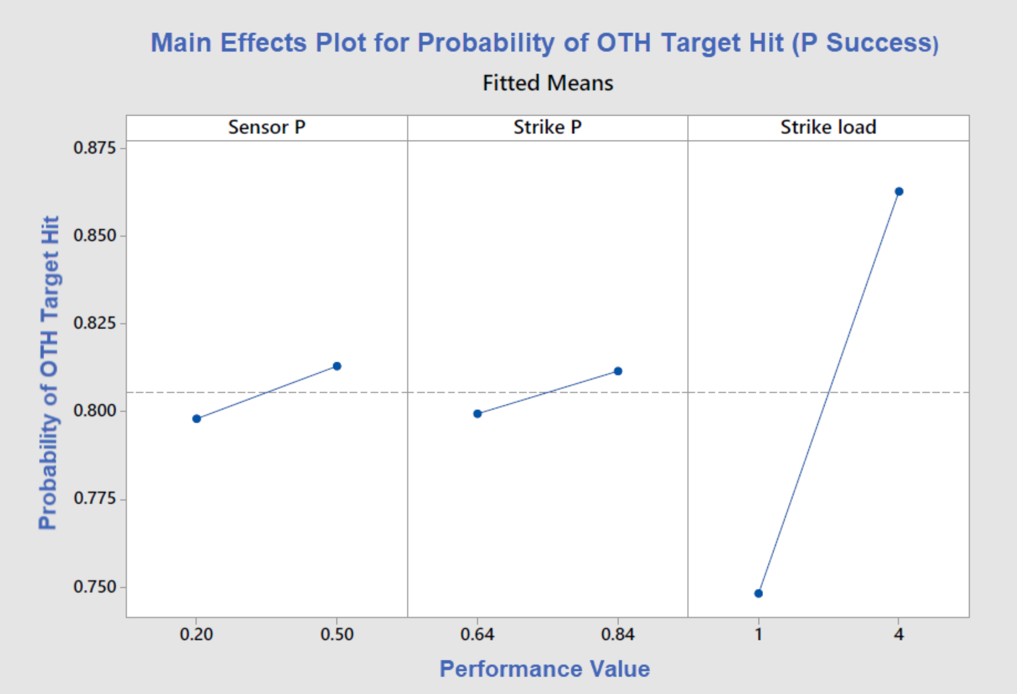


Figure 26. Swarm Strike Simulation Probability of Success Main Effects Plot

This simulation could be utilized to further explore the UAV performance through the addition of an extended time delay for the engagements, which was not captured in this data. If the time between the release of the OTH weapons was lengthened to the point where an A/A UAV was hit, the swarm capability to intercept the next weapon would be reduced. This could result in changes to the performance driver analysis.

The M&S effort produced data that was well-matched and provided confidence that the scenario is producing believable results. It also provided the performance assessments for this project. Based on the development and assessment of the M&S tool, a usable table of swarm configurations was developed. The UAV performance factors that were identified as scenario success drivers helped identify critical UAV capabilities within the swarm. The data and analyses developed can be used to help inform the development of a BREM swarm capability.

D. COST ANALYSIS

With the move towards the usage of UAVs for combat, it is important to look at the cost implications. In a 2012 study, the average unit cost for a Lockheed Martin F-22 Raptor was approximately $186M (Boyle 2012). In addition, the average yearly cost for operations and support for each aircraft was approximately $11.5M with each flight hour costing the military $11.5K (Boyle 2012). Likewise, the Lockheed Martin F-35 Lighting II has an estimated unit cost of $91M with an average yearly operations and support cost of $5M per aircraft (Boyle 2012); current estimates expect the Lighting II’s cost per flight hour to be reduced to $25K (McCarthy 2018). The premier electronic attack platform, the Boeing EA-18G Growler, costs an estimated $70M per unit (Defense Acquisition Management Information Retrieval 2017) with an average yearly operations and support cost per aircraft of approximately $6M; the cost to operate the Growler per flight hour is $25K (Defense Acquisition Management Information Retrieval 2017). With the high unit and operational and support costs, it is worth considering the cost-benefit of tasking UAV platforms to fulfill these critical roles.

From the same 2012 study, the unit cost for a General Atomics MQ-1C Gray Eagle was cited at $26.5M with an average yearly operations and support cost of $8M per unit, per year (Boyle 2012). Similarly, the General Atomics MQ-9 Reaper was reported to have a per-unit cost of $6.5M per unit with operations and support cost of $3M per unit, per year; the per flight hour cost for the Reaper is estimated at $3.25K (Boyle,2012). Likewise, the Northrop Grumman RQ-4 Global Hawk's has an average unit cost was $103M with an operations and support cost of $15.6M per unit, per year; the per flight hour cost for the Global Hawk is estimated at $31K (Boyle 2012). Table 13 summarizes unit and flight-hour costs.

Table 13. Cost Comparison of Manned and Unmanned Platforms

Mission Role	Strike/A/A				Sensor/ECM	
Platform	F-22 (M)	F-35 (M)	MQ-1C (U)	MQ-9 (U)	EA-18G (M)	RQ-4 (U)
Unit Cost ($M)	186	91	26.5	6.5	70	103
Flight Hour Cost ($K)	11.5	25	-	3.25	25	31
(M) – manned platform, (U) – unmanned platform						

A comparison of the costs of aerial vehicles shows an especially large variance between the unit cost. Both the MQ-1C Gray Eagle and MQ-9 Reaper are used specifically for combat, like the F-22 Raptor and F-35 Lightning II. The F-22 and F-35 may be equipped with an ECM system. Similarly, the MQ-1C Gray Eagle and MQ-9 Reaper have an available ECM payload (Air Force Technology n.d.). When comparing the UAVs to the manned combat vehicles, the conclusion becomes clearer. The average unit cost of the two conventional manned aircraft is $132M. Conversely, the two combat-capable UAVs average $19M per unit. The RQ-4 Global Hawk is primarily used for its reconnaissance capabilities which makes it a great selection for the sensor-enabled UAV. On a similar note, the EA-18G Growler is strictly purposed for electronic warfare, surveillance, and reconnaissance. Evaluated strictly on cost, the UAV option is less favorable. Although the RQ-4 Global Hawk exceeds the EA-18G Growler in unit cost, O&S cost, and flight-hour costs, its deployment eliminates the risk of service member casualties.

Reflecting on Chapter IV, the foundation provided by previous chapters allowed for the modeling and simulation of the OTH mission execution by the UAV swarm. The follow-on analyses found consensus in that OTH mission success is most affected by weapon stores (A/A and strike munitions). Also, the comparative cost analysis for manned versus unmanned platforms found the unmanned platform alternatives to be less costly, save for the ECM function, while eliminating the risk to service members that would otherwise be fulfilling platform role. Moving into Chapter V, the findings of this project will be further discussed with the contributions and potential application benefits identified. The chapter will conclude with a look towards future work that would aid in the further development of the BREM project.

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V. FINDINGS AND FUTURE WORK

A. FINDINGS

The team used a modified system engineering approach to study the operational utility of adding a swarm of UAVs for the OTH mission. The approach was based on the traditional systems engineering “vee” with a focus on the development of a CONOPs and system architecture, and modeling and simulation (M&S) analysis. The team developed the SSM and ran scenarios to conduct three sets of analyses. The analyses centered on the execution of the OTH mission and included a UAV performance analysis, a swarm size analysis, and a swarm configuration analysis.

The CONOPs development process identified specific UAV configurations for use in the swarm. The process also captured the functional description of the UAV configurations and related the performance of the respective UAV platform as a member of the swarm. The CONOPs itself described the basics of swarm configuration as it relates to executing the OTH mission. The CONOPs also began the development of the BREM swarm mission definitions and the OTH mission scenarios.

The architecting processes that followed the CONOPS development further matured the CONOPs by establishing the system of systems definitions for the BREM swarm. The team produced a series of operational and system views that identified UAV configuration data and communications needs. The architecture aided in describing the need for support assets in the execution of the BREM swarm mission.

The team conducted an M&S effort as a quantitative approach for assessing swarm success during the execution of the OTH strike scenario. The SSM, developed in Microsoft Excel, took a probabilistic approach to capture and evaluate the OTH strike scenario. The SSS used a similar approach to scenario execution but added fidelity to the weapon engagements and was developed in ExtendSim9. The scenario utilized in the M&S effort was developed using the information captured in the CONOPs. The quantitative approach of the M&S effort established performance metrics for the various UAV configurations. The effort also allowed for the capture of swarm size and configuration on OTH mission success. To this end, mission success was evaluated using the probability the swarm would kill the OTH target contrasted against the probability of a loss of a swarm UAV.

A DOE was developed for the UAV performance using the M&S metrics and analysis was completed using the SSM. The results from each of the DOEs were evaluated for main effects drivers. In the UAV performance modeling analysis, the strike loadout was identified as the driving parameter for the OTH hit probability. The analysis also revealed the A/A loadout to be the main driver of the probability that an incoming threat would hit a UAV. The swarm performance assessment was repeated using the SSS with comparable results.

The swarm size assessment and configuration analysis used a standard set of UAV performance values. A DOE was developed for the swarm size assessment and completed using the SSM. The analysis found the strike UAV configuration to be the critical UAV platform for the successful engagement of the OTH target. In addition, loss of the strike UAV was most detrimental to the success of the OTH strike mission. Successive runs of the SSM were completed to obtain the data used in swarm configuration analysis. The swarm configuration analysis provided the probability of an OTH kill as well as the probability of UAV loss for the various configurations. The team produced a table of recommended swarm configurations that depend on the number of red force return fire weapons. When the red force return fire loadout is known, the look-up table (contained in Table 9) shows the minimum number and type of UAV swarm that produces a high probability of success and a low probability of being hit.

The cost analysis for utilizing current UAV technology in the execution of the OTH mission showed that a swarm implementation would likely increase the cost. However, two factors could drive the decision in favor of the use of a UAV swarm for OTH missions. The first is that delivering more UAVs in more mission areas will reduce the unit cost. The second is that as the UAV technology matures with the higher demand, the cost of delivering UAVs will be reduced. These factors, in addition to the casualty risk associated with OTH mission execution, push the decision in favor of utilizing UAVs.

B. CONTRIBUTIONS

The modified systems approach completed during this capstone project produced several contributions to the BREM system. The project developed a CONOPs and architecture for the OTH mission that can be utilized in the pursuit of enabling swarm mission capability. In addition, the usable swarm configuration could be used as a lookup table by surface ship combat systems for the execution of the BREM swarm missions. The results of the M&S effort can aid in developing further analyses to unlock new capabilities to be implemented in the OTH mission. The method, data, and tools established by this project could be leveraged to develop similar analyses of existing naval capabilities.

C. POTENTIAL BENEFITS

A practical and near-term benefit of the study will be an Excel application and ExtendSim model to support BREM development and to be used for this project's analysis as well as future analyses. The Excel application will have an interface in which the user may input information regarding the UAVs, coordinates, weaponry, and opposing forces. The application is expected to output the strategic positioning and predictive engagement strategy. The ExtendSim program is expected to mirror the results of the Excel application and provide graphs and visuals to help illustrate.

The results of the project's analysis will provide recommendations and lessons-learned for implementing the addition of UAVs into the BREM automated mission planning decision aid. The M&S of a variety of UAV combinations and configurations for OTH missions will provide an understanding of the operational utility of UAVs for this mission domain. The analysis results will inform the stakeholders of the benefits of integrating the UAVs to the existing BREM gaming system. The stakeholders may also leverage the project towards further development of, and insight into, the BREM functionality as well as UAV capability.

UAV system developers at the forefront of the BREM project will benefit greatly from the project. The results of this study will support the autonomous decision-making component of BREM by adding the potential operational utility of UAVs to the OTH mission. The objective of BREM is consistently to stay in the optimal battle condition of the matrix, leading to the highest probability of battle success. With the addition of UAV capabilities and strategies, the BREM will have the potential to achieve even more significant improvements in battle-readiness for OTH missions.

D. FUTURE WORK

The team recommends the swarm size and configuration modeling analysis be repeated using real-world data for UAV effectiveness and reliability. For a baseline, the UAV probabilities could be given F/A-18 performance metrics for similar missions as it is equipped with a sensor package that is similar in concept to the sensor-enabled UAV. In addition, the F/A-18 also features an escort jamming capability that matches the ECM UAV functionality. Lastly, the F/A-18 load outs could be leveraged for the A/A and strike mission package probabilities. By using the F/A-18 data, a better-informed analysis could be completed for the mission effectiveness of the BREM swarm UAVs. The use of measured or predicted values for known UAV reliability could also increase the fidelity of the modeling analysis.

The team also recommends the OTH mission, as completed by manned platforms, should be analyzed to establish a comparative baseline. The data provided by the baseline analysis would allow for a comparative analysis between manned and unmanned assets. In addition, an analysis of manned and unmanned platforms may yield a higher mission probability than either platform on its own.

Further work could be directed towards evaluating the impact of changing the UAV targeting priority during the execution of the OTH scenario. For instance, the ECM and sensor-enabled UAVs could effectively remain outside the OTH engagement range if the ECM UAV supported the swarm as a stand-off jammer with the sensor-enabled UAV acting as a loitering sensor. Removing two UAVs from the engagement area would concentrate on inbound threats, which may increase the probability of successful interception by the A/A weapons. The resulting changes to the OTH targeting methodology would likely necessitate the iteration of the UAV performance drivers and swarm size analyses.

Another area of development would be enhancing the OTH scenario to reflect a dynamic environment. The addition of swarm UAV countermeasures, environmental factors, and OTH target capabilities would add a layer of fidelity to the SSM. The inclusion of swarm countermeasures would further enhance UAV survivability. Environmental factors affecting UAV and weapon performance would provide insight into optimal swarm configurations for varying environmental conditions of real-world scenarios. Predicting and acknowledging the capabilities of the OTH target are vital to reflect the complex environment accurately in which the strike weapons must operate. Each of these factors necessitates iteration of the UAV performance drivers and swarm size analyses to enable a more versatile swarm configuration.

Further engagement cost analysis would prove beneficial. Dependent on the acceptable level of risk, it would be advantageous to know which UAV configuration yields the greatest probability of success at the lowest cost. This information would provide engagement decision makers with the best cost-benefit analysis. In turn, this would support the allocation of defense spending towards the areas that have the greatest impact on OTH engagement success probability.

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