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Advancing Autonomous Swarm Behavior in a Simulated Anti-access Area Denial (A2AD) Environment

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ADVANCING AUTONOMOUS SWARM BEHAVIOR IN A SIMULATED ANTI-ACCESS AREA DENIAL (A2AD) ENVIRONMENT

THESIS

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Abstract

Recent advancements in modern integrated air defense systems (IADS) have bolstered anti-access area denial (A2AD) environments and subsequently degraded the advantages that the United States Air Force once held with highly sophisticated stealth platforms, prompting a call by senior defense leaders to reform the nature of aerial warfare in order to challenge these threats. A solution to this new requirement is that of a weapon swarming technology, which has the ability to overwhelm IADS by engagement of a large numbers of low-cost, but lethal air assets that are enhanced by autonomous functionalities. This research proposes the application of a four dimensional framework of autonomy to a weapon swarm of high subsonic cruise missiles. This framework is defined as the ability to act alone, ability for intra-swarm communication, ability to adapt, and ability for leader-follower cooperation. A virtual A2AD environment involving combat operations between two opposing forces is constructed using the Advanced Framework for Simulation, Integration, and Modeling (AFSIM), wherein a manned bomber is seeking to penetrate into an enemy IADS in order to destroy a high value target. The manned penetrating bomber will then release a swarm of autonomous cruise missiles in order to compete within the A2AD battle space. The effects of the dimensions of autonomy on the strike package is statistically tested using a designed experiment. Analysis of the results show that the framework for autonomy is significant at a 95% level of confidence towards all measures of effectiveness. The ability for intra-swarm communication provides the largest benefit to both offensive and defensive performance of the swarm, most notably with 51.9% increase in the swarm's capacity to detect and destroy new threats.

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ADVANCING AUTONOMOUS SWARM BEHAVIOR IN A SIMULATED ANTI-ACCESS AREA DENIAL (A2AD) ENVIRONMENT

I. Introduction

1.1 Motivation and Background

As warfare continues to advance, the necessity to incorporate data-driven process has become increasingly apparent. The complexity of the decision space in which command and control (C2) nodes must now operate will far exceed the capability of existing chain of command procedures. Autonomous systems that incorporate human-machine interactions offer a potential solution to this imminent problem. The United States of America emphasizes this goal specifically within the 2018 National Defense Strategy (NDS) and Department of Defense (DoD) directives, where it is stated that the Department will invest broadly in the application of autonomous and semi-autonomous functions in weapon systems to gain competitive military advantages [9, 16]. A driving factor for the research, development, and application of autonomy is characterized by Lockheed Martin's technical report on *A Framework for Autonomy*, where it is described that future conflicts will likely be characterized by a complex, highly unpredictable, multi-domain warfare environment [1]. Such an environment, as explained by General David Perkins (USA Ret.), will be completely defined by an enemy who will challenge the ability of the United States to conduct military operations and maintain superiority across the air, space, cyberspace, land, and maritime domains, as well as the electromagnetic spectrum [18]. These environments may quickly exceed human cognitive capacity and cause operators to be overloaded with information and highly prone to mistakes, all while requiring shorter decision timelines for potentially vastly decreased kill-chains. Autonomous systems may allow for manned-unmanned teams to successfully compete under these conditions.

Another result of the highly proliferated global defense industry of the twenty-first century is that of increasingly complex A2AD environments that contain Integrated Air Defense Systems (IADS). The United States Air Force (USAF) Science and Technology strategy identifies modern advanced IADS as a “threat to the technological superiority of U.S. military forces” by inhibiting the prospect of air superiority through conventional methods of highly sophisticated air assets [2, 5]. Meanwhile revisionist powers such as China and Russia, as described by the NDS, have invested heavily in the advancement and development of such A2AD capabilities. In order to deter aggression and overcome the long-term strategic competition of near-peer adversaries, efforts must be concentrated on progressing capabilities for attritable, low-cost autonomous missile swarms that have shown potential in successfully overcoming A2AD environments [14].

This research advances the findings of Goggins, who presents a three-dimensional framework for autonomy that both positively influences friendly force survival rate and lethality of cruise missile swarms against enemy IADS when compared to a non-autonomous baseline.

1.2 Problem Statement

This research seeks to simulate multiple different conditions of autonomy in order to assess the relative effect on performance of Blue (friendly) forces in an A2AD environment. The scope is the scenario by which a networked swarm of autonomous cruise missiles engages the Red (enemy) IADS in order to allow for a succeeding strike by the Blue manned penetrating bomber on the Red high value target (HVT).

Complicating factors such as a stochastic IADS layout, pop-up threats, and moving surface-to-air missile (SAM) launchers increase the complexity of the action space in which the swarm agents must operate and succeed if the Blue manned bomber is to survive and complete its mission objective. All modeling and simulation is conducted in the Advanced Framework for Simulation, Integration, and Modeling (AFSIM).

1.3 Research Questions

The problem statement will be addressed by answering the following research questions:

1. To what extent can autonomy in the application of cruise missile swarms be advanced from a previously defined three-dimensional framework?
2. To what degree does autonomy aid in the offensive and defensive capabilities of Blue forces under the prescribed conditions?

1.4 Thesis Organization

The remainder of this thesis is organized as follows: Chapter II provides a review of the relevant literature relating to this research effort. The topics include autonomy (both classification and application), A2AD environments, modeling and simulation, and design of experiments (DOE). Chapter III defines the application of autonomy, the AFSIM model, the experimental design, and our measures of effectiveness for this study. Chapter IV presents the findings through results and analysis of experimental simulations. Lastly, Chapter V draws conclusions and suggests recommendations for further research.

II. Literature Review

2.1 Chapter Overview

This section will present a review of existing literature pertaining to both this research topic and the various methodologies surrounding it. The topics included are the classification and applications of autonomous systems in military environments, anti-access area of denial (A2AD) environments, modeling and simulation, and design of experiments.

2.2 Definition and Classification of Autonomous Systems

Huang et al. provides a systematic method of standardization for the terminology related to specifying levels of autonomy in unmanned systems (UMS's) [15]. Autonomy in the application of UMS's is then defined to be "the ability of sensing, perceiving, analyzing, communicating, planning, decision-making, and acting, to achieve its goals as designed by its human operator(s) through designed human-robot interaction." Or, more broadly, autonomy is the quality of being self-governing. Further, human-robot interaction is defined to be "the activity by which human operators engage with UMSs to achieve the mission goals" [15]. By extending the definitions provided by Huang et al., we explicitly define autonomy within the scope of this research to be a cruise missile's capacity to make command, control, and communication decisions once actively deployed within the battle space in support of the mission objectives of its human operators. The ability to actively send and receive communications in conjunction with manned teams allows for a deeper integration into the in the different systems that may be used within an operational environment. In practice, autonomy is often implemented in the form of a framework with which respective dimensions and levels can be applied to a weapons system. Huang et al. proposes the Autonomy Levels for Unmanned Systems (ALFUS) as a three dimensional framework to autonomy comprised of mission complexity, environmental complexity, and human independence [15]. This framework allows for quantification of a UMS's capability for performing autonomous missions and provides a standard from which to progress.

The three principles of autonomous systems defined by Goggins are the ability of a missile swarm to act alone, to cooperate, and to adapt to situational changes. Goggins then further categorizes each dimension of autonomy into three different levels of performance: low, medium, and high. Each level corresponds to the overall intelligence of how the swarm will behave. Importantly, Goggins shows this framework for autonomy can be successfully applied to a swarm network without the use of a governing Air Battle Manager. His research determines that the lower autonomy settings within the three tiered model perform better than higher autonomy settings; medium level of performance for both the ability to cooperate and the ability to act alone provides better results than the high level of performance, contradictory to what one might expect [14]. Lastly, Goggins finds that the ability to act alone is insignificant towards the friendly force survival rate. This implies there is room for advancement and adaptation in his model for autonomous cruise missile swarms in an A2AD environment.

Lockheed Martin's Framework for Autonomy provides an extensive look into the design of concept and theoretical application of autonomous systems. Lockheed Martin views autonomy as a continuous and measurable capability, wherein the system can operate independently of human input [1]. Autonomy is decomposed into 7 different dimensions, providing a high-resolution structure for defining a system's framework [1]. Each dimension contributes to an overall autonomy score, rated on a scale from level 1 - 10, with 10 being a fully autonomous system as shown below in

Figure 1. Several of these seven dimensions were adapted by Goggins into his final analysis of the three-leveled, three-dimensional autonomous missile swarm. Fusing the dimensions by Lockheed Martin into a more usable format allowed Goggins to explore new scenarios and paved a path in which this research will follow.

Figure 1: Lockheed Martin's Autonomy Maturity Level

Pollack similarly defines an autonomous system using a three-tiered taxonomy, pulling directly from Lockheed Martin's seven dimensions of autonomous systems [19]. Pollack specifically uses situation understanding, multi-system operations, and planning and control as relevant to the scenario of high value airborne asset defense. Additionally, his thesis relinquishes the dimensions related to human-system or human-machine interaction, stating a human component is not considered. However, a requirement for human-machine interaction is likely necessary for future fielding of concept according to the DoD's task force report [4].

The Defense Science Board researched the creation of an autonomous systems reference framework to replace the standard definition of autonomy using levels or dimensions. The finding is that many of the DoD-funded studies of levels of autonomy do not yield anything significant for autonomous design processes [4]. Further, it seeks to clarify the pitfall of taxonomies in relation to autonomous systems, which imply that they have exact or discrete levels of intelligence. Instead, the proposal is to research how a continuum framework can better define autonomy. This framework is examined from three different viewpoints: cognitive echelon, mission dynamics, and complex systems trade space [4]. Doing so allows a broader, more generalized classification for autonomy which will be required for eventual fielding of many different types of autonomous systems. The science board goes further into stating that defining levels of autonomy may not even be practical, as the ubiquitous effort to discretize autonomy is not only counterproductive, but competing definitions of autonomy commonly leads to confusion among both developers and end users [4]. Therefore, it may be of benefit for future fielding to abandon the traditional and possibly outdated discrete definition of autonomy and move towards a continuum viewpoint.

2.3 Applications of Autonomous Systems in Military Environments

In order to maintain superiority as a military force, the DoD recognizes that it must not only embrace autonomous capabilities but also begin adopting the enterprise processes to support the strategic advantages it will bring [3]. The Defense Science Board summer study on autonomy finds that autonomous weapon systems integration will be imperative to operational accomplishment of the future. Understanding the globalized impact of such technology on the DoD and its potential adversaries must remain an utmost priority if the USAF wishes to continue being the dominate power in future conflicts across all operating domains [5]. However, the slow integration of autonomy reflects the internal hesitation to abdicate command authorities to autonomous systems [3]. The discussion below consists of developmental programs and research that will aid in combating these institutional reservations by providing evidence for well-defined parameters in which autonomous systems may be used, allowing for the confidence necessary to support greater organizational change.

Giles and Giammarco [13] research swarm system technologies from a holistic systems engineering perspective. They find that the difficulty related to the human management and control requirement exceeds the technical challenge that is often prioritized by autonomy researchers [13]. A concept of mission engineering to swarm systems, which includes the deliberate planning, analyzing, organizing, and integrating of capabilities, shows promise by better achieving the desired outcomes to autonomous systems integration. Providing an architecture based upon human operator interactions may increase the flexibility of the system required to balance manual and hands-off controlling during unpredictable conditions within combat missions. This top-down approach to mission-based systems engineering is an important consideration to the many different operational perspectives and solution architectures that may be required by the DoD within A2AD environments.

Boskovic et al. investigate an autonomous hierarchal architecture for controlling unmanned aerial vehicles (UAV). The architecture that controls the UAVs, ComPACT, provides six different hierarchies which encase mission planning objectives and tasks that allow for the execution of the mission [7]. Their system finds success in the ability to scale up to very large architectures with many autonomous agents. While in that setting, mission related objectives can still be accomplished under both dynamic and ambiguous environments during real-time mission re-planning, agent-to-task assignment, and reactive motion planning. This type of architecture allows for autonomous agents, such as cruise missiles, to independently cooperate towards the achievement of grander mission objectives in a changing environment. Applicability of Boskovic et al.'s research supports the utility of modeling and simulation efforts on cruise missile swarms, as in our proposed scenario.

2.4 Anti-Access Area of Denial

Joint Publication 3-01 on Countering Air and Missile Threats defines anti-access/area of denial as a military strategy that relies on the threat of or employment of missiles and aircraft to destroy enemy targets or power projection capabilities [20]. These are commonly employed through means of integrated air defense systems and may be done in coordinated operations with advanced, next generation aircraft. IADS is not a formal system in itself but is the amalgamation of service components and air and missile defense (AMD) systems. AMDs are often comprised of C2 networks that enable the use of early warning (EW) radars, target selection and acquisition radars (TAR), target engagement radars (TER), SAM launchers, and all required personnel that operate within the theater [20]. The modern advancement of these systems can effectively prevent aerial forces from entering into a geographic zone, eliminating the possibility for domain superiority and requiring additional supplemental capabilities of the offensive force to achieve its intended effect.

Joint Publication 3-09 on Joint Fire Support discusses how these surface-to-air missiles within IADS use dynamic targeting procedures, called the kill chain, to find, fix, target, track, engage, and assess targets of opportunity [21]. This poses serious threat to conventional aircraft that invade protected airspace, and a new method of countering such capable defense will be required. The cruise missile swarm was studied for this specific purpose.

2.5 Modeling and Simulation

Modeling and simulation is a method of statistical application to computer-based software that allows for the imitation of real-world operations to be executed under specific conditions [6]. This enables research to be conducted by studying the interactions of entities during the evolution of a system. Implementation provides a cost effective and comparatively simple method for data collection when chosen over live experimentation [6]. Yang et al. showed that modeling and simulation efforts within the context of regional air defense combat allows for the study of complex transactions between invading aircraft and IADS in a multi-dimensional, probabilistic environment [22]. This provides further support for the application of modeling and simulation towards this research effort.

AFSIM is a modeling and simulation software originally developed by Boeing and is maintained by the Air Force Research Lab (AFRL) [12]. AFSIM provides the resolution to program various weapons, platforms, and capabilities for complex model building. Modeling efforts within AFSIM are primarily conducted at the mission and engagement levels of combat modeling, as shown in Figure 3. AFSIM's capabilities are achievable due to discrete-event timing through agent based modeling approaches that allow for specifically modeled characters to be defined as individual agents [12]. This paradigm supports an increase in individual autonomy of each cruise missile, and provides a desirable level of flexibly to the overall modeling architecture. Bruns demonstrates these capabilities within AFSIM through the application of highly technical combat functionalities added to both friendly and enemy forces [8]. This is also seen in research by Ciaravino, where AFSIM is utilized to characterize various levels

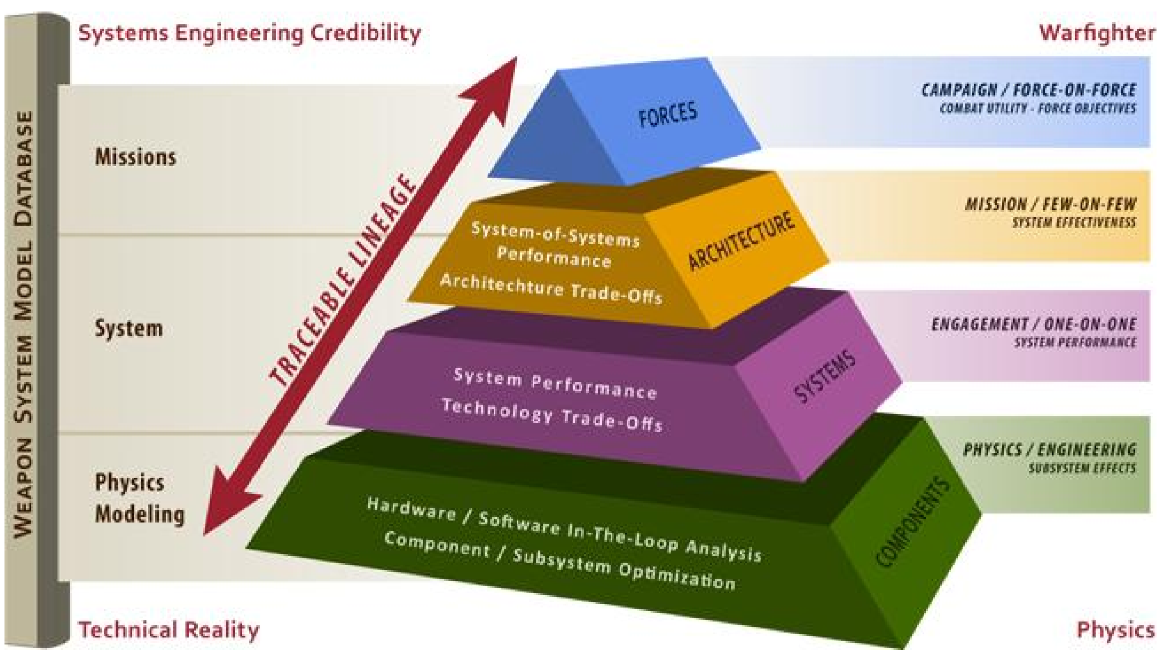


Figure 2: Combat Modeling Hierarchy by AFRL/RY

of effectiveness in offensive strategies within an A2AD environment [10]. The integration of non-material cyber effects into Blue force capabilities allows for IADS airspace penetration by friendly forces. Additionally, Ciaravino programs the functionality to extend defensive cyber capabilities into the Red forces platforms.

Yu et al. provides further applications to the success of modeling and simulation efforts on unmanned swarming technologies through the design of a new obstacle avoidance behavior. The simulations conducted allow for a combination of two previously researched obstacle avoidance algorithms to produce a third, new behavior called aggregation and disaggregation. The results give evidence for the feasibility of developing and testing autonomous behaviors within a dynamic environment [23]. Programming and implementing different agent capabilities such as aircraft platforms, communication devices, weapons, and sensors allows for a study of behaviors that yields information about the simulation players, providing analysts the ability to gather insight. Further, these studies confirm that agent-based modeling within AFSIM is compatible with various types of designed experiments.

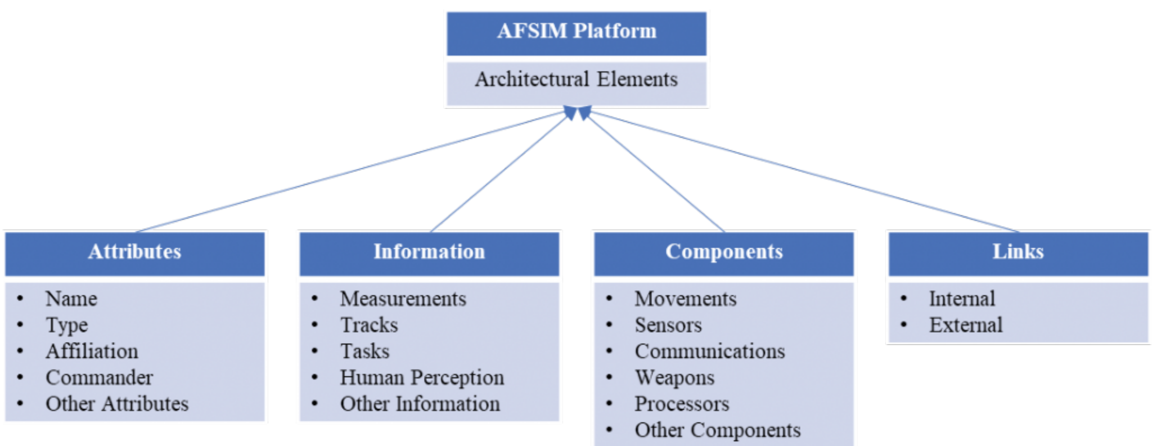


Figure 3: AFSIM Platform Structure

2.6 Design of Experiments

DOE provides a statistically rigorous foundation with which one can soundly execute the scientific method on a problem set. Experiments are designed by identifying response(s) as the variable of interest to the experimenter, defining the factor(s) that influence these responses, creating means by which to efficiently collect data, conducting the experiment, and running statistical analysis of the resulting data [17]. DOE methods allow for a resourceful gain of information by accepting some (or no) reduction of statistical power in the resulting model, as set by the experimenter. Therefore, adhering to the principles and underlying statistical theory of DOE allows for a relationship between the factor(s) and response(s) to be determined.

Applying the DOE statistical method to computer-based simulations provides a range of possible experimental settings to be executed. Designs could include two-level factorial designs, n-level factorial designs, fractional factorial designs, non-regular central composite designs, space-filling designs, and many others [17]. A visual explanation of three different two-level factorial designs is shown in Figure 5. Of these designs, recent theses have shown success in using either a full factorial or fractional factorial with computer-based simulation efforts [8, 10, 14, 19]. Additionally, factorial designs are often categorized by their ability to efficiently study the effects or two or more factors within an experiment [17]. From this, a factorial-designed experiment was selected for this research.

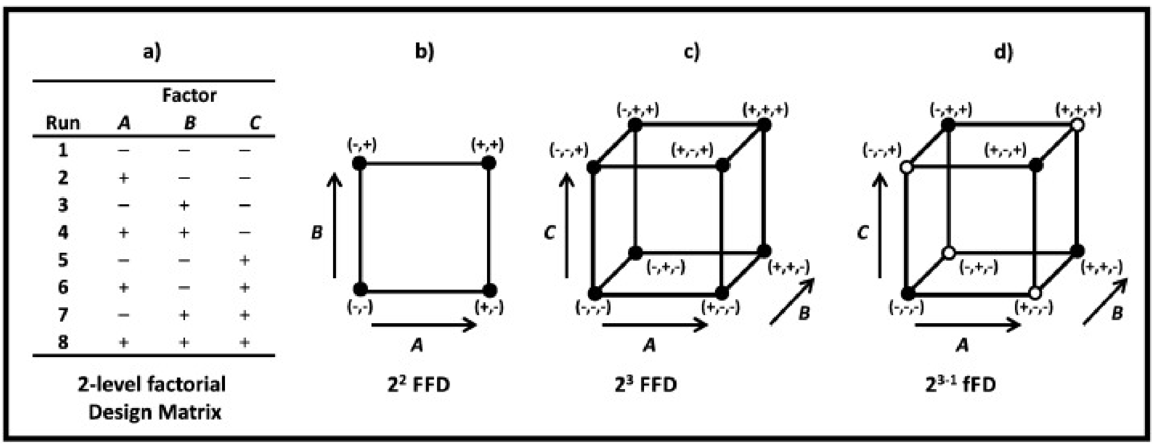


Figure 4: Example Factorial Designs

III. Methodology

3.1 Chapter Overview

This chapter provides a solution methodology to the research questions posed within this work. The methodology will be divided into four parts: defining autonomy and its levels within, establishing the A2AD scenario that Blue forces will attempt to penetrate, establishing the designed experiment in order to provide a statistical foundation for data collection and analysis, and finally providing measures of effectiveness (MOEs) that will be specifically outlined so as to allow an evaluation of the dimensions of autonomy.

3.2 Defining Autonomy

The cruise missile swarm is endowed with four independent dimensions of autonomy that provide the ability for self-governance and cooperation with the Blue penetrating bomber. These dimensions are the ability to act alone, ability for intra-swarm communication, ability to adapt, and ability for leader-follower cooperation. Each of these four dimensions is further defined by a low setting or a high setting, which corresponds to the level on the continuum of capability that the dimension provides the swarm when engaging the Red IADS.

Ability to act alone refers to a cruise missile's capability to individually navigate the battle space. Specifically, this defines how an agent within the swarm will calculate a three dimensional flight path that will allow them to engage a member of the Red IADS. The low setting for this dimension sends a pre-briefed targeting scheme to the swarm, whereby each swarm member will directly engage their target in a straight line route, without course deviation. The high setting for this dimension allows for "smart" targeting; circumnavigating known threat rings from each tactical operations center (TOC), and calculating shortest distance-to-target ranges for more optimal threat engagements. This advances the previously defined dimension of autonomy from Goggins by incorporating a route calculation algorithm. This algorithm first determines if the agent must violate the airspace of a known threat ring in order to engage its target; if so, then the on-board processor will calculate a route that least violates any additional airspaces beyond the one they must enter in order to engage their target. The term *least violates* refers to the maximal radial distance from the center point of the threat ring that the swarm agent must pass through in order to engage its target.

Ability for intra-swarm communication refers to the cruise missile swarm's capability for relaying and acting upon internal targeting information as a single entity in support of the execution of the mission objective. This dimension establishes a communication network between all cruise missile agents that defines a master targeting array, populated with the priority score of each known Red entity. The low setting for this dimension turns the communications network off, whereby each cruise missile enters a state of individual agency and cannot relay information with any other agents. The high setting for this dimension enables the internal communications network, which allows for each agent to use their sensor suite to fuse battle space information and communicate that information with each other; effectively creating the "swarm" network. The purpose of this network is to report individual entity status, enhance awareness of the mission environment, and create a targeting scheme that allows for a more effective attack configuration on the Red entities. This occurs when each swarm member is assigned its initial pre-briefed target and the internal data manager appends the master targeting array with the respective target inputs. Two different actions may then follow; first, if there exists a target of higher priority and of closer distance to an agents existing target, then the agent will switch targets. Second, if a Red target entity is created via a pop-up threat or a Blue cruise missile agent is destroyed, then a reprioritization may take place based upon the logic above. A cruise missile may change targets if a Red entity is detected that is of higher priority than the current target and further distance away, but only if the remaining distance to the existing target is greater than a certain threshold. These logical requirements to be satisfied before a cruise missile may change its target are enhanced to the existing framework developed by Goggins [14].

Ability to adapt refers to a cruise missile's capacity to detect variations within the mission environment and respond accordingly. With this dimension, the agent's on-board sensor suite is outfitted with a Radar Warning Receiver (RWR) that allows for situational awareness of the battle space. The low setting for this dimension turns the RWR off and does not allow the swarm members to actively track any radiation-emitting IADS members. The high setting for this dimension turns the RWR on, which upon successful capture of emitted radiation provides location and tracking information of said IADS members. Additionally, a threat processing algorithm is added to each swarm member's functionality which provides both detection of any incoming SAMs and the ability to execute evasive maneuvering of the threat. Evasive maneuvering is defined as the ability for banking angles up to 45 degrees and changes in the agents existing acceleration vector for redirection of their flight path. Advancements made in the threat processor of each cruise missile agent allow for an 80% faster response time as compared to the previous model [14]. Figure 6 shows an example of a SAM engagement upon a cluster of swarm agents and the associated evasive maneuvering they each execute, depicted by an acceleration vector shown in green.

The final dimension of autonomy is the ability for a leader-follower cooperation. This dimension refers to the Blue strike package's capacity for human-machine inter-

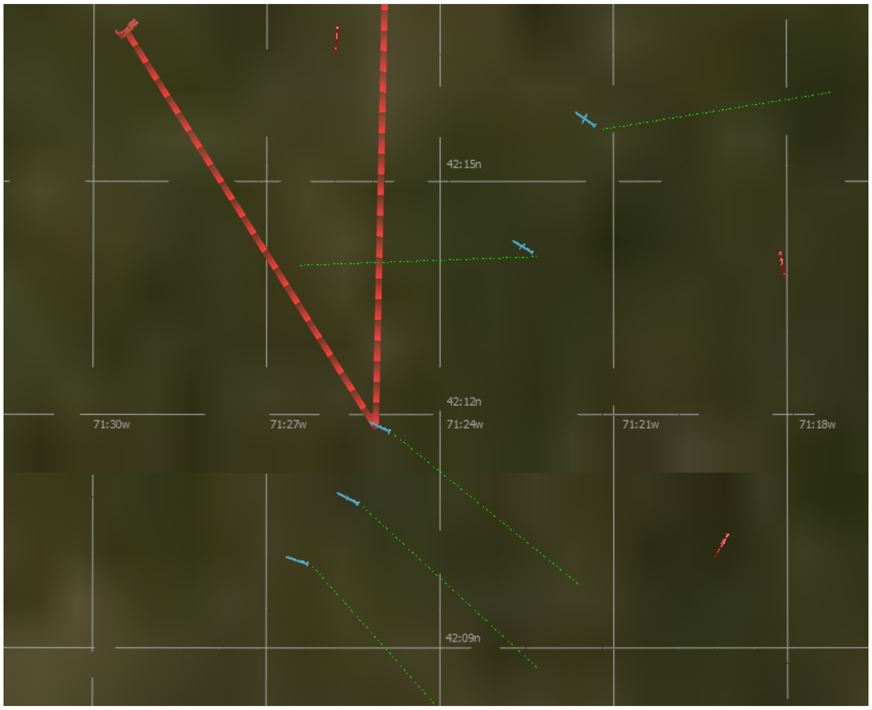


Figure 5: Evasive Maneuvering by Cruise Missile Entities

action. A communications network is established between the manned Blue bomber and each agent within the swarm which provides the ability for a transfer of information in a bi-directional manner between the Blue entities. The low setting for this dimension turns off the communications network between the bomber and the cruise missile swarm. The high setting for this dimension enables the communications relay, allowing the manned bomber and unmanned swarm to share targeting and location information. This setting establishes an elliptical targeting zone around the bomber which mimics a logical gate for the bomber to issue commands of engagement to swarm members, based upon violation of the zone by IADS entities. The commands given to the cruise missiles will either be in a direct manner to specific individual agents, or to the swarm as a single entity for internal processing and execution, based upon which setting is enabled for the dimension of intra-swarm communication. Figure 7 depicts an example of the leader-follower cooperation. Table 1 summarizes each dimension of autonomy and its associated levels.

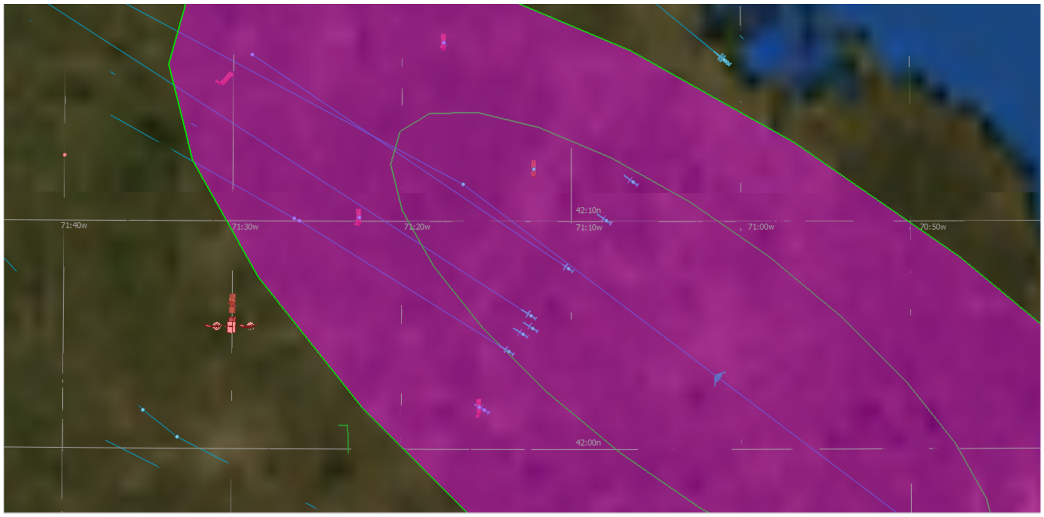


Figure 6: Sample Leader-Follower Cooperation via Bomber Command

Table 1: Dimensions and Levels of Autonomy

Dimension	Low Level	High Level
Ability to Act Alone	Engage target directly without course deviation	Avoid known threat zones and has “smart” engagement
Ability for Intra-Swarm Communication	Comms disabled	Enabled comms allow for target reassignment
Ability to Adapt	RWR disabled	RWR enables geolocation and allows for inbound threat recognition with evasive maneuvering
Ability for Leader-Follower Cooperation	Comms disabled	Bomber issues commands to swarm and information is relayed in a bidirectional manner

3.3 A2AD Scenario

The scenario used for this research study is a simulation consisting of two forces in conflict with each other. The Red force is defensive in posture, positioned on a coastal land segment with an IADS that defines the A2AD environment itself. The Blue force is an offensive strike package that ingresses from the sea and consists of a manned penetrating bomber that releases an autonomous cruise missile swarm in response to the Red IADS. The Blue forces seek to overwhelm the Red IADS with the cruise missile swarm, providing a veil of protection over the manned bomber as it engages the Red HVT. Together these forces make up the entire combat scenario. It is noted that the systems represented and discussed herein are modeled to provide insight through realistic performance, but they are not representative of any real-world existing or planned platforms.The following sections describe the simulation specifications, assumptions, and limitations, as developed within AFSIM.

3.3.1 Red Integrated Air Defense System

The Red IADS consists of several distinct entities in order to accurately portray a real-world military conflict. These include an Air Operations Center (AOC), TOCs, EW radars, TARs, TERs, EW fusion centers, and SAM battalions with associated launchers. Each entity is derived from AFSIMs platform repository, and is therefore defined by preset capabilities. The AOC acts as the highest level command authority within the IADS. The AOC assigns engagement tasks to TOCs after receiving and processing subordinate command information. The first of the two subordinate commands to the AOC is the EW fusion center. The EW fusion center commands 11 EW radar sites, which obtain radar information and relay it to the fusion center for processing before being sent to the AOC. The six TOCs are the second of the two subordinate commands to the AOC and act upon the AOCs commands by controlling their own respective SAM battalion. Each SAM battalion therefore consists of one TOC (commander), one TAR entity, one TER entity, and four SAM launcher entities.

The 11 EW radar sites provide the AOC with advanced warning capabilities by operating continuously for detection of inbound aerial or sea-based threats. However, the TAR and TER entities within each SAM battalion only operate once commanded upon by their TOC (as commanded by the AOC). The AOC issues commands by developing an engagement priority for the chosen SAM battalion to act upon once an inbound enemy threat is detected. The IADS layout also includes a stochastically-determined pop-up threat to test the autonomous cruise missile swarm's ability to adapt to a changing scenario [14]. This research has also extended the IADS design in several ways. First, an additional stochastic element was added to the starting position of the SAM launchers. A uniformly distributed random 20 kilometer displacement in both latitude and longitude was added to each launcher at the beginning of each scenario; this forces additional complexity on the swarm, allowing for an improved test of autonomy due to environmental configuration. Secondly, the pop-up threat has changed priorities to category one; the highest level of importance to the swarm, and equivalent to the Air Operations Center. Lastly, the offensive capabilities of the IADS will be defined solely by the SAM launchers. The air defense artillery was removed from the scenario to impose a stricter control on the experimental testing. Figure 8 displays the AFSIM IADS scenario as described above.

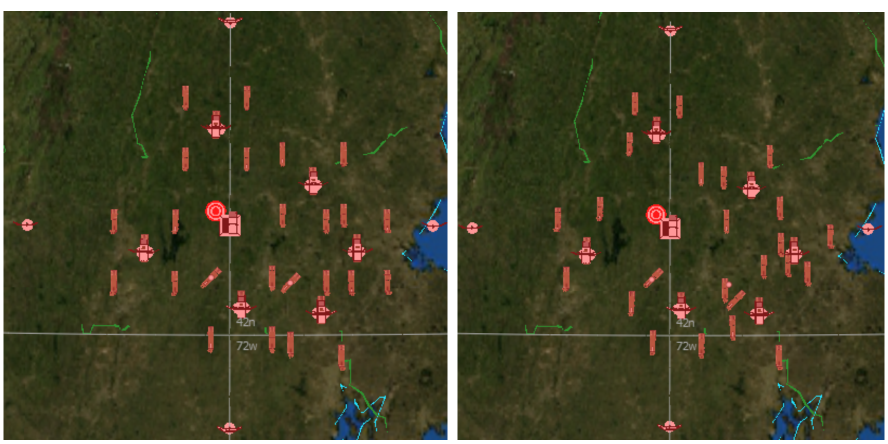


Figure 7: Red IADS Laydown (Before and After Displacement)

3.3.2 Blue Penetrating Bomber

The first component of the offensive Blue force is the manned penetrating bomber that seeks to destroy the Red HVT. The entity used within AFSIM is a generic low-observable strategic bombing aircraft that is defined by preset capabilities. The bomber is equipped with a communications network that allows for data and task processing for both itself and the swarm. The bomber can also enable an internal transceiver to allow for a command structure of the Blue forces. Doing so enables operating conditions such that the bomber now has command authority over the swarm, and therefore may issue commands to the swarm that must be executed. This protocol simulates the leader-follower relationship of a manned-unmanned team.

The bomber ingresses from the sea via a fixed, high-altitude route towards its primary objective. When engaged upon by the Red IADS, the bomber entity continues its mission objective due to the simulation argument set for its invulnerability. Setting this condition allows for a greater assessment in the overall functionality of the combat model and autonomy of the swarm, as the simulation is able to continue even after a successful SAM engagement on the bomber aircraft.

3.3.3 Blue Cruise Missile Swarm

The autonomous cruise missile swarm is released by the Blue penetrating bomber in response to the A2AD threat environment from the Red IADS. The cruise missile platform within AFSIM is adapted from Goggin's scenario [11, 14]. An initial screening design was implemented and used to test various swarm topologies within the combat model. This included the option for different amounts of swarms to be released during the operation; two swarms of 12 cruise missiles were tested against a single swarm of 24 cruise missiles. Being released at various times, the multi-swarm capability failed to perform as well as the single swarm implementation; however, it is useful to note that the dimensions of autonomy do support this change in swarm structure, as it may be necessary in different combat scenarios.

The release of the swarm consists of 24 cruise missile entities. Each missile has an initialization failure rate set at five percent in order to provide a more operationally realistic scenario. Each missile entity also carries enough fuel for up to 250 nautical miles of travel. Upon successful deployment, each missile is equipped with wings that allow for in-flight maneuverability to a maximum aerodynamic load of two times the force of gravity (2 g). Each cruise missile has a binary response probability to kill based off of the radial distance of impact from its target: a 1.0 probability to kill within a 100-meter radius, and a zero probability for any impact distance beyond.

Each cruise missile is equipped with a suite of sensors that provide information with respect to their navigation, location, threat detection, and communication networks. The sensor suite is composed of a global positioning system (GPS), a RWR, and a datalink transceiver. The RWR sensor operates at a 200km range with a 0.1 to 20 GHz frequency band. The transceiver operates in support of both the intra-swarm network internal to each cruise missile agent, and the leader-follower network that is commanded by the Blue bomber. The communications transfer is set to a rate of 100 megabits per second. Previous advancements made by Goggins [14], show that each cruise missile within the swarm is capable of individual agency without a centralized governing Air Battle Manager; allowing for situational awareness and individual perception based upon the set dimension and level of autonomy. This idea is further extended by the dimension of autonomy for leader-follower cooperation, whereby each cruise missile is subordinate to the manned bomber.

In this scenario, the number of Red SAMs and other IADS entities outnumber the available cruise missiles, forcing the swarm to calculate: 1) if an acceptable solution exists (i.e. the Blue penetrating bomber can destroy the Red HVT and survive), or 2) if an acceptable solution does not exist, what is the method of attack which produces the fewest number of engagements upon the Blue penetrating bomber. With this goal in mind, the simulation is set such that each Red IADS entity is assigned a priority category that influences how the swarm will calculate a targeting scheme, with highest priority being one and lowest priority being four. Upon successful deployment, each swarm entity is pre-briefed the initial targeting scheme that corresponds to a specific target platform, as well as information on the known SAM threat rings [14]. However, the viability to reach and destroy each threat is also an important element that the swarm must consider; therefore, the product of the target priority category and its associated distance from the cruise missile determines the overall priority score for each Red entity. The lowest priority score corresponds to the highest target priority for the swarm. The Red entity priority breakdown is shown below in Table 2. This configuration creates an initial battlefield assessment for both the Blue bomber and the Blue swarm; any further information gained via a sensor within the sensor suite must be communicated as based upon the dimensions for adaptation and intra-swarm communication. Lastly, pop-up entities will be considered within the targeting scheme based upon their priority level and associated distance to the Blue bomber, unlike the scenario developed by Goggins wherein each pop-up entity became an immediate target so long as its presence was detected by the swarm [14]. This adaptation forces the swarm to solve a more complex targeting problem while undergoing active mission operations.

Table 2: Swarm Priority Category Based off of IADS Entity Type

Category	Entity Type
1	AOC/SAM Launcher/Pop-Up Threat
2	TOC/EW Fusion Center
3	EW Radar
4	TER/TAR

3.4 Designed Experiment

Designing and implementing a simulation based experiment allows for statistical testing and analysis of results. Forming a model between control factors and responses provides the ability for rigorous interpretation between their causal relationship. The control factors used within this experiment are the dimensions and levels of autonomy for the cruise missile swarm; all other nuisance factors within the simulation experiment will be kept constant and left untested. The factors are assumed to be inherently orthogonal, and therefore independent of one another, which provides the necessary framework for a factorial design. Specifically, a 2^4 full factorial design with 16 unique treatment combinations is used, as shown in Table 3. Additionally, the dimensions and levels of autonomy are represented by categorical variables, whereby an in-between value (or center point) holds no meaningful interpretation. Each treatment is replicated 100 times, which allows for the statistical aggregation of data points by using a random number seed. The total simulation experiment contains 1600 runs.

Table 3: Design of Experiment Matrix

Treatment	Alone	Intra-Swarm	Adapt	L/F Coop
1	Low	Low	Low	Low
2	Low	Low	Low	High
3	Low	Low	High	Low
4	Low	Low	High	High
5	Low	High	Low	Low
6	Low	High	Low	High
7	Low	High	High	Low
8	Low	High	High	High
9	High	Low	Low	Low
10	High	Low	Low	High
11	High	Low	High	Low
12	High	Low	High	High
13	High	High	Low	Low
14	High	High	Low	High
15	High	High	High	Low
16	High	High	High	High

3.5 Measures of Effectiveness

Measures of effectiveness provide a foundation with which the effects of the dimensions of autonomy developed and simulated in AFSIM can be quantified, allowing answers to the primary research questions formed within this study. Measuring offensive and defensive capabilities are two ways to quantify the simulation outcome and will be broken into four different MOEs, as shown below in Table 4. It is noted that due to the set invulnerability of the Blue penetrating bomber, the Red HVT will always be destroyed.

The first MOE for offensive capability is a count of the number of Red Entities destroyed by the cruise missile swarm. This quantifies the lethality rate of the swarm and primarily encompasses how well the swarm is reacting to and destroying the Red SAMs in support of the primary mission objective for the strike package. The second MOE for offensive capability will be whether or not the pop-up entity from the Red IADS gets destroyed by the cruise missile swarm, as measured by a boolean response of true/false. This single pop-up entity evaluates the swarm's capability of adapting to a threat using geolocation of transmitting radar sites and incoming threat detection, while still focusing on the known Red IADS threats [14]. These two MOEs allow a quantifiable determination of the effectiveness of the swarm's ability to execute its kill chain.

The first MOE for defensive capability is a count of the number of times that the Blue penetrating bomber is struck by Red SAM missiles. The most ideal outcome for the bomber would result in zero successful SAM engagements, which would come as a result of the bomber being perfectly defended by the swarm. The second MOE for defensive capability is a count of the number of cruise missile swarm members that are destroyed by the Red SAM missiles. This allows for a test of the dimensions

Table 4: Measures of Effectiveness

Type	Category	Metric
MOE 1.1	Offensive	# of Red Entities Destroyed
MOE 1.2	Offensive	Pop Up Threat Eliminated (Boolean)
MOE 2.1	Defensive	# of SAM Strikes on Bomber
MOE 2.2	Defensive	# of Cruise Missiles Destroyed

of autonomy for the ability to adapt and ability to act alone, which provide evasive maneuvering and avoidance of threat zones, respectively. These two MOEs therefore test the swarm's ability to survive and thwart the Red IADS kill chain.

3.6 Follow-on Analysis

Upon completion of the simulation testing, experimental results for the three non-boolean MOEs are analyzed using analysis of variance (ANOVA). An ANOVA methodology applied to each MOE allows for statistical testing of each of the dimensions of autonomy. The null hypothesis for each test is that none of the dimensions of autonomy (or interaction effect) has significant effect on the respective MOE. The alternative hypothesis is that at least one dimension of autonomy (or their interaction effects) have a significant effect on the respective MOE. The first step of this analysis will be determining the rejection decision for the null hypothesis, followed by a multi-way interaction effects model (maintaining hierarchy) in order to determine which specific effects are significant. If a multi-way interaction effect is not significant, it will not be reported in the results table. The boolean MOE for the pop-up threat will follow a similar structure, except the ANOVA methodology will be replaced with log-likelihood methods.

IV. Results and Analysis

4.1 Chapter Overview

This chapter provides results of the designed experiment conducted for this research. The associated analytical discussion is comprised from ANOVA and log-likelihood techniques being applied to the dataset gathered. These methods allow for statistical justification of the relationships between the response variables and factor settings. All statistical testing is conducted at a 95% significance level ($\alpha = 0.05$) using JMP Pro 16.

4.2 Offensive Performance

4.2.1 MOE 1.1: Number of Red Force Entities Destroyed By Blue Force Swarm Member

The mean number of Red entities killed by the swarm members for each of the 16 treatments is plotted below in Figure 9. A higher value corresponds to a better offensive performance of the swarm members in support of the overall Blue strike package objective. The ANOVA test results show an overall F-statistic of 21.03 with an associated p-value of less than 0.0001. Since this p-value is less than the set level of significance of 0.05, the decision is to reject the null hypothesis that there is no difference between the treatment means (i.e., that there was not a significant effect from the application of autonomy) in favor of the alternative hypothesis that autonomy provides at least one statistically significant effect towards the swarm members ability to destroy the Red IADS members. Visually examining the 95% confidence intervals shown on each treatment mean provides a secondary justification for this result, as there are treatment pairs whose confidence internals do not overlap, such as Treatment 8 and Treatment 9. Analyzing the residual normal quantile plot confirms that our model follows a normal distribution. Further, visually examining the residual by predicted plot confirms that our model is homoscedastic, or has constant variance.

Table 5 depicts the individual effects test for each main and multi-level interaction effect of autonomy. By examining the p-values at the corresponding 0.05 significance level, the conclusion is that all four main effects statistically contribute to the swarm's offensive capability against their targets. Additionally, there is statistical significance between the two-level interaction for the ability for intra-swarm communication and ability for leader-follower cooperation, as well as the three-level interaction for the ability for intra-swarm communication, ability to adapt, and ability for leader-follower cooperation. These results show that autonomy, as defined in this four dimensional framework, enhances the swarm's lethality when compared to the baseline model.

By calculating the average relative change across treatment levels, the largest differential in mean Red entities killed is found to be from changing the ability to adapt from low to high when all other levels of autonomy are set to low. This change decreases the mean Red entities killed by 5.48%. This reduction in offensive capability is surprising, as enabling the high level for ability to adapt allows the RWR to detect incoming threats and respond accordingly. The remaining three dimensions of autonomy each have a small, but positive effect on the mean number of Red entities killed by the swarm when transitioning from low to high levels; the largest average increase is 1.0% from the ability for intra-swarm communication. All remaining calculations for each significant dimension's impact on the measures of effectiveness are conducted in a similar fashion.

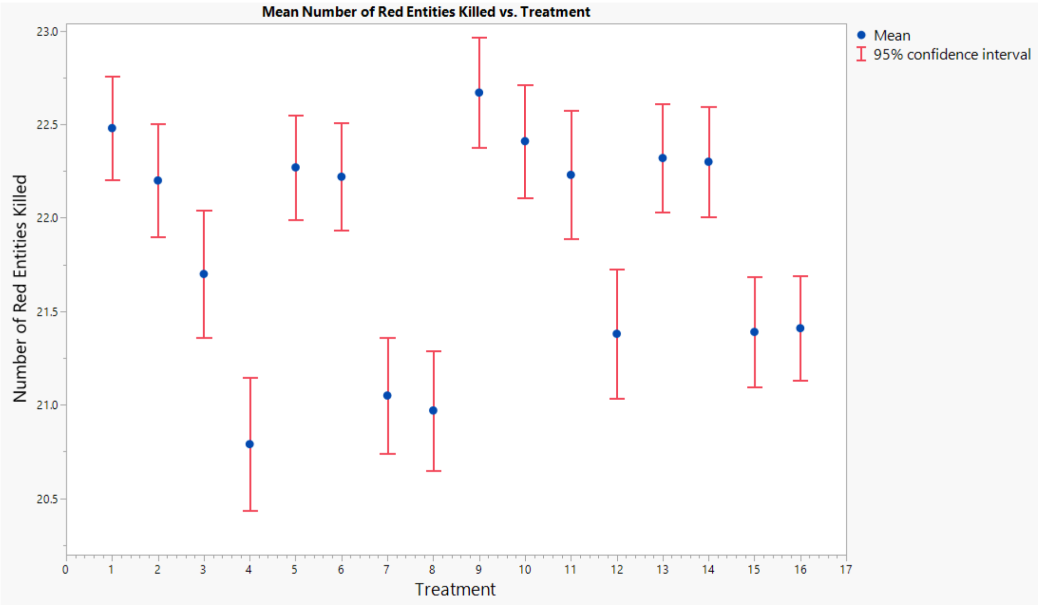


Figure 8: Number of Red Entities Killed versus Treatment

Table 5: Number of Red Entities Killed Effect Tests

Source	**Sum of Squares**	**F Ratio**	**Prob > F**
Alone	36.91	15.33	**< 0.0001**
Intra-Swarm	23.28	9.669	**0.0019**
Adapt	395.0	164.1	**< 0.0001**
L/F Coop	36.91	15.33	**< 0.0001**
Alone*Intra-Swarm	2.326	0.966	0.3259
Alone*Adapt	11.73	4.872	**0.0274**
Intra-Swarm*Adapt	2.481	1.030	0.3103
Alone* L/F Coop	0.276	0.115	0.7352
Intra-Swarm*L/F Coop	29.43	12.22	**0.0005**
Adapt*L/F Coop	9.151	3.801	0.0514
Intra-Swarm*Adapt* L/F Coop	9.456	3.927	**0.0477**

4.2.2 MOE 1.2: Pop-Up Threat Eliminated

The treatment means and their 95% confidence intervals for MOE 1.2 are shown below in Figure 10. Quantifying the mean proportion of runs in which the pop-up threat was destroyed by a Blue swarm member allows for determination of the swarm's flexibility in complex combat scenarios. The treatment combinations 1,3,9, and 11 encompass both the ability for intra-swarm communication and ability for leader-follower cooperation at a low level and never succeed in eliminating the pop-up threat, as the Blue cruise missile swarm does not have a means by which to dynamically reassign targets.

A log-likelihood method of statistical testing is applied for MOE 1.2 due to the requirement of this response to be boolean. This response would violate the assumption of normality that is necessary to ensure when using ANOVA statistical methods. The log-likelihood test results in a χ^2 statistic of 1029 with a p-value of less than 0.0001. Since this p-value is less than the level of significance of 0.05, we reject the null hypothesis that all treatment means are equal in favor of the alternative hypothesis that autonomy provides at least one statistically significant effect towards the swarm's ability to eliminate the pop-up threat. Figure 10 also displays the 95% confidence intervals shown on each treatment mean, providing a secondary justification for the above result, as there are treatment pairs whose confidence internals do not overlap such as Treatment 6 and Treatment 7. Analyzing the receiver operating characteristic (ROC) plot provides an area under the curve (AUC) of 0.91, indicating that our model has a strong predictive accuracy.

Table 6 depicts the individual effects test for each main and two-level interaction effect of autonomy. By examining the p-values at the set significance level, we are able to conclude that the main effects of ability for intra-swarm communication, ability to adapt, and ability for leader-follower cooperation all statistically contribute

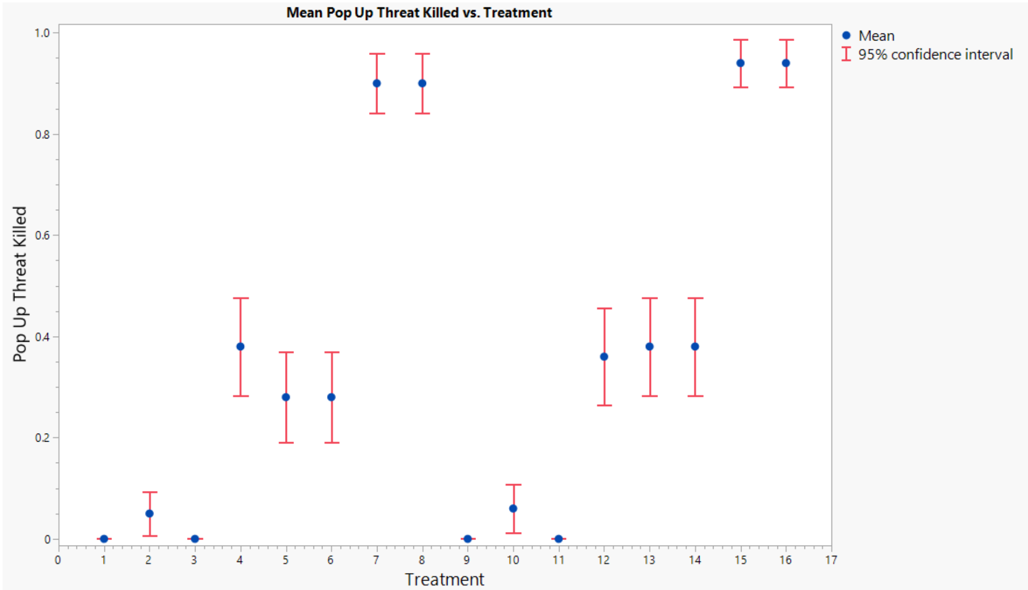


Figure 9: Pop-Up Threat Killed versus Treatment

to the swarm's ability to seek and destroy the pop-up threat. Additionally, there is statistical significance between the two level interaction for the ability for intra-swarm communication and ability for leader-follower cooperation; this is an expected result due to the nature of the interaction in the battle space between the manned-unmanned team.

The largest differential in the proportion of pop-up threat kills is from changing the ability for intra-swarm communication from low to high. The activation of this level of autonomy corresponds to an average increase of 51.9% in the probability for a swarm member to destroy the pop-up threat. Such an increase in the capacity for swarm members to detect changes within the IADS architecture, develop a targeting solution, and execute that solution in lethal effect exemplifies the importance of internal communication protocols within swarming technology.

Table 6: Pop-Up Threat Killed Effect Likelihood Ratio Tests

Source	**Likelihood Ratio χ 2**	**Prob > χ 2**
Alone	1.412	0.2347
Intra-Swarm	620.1	< **0.0001**
Adapt	211.1	< **0.0001**
L/F Coop	94.24	< **0.0001**
Alone*Intra-Swarm	1.419	0.2336
Alone*Adapt	0.001	0.9808
Intra-Swarm*Adapt	3.477	0.0622
Alone*L/F Coop	0	1.000
Intra-Swarm*L/F Coop	67.24	< **0.0001**
Adapt*L/F Coop	0	1.000

4.3 Defensive Performance

4.3.1 MOE 2.1: Number of SAM Strikes on the Blue Penetrating Bomber

Figure 11 displays the treatment means and their 95% confidence intervals for MOE 2.1. The lower the number of successful engagements by the SAM onto the Blue bomber corresponds to a higher rate of survivability and overall better defensive performance of the Blue strike package. The ANOVA test results show an overall F-statistic of 4.116 with an associated p-value of less than 0.0001. Since this p-value is less than the set level of significance of 0.05, the decision is to reject the null hypothesis in favor of the alternative hypothesis. This result shows that autonomy provides at least one statistically significant effect towards the Blue strike package's ability to disrupt the Red IADS kill chain. The 95% confidence intervals of each treatment mean display validation for this result, since there are several treatment pairs whose confidence internals do not overlap such as Treatment 4 and Treatment 5.

Analyzing the residual normal quantile plot and residual by predicted plot confirms that our model follows a normal distribution and has constant variance, respectively.

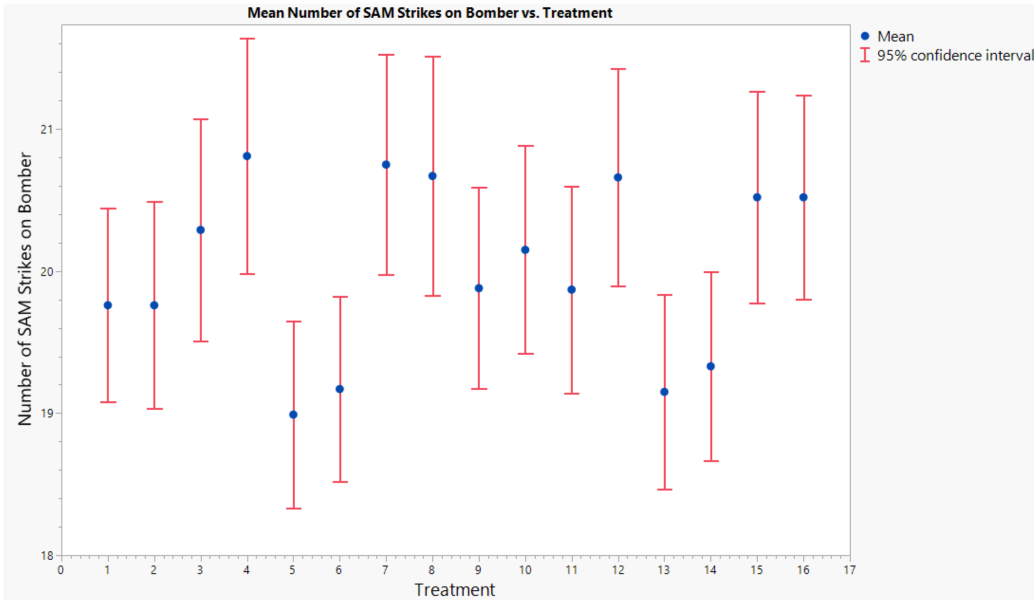


Figure 10: Number of SAM Strikes on Bomber versus Treatment

Table 7 displays the individual effects test for each main and two-level interaction effect for the dimensions of autonomy. Examining the p-values at the corresponding 0.05 significance level provides the conclusion that the ability to adapt main effect and ability to adapt with ability for intra-swarm communication interaction effect statistically contribute to the number of times that the bomber was successfully engaged upon by the SAM launchers. Further examining the insignificant results, there is little statistical effect from the other dimensions of autonomy.

Aggregating the means by transitioning from low level to high level for the ability to adapt corresponds to an average increase of in the number of SAM strikes on the bomber by 4.81%. This may be due to the fact that enabling the RWR for incoming threat detection and evasive maneuvering of the cruise missiles delays the agents time-to-impact, and ultimately prolongs the threat that the Red IADS entities (specifically SAM launchers) pose to the penetrating bomber. The ability for intra-swarm com-

Table 7: Number of SAM Strikes on Bomber Effect Tests

Source	Sum of Squares	F Ratio	Prob > F
Alone	0.090	0.007	0.9353
Intra-Swarm	27.04	1.978	0.1593
Adapt	390.1	28.53	**< 0.0001**
L/F Coop	21.62	1.585	0.2082
Alone*Intra-Swarm	0.000	0.000	1.0000
Alone*Adapt	19.80	1.452	0.2284
Intra-Swarm*Adapt	87.42	6.410	**0.0114**
Alone*L/F Coop	2.403	0.176	0.6747
Intra-Swarm*L/F Coop	10.56	0.775	0.3790
Adapt*L/F Coop	2.250	0.165	0.6847

munication aids in contributing to the survivability of the penetrating bomber by reducing the number of SAM strikes on average by 3.66%; providing evidence that enabling dynamic reassignment of targets of higher priority or of greater threat to the bomber increases bomber safety. However, even an overwhelming offensive force acting on behalf of the Blue bomber is not a substitute for proper defensive posturing, unless all enemy threats are first eliminated.

4.3.2 MOE 2.2: Number of Blue Cruise Missiles Destroyed

Figure 12 displays the treatment means and their 95% confidence intervals for MOE 2.2. The lower numbers correspond to less cruise missiles being destroyed and overall better survivability and defensive performance of the swarm. The ANOVA test results report the F-statistic to be 7.842 with an associated p-value of less than 0.0001, leading to rejection of the null hypothesis that there is no effect on cruise missile survivability from the application of autonomy in favor of the alternative hypothesis that our autonomous framework provides at least one statistically significant effect towards the swarm's survival rates. The existence of treatment pairs whose 95%

confidence intervals do not overlap confirm this result, such as Treatment 12 and Treatment 13. Analyzing the residual normal quantile plot indicates that the model for this MOE may have issues with our assumption of normality. The residual by predicted plot also indicates that there may be issues with our assumption of constant variance. Box-Cox transformations are tested to no significant effect. It is determined that these deviations will have minimal influence on the experimental results, and will therefore be accepted.

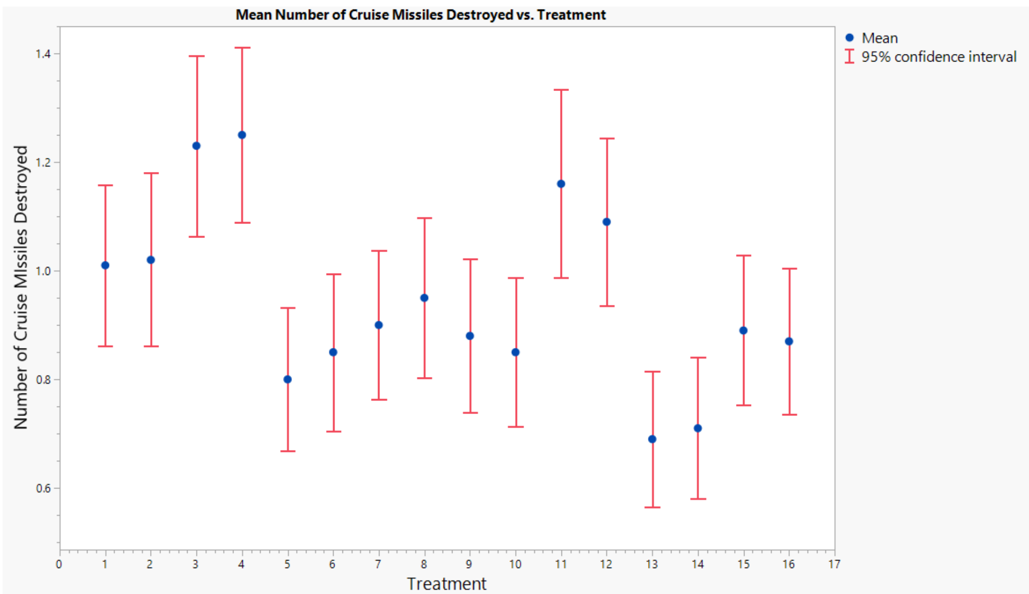


Figure 11: Number of Cruise Missiles Destroyed versus Treatment

Table 8 displays the individual effects test for each main and two-level interaction effect for the dimensions of autonomy. The ability to act alone, ability for intra-swarm communication, and ability to adapt main effects all show statistical significance with a p-value of less than 0.05. These results are sound in that the significant dimensions of autonomy directly influence how each swarm agent navigates the battle space, locates a target, and engages that target. This in turn places the swarm agent in a state at which a SAM launcher may target them. The insignificance of the ability for leader-follower cooperation is to be expected, as the functionality of the command structure is for purely offensive purposes.

Table 8: Number of Cruise Missiles Destroyed Effect Tests

Source	Sum of Squares	F Ratio	Prob > F
Alone	4.731	8.740	**0.0032**
Intra-Swarm	20.93	38.67	< **0.0001**
Adapt	14.63	27.03	< **0.0001**
L/F Coop	0.006	0.010	0.9188
Alone*Intra-Swarm	0.226	0.417	0.5186
Alone*Adapt	0.331	0.611	0.4346
Intra-Swarm*Adapt	1.051	1.941	0.1637
Alone*L/F Coop	0.331	0.611	0.4346
Intra-Swarm*L/F Coop	0.181	0.333	0.5636
Adapt*L/F Coop	0.031	0.057	0.8120

Aggregating the means for all three significant dimensions at their low and high levels provides limited results for MOE 2.2 due to the large confidence intervals of each response. Enabling intra-swarm communication while disabling the RWR interestingly provides a 37.8% average decrease in cruise missiles destroyed. Though this seems impactful, there are typically only one to two cruise missiles destroyed for every simulation run. Importantly, this result shows that the existing capability of cruise missiles to detect incoming threats and take appropriate counter measures may not only be insufficient, but also detrimental. With advancements in the threat processing algorithm, it is likely that the aerodynamic maneuvering available to each agent is unable to deal with the speed at which SAMs engage them.

V. Conclusions and Future Research

5.1 Chapter Overview

This chapter presents a conclusion to the research effort conducted for this study. The results gathered from the designed experiment are tied back in to the problem statement and answers to the research questions are provided. Finally, recommendations for future research are discussed based upon the conclusion.

5.2 Conclusion

As requirements for autonomous technology in military applications grow, so does the need for continual research, development, testing, and evaluation of these systems. This research effort proposed a four dimensional framework for autonomy, aiming to increase the versatility and effectiveness of previously defined lower dimensional efforts [14, 19]. Specifically, this study defines autonomous systems based on their ability to act alone, ability for intra-swarm communication, ability to adapt, and ability for leader-follower cooperation. By applying this framework to a swarm of cruise missiles, an experiment was able to be executed on the effectiveness of autonomy in support of a strike mission by a manned penetrating bomber through an A2AD battle space. The two research questions which guided this study are discussed below.

1. To what extent can autonomy in the application of cruise missile swarms be advanced from a previously defined three-dimensional framework?

The advancement of autonomy can first be described by necessary changes made to previously existing dimensions and secondly by the addition of a new fourth dimension. The ability to act alone originally provided an understanding of known threat zones to each cruise missile, forced agents to avoid them if possible, and, if unable to, then simply ignore them. This ability was advanced by first understanding that each cruise missile must enter a known threat zone in order to engage its target, and then by creating a "smart" engagement algorithm that allows for least intrusion into all threat zones by an agent during the calculation of its flight path. This maximized the radial distance from the center of known threat zones that each cruise missile flew into, allowing the lowest probability for detection by radar. The ability for intra-swarm communication was advanced by improving targeting criteria for the swarm, enabling reassignments to happen only if the subsequent Red entity was of higher value and closer to the individual agent. Additionally, enforcing a minimum distance that each agent must be from their current target before reassigning to a new target prevented unrealistic and last second changes. The ability to adapt involves a threat processing algorithm that detects radiation emitting sources and enables evasive maneuvering, if necessary. Improvements in the speed at which the algorithm can be executed allowed for an 80% increase in internal threat processing time. Lastly, a fourth dimension was added onto the autonomous framework that defined the ability for leader-follower cooperation through a manned-unmanned team. This provides an operational structure for the Blue strike package whereby the manned penetrating bomber acts as the commander of the swarm of cruise missiles. This affords the bomber the ability to issue commands to the swarm and override the swarm's targeting scheme. This dimension also sets a logical requirement for swarm members to attack any Red entities that violate the bombers projected flight path.

2. To what degree does autonomy aid in the offensive and defensive capabilities of Blue forces under the prescribed conditions?

When examining the offensive capabilities of the Blue force, all four dimensions of autonomy are statistically significant in their effect on the swarm. The ability to act alone, ability for intra-swarm communication, and ability for leader-follower cooperation all provide a small, but positive increase on the average number of Red entities killed. The largest average increase being the ability for intra-swarm communication at 1.0%. The ability to adapt surprisingly decreases the number of Red entities killed by on average 5.48%. However, when considering all levels set to low (i.e. no autonomy), the cruise missiles still engage their pre-briefed targets to a lethal degree. The low variation among the application or omission of autonomy on the number of Red entities killed by the swarm suggests that this IADS scenario may not be complex enough to fully answer the research question. When considering the pop-up threat, the ability for intra-swarm communication, ability to adapt, and ability for leader-follower cooperation all positively affect the swarm's capacity for detecting and destroying the stochastic entity. The ability for intra-swarm communication increases the probability of this occurring by 51.9%. The ability to adapt and ability for leader-follower cooperation follow with a 37.4% increase and 10.6% increase, respectively. Lastly, the ability for leader-follower cooperation showed significance towards the lethality of the swarm in both MOE 1.1 and 1.2, providing evidence that the interaction of manned-unmanned teams will benefit combat operations within an A2AD environment.

When examining the defensive capabilities of the Blue force, the ability to act alone, ability for intra-swarm communication, and ability to adapt are all statistically significant in their effect on the swarm. However, once again, the ability to adapt causes detriment to the capabilities of the swarm. This time there is a 4.81% increase in the number of SAM strikes on the manned bomber as well as an 18.66% increase in the number of cruise missiles shot down. The ability for intra-swarm communication proves to be the most valuable defensive measure within the autonomous framework by causing a 3.66% decrease in the number of SAM strikes on the manned bomber, as well as a 21.8% decrease in the number of cruise missiles shot down. Though it is again important to note that there are typically fewer than two cruise missiles shot down for every simulation run. Lastly, the ability to act alone decreases the number of cruise missiles shot down by 11.0%. As expected, the ability for leader-follower cooperation is not significant towards the defensive capabilities of the blue force due to the purely offensive nature of its implementation.

5.3 Recommendations for Future Research

The application of autonomy in cruise missile swarm technologies has nearly reached its limits within this scenario's formulation. The capabilities of the IADS acting within an A2AD role should be expanded to simulate more complex, real-world scenarios. Several other avenues for future research can be explored by testing the application of autonomy to various joint assets within the DoD's arsenal, implementing new operational tactics like the mission-based architecture for swarms, or furthering the manned-unmanned framework that has been established herein.

Another approach may involve reframing the definition of autonomy to that of a continuous spectrum, whereby context specific solutions will emerge for optimal performance depending on the battle space, as in the DoD Science Board's report. In this setting, the potential to leverage advances in machine learning techniques such as reinforcement learning and decision tree based algorithms exists. The resulting performance of the swarm as a whole may prove superior when compared to the discretized version of autonomy. Studying new and inventive ways to define and implement autonomy will nonetheless aid in maintaining the overall posture of air superiority by the United States Air Force.

Appendix A. JMP Statistical Output

Table 9: MOE 1.1 Full Model Analysis of Variance (ANOVA) Test Results

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	11	556.9	50.63	21.03
Error	1588	3824	2.401	**Prob > F**
Total	1599	4380		< 0.0001

Table 10: MOE 1.2 Full Model Log-Likelihood Test Results

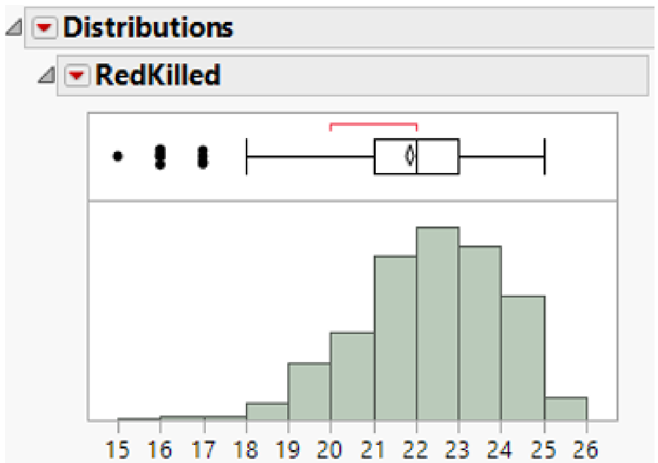
Model	-LogLikelihood	DF	χ 2
Difference	-514.3	10	1029
Full	536.2		**Prob > χ 2**
Reduced	1051		< 0.0001

Table 11: MOE 2.1 Full Model ANOVA Test Results

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	10	561.26	56.13	4.116
Error	1589	21670	13.64	**Prob > F**
Total	1599	22232		< 0.0001

Table 12: MOE 2.2 Full Model ANOVA Test Results

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	10	42.45	4.245	7.842
Error	1589	860.1	0.541	**Prob > F**
Total	1599	902.5		< 0.0001



Quantiles

100.0%	maximum	25
99.5%		25
97.5%		25
90.0%		24
75.0%	quartile	23
50.0%	median	22
25.0%	quartile	21
10.0%		20
2.5%		18.025
0.5%		17
0.0%	minimum	15

Summary Statistics

Mean	21.861875
Std Dev	1.6551461
Std Err Mean	0.0413787
Upper 95% Mean	21.943037
Lower 95% Mean	21.780713
N	1600

Figure 12: MOE 1.1 Distribution

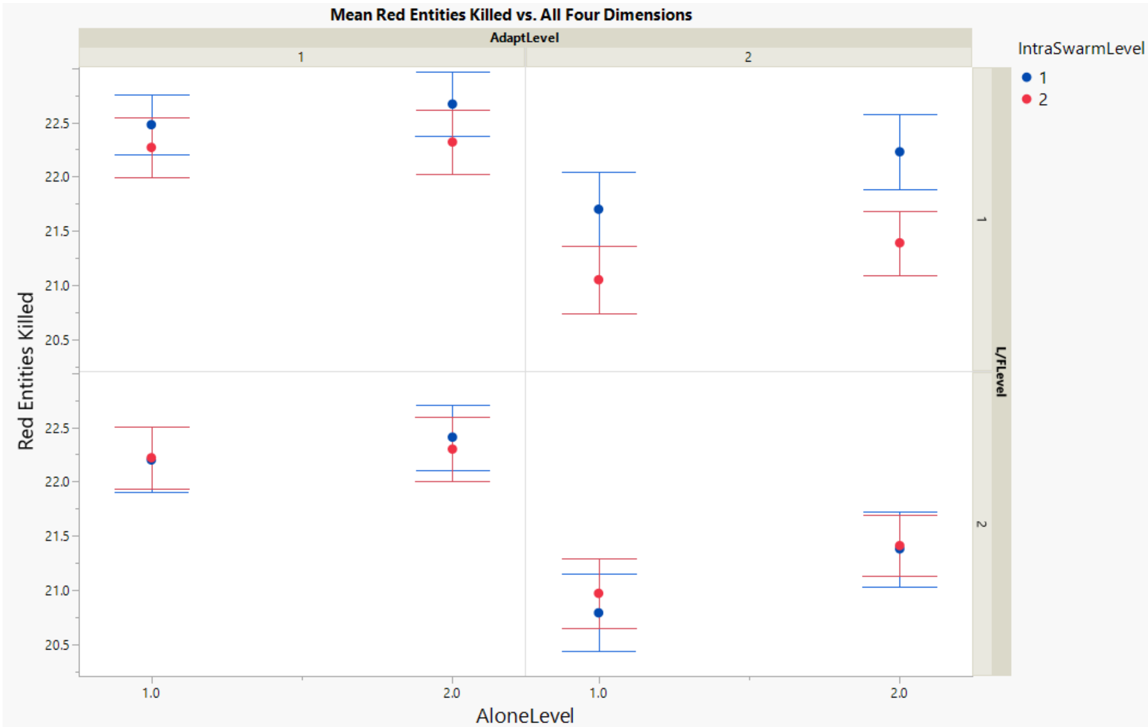
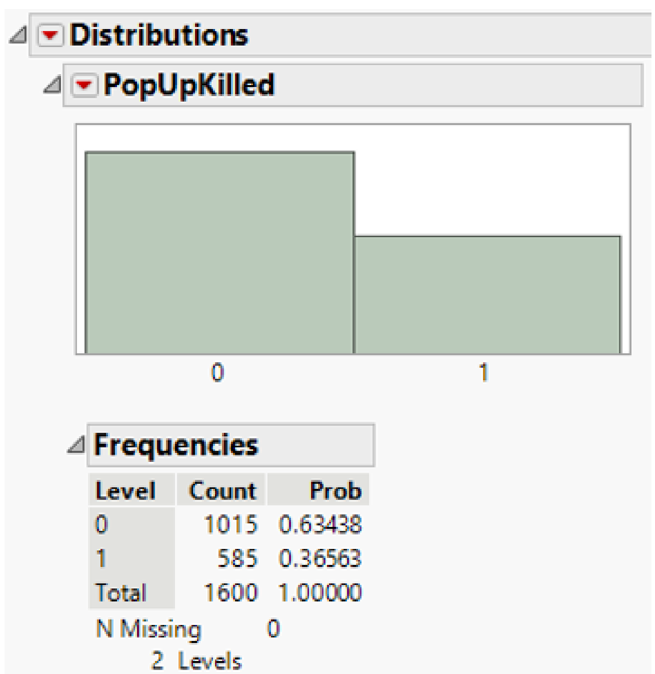


Figure 13: Number of Red Entities Killed versus All Four Dimensions



Level	Count	Prob
0	1015	0.63438
1	585	0.36563
Total	1600	1.00000

N Missing 0
2 Levels

Figure 14: MOE 1.2 Distribution

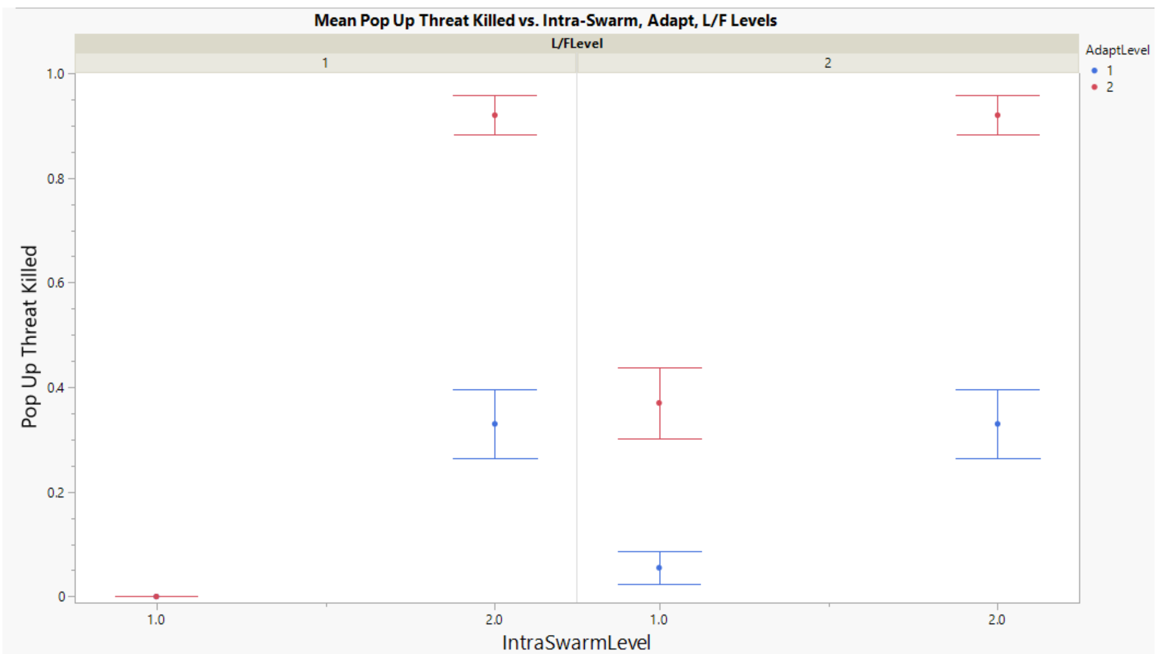
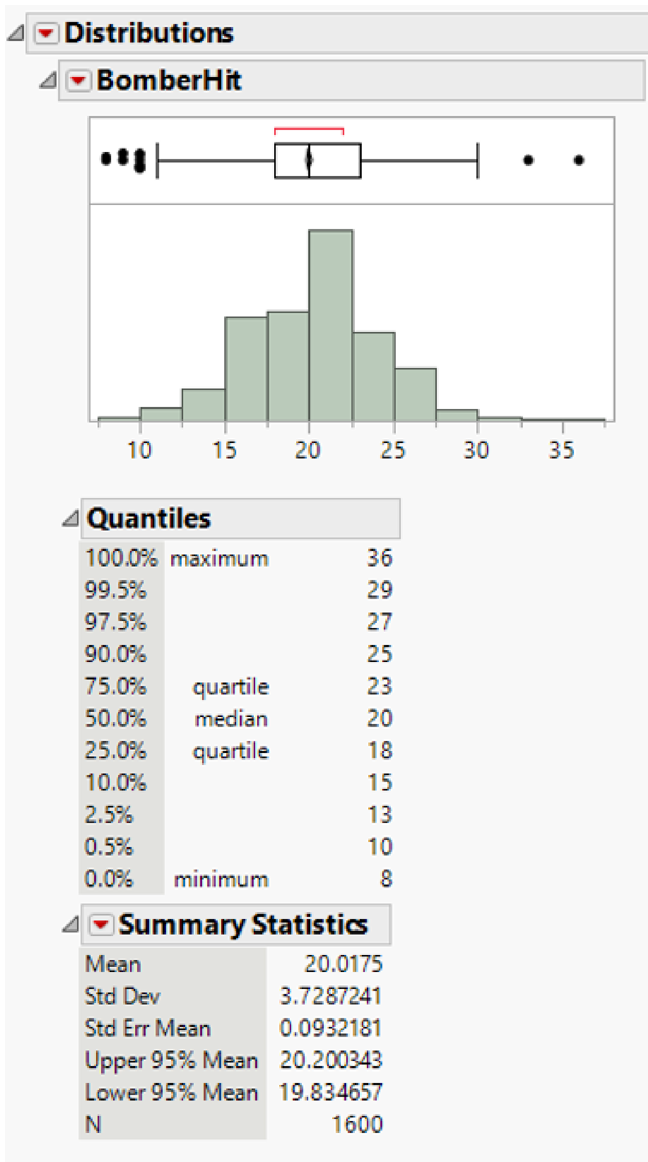


Figure 15: Pop-Up Threat Killed versus Coop Level, Adapt Level, and Relay Level



Quantiles

100.0%	maximum	36
99.5%		29
97.5%		27
90.0%		25
75.0%	quartile	23
50.0%	median	20
25.0%	quartile	18
10.0%		15
2.5%		13
0.5%		10
0.0%	minimum	8

Summary Statistics

Mean	20.0175
Std Dev	3.7287241
Std Err Mean	0.0932181
Upper 95% Mean	20.200343
Lower 95% Mean	19.834657
N	1600

Figure 16: MOE 2.1 Distribution

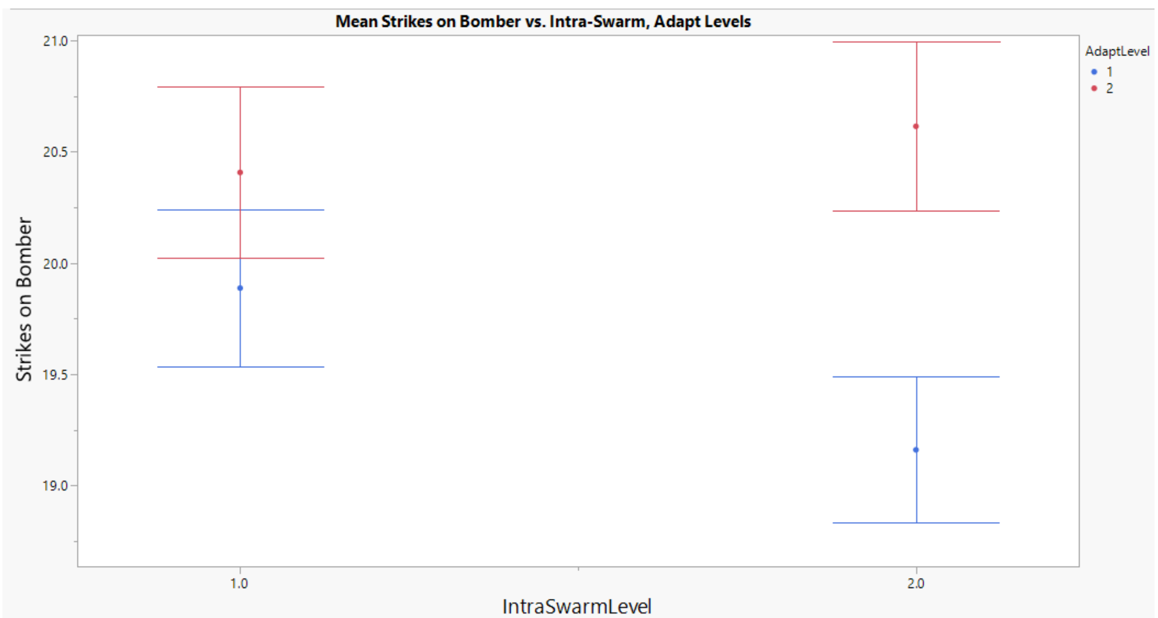


Figure 17: Number of SAM Strikes on Bomber versus Coop Level and Adapt Level

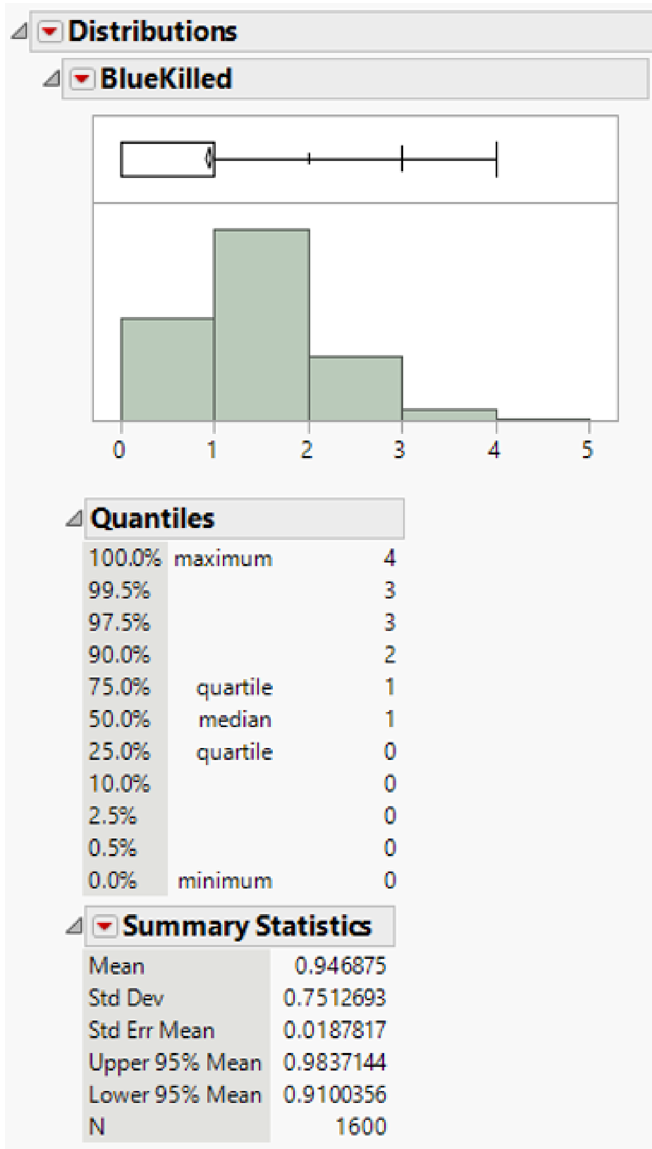


Figure 18: MOE 2.2 Distribution

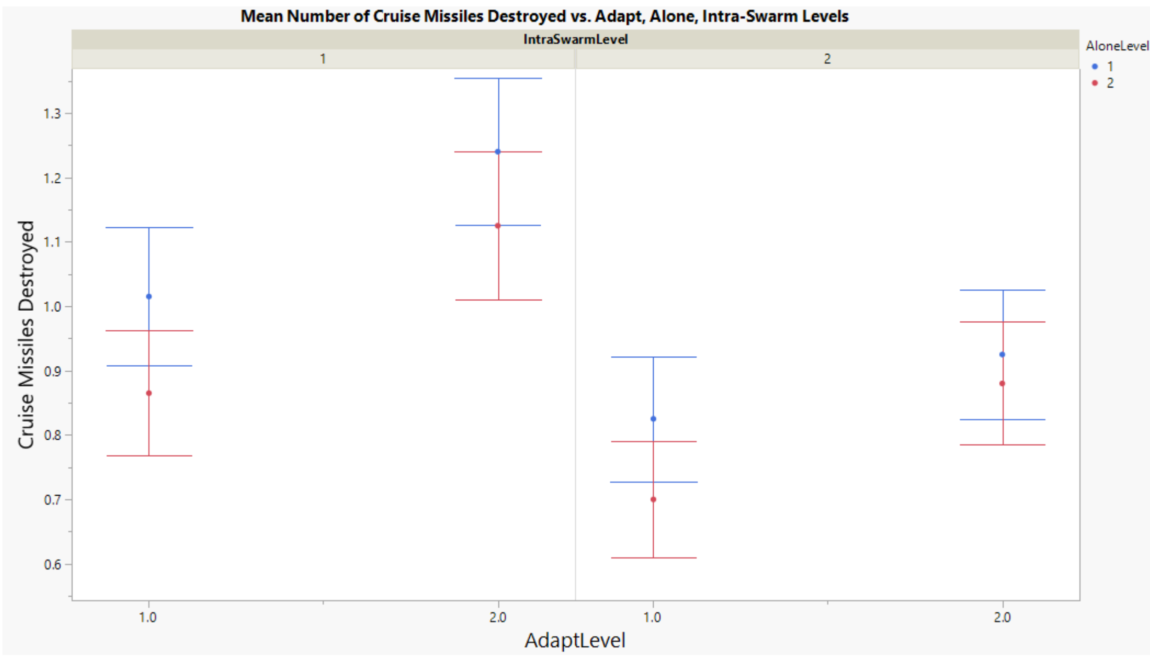


Figure 19: Number of Cruise Missiles Destroyed versus Adapt Level, Coop Level, and Alone Level

Appendix B. Simulation Experiment Results

Table 13: Simulation Experiment Results, Runs 1-46

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
1	1	21	0	1	21
2	1	22	0	2	21
3	1	22	0	2	12
4	1	24	0	1	17
5	1	24	0	1	17
6	1	24	0	0	16
7	1	22	0	2	21
8	1	24	0	0	22
9	1	23	0	1	18
10	1	20	0	1	16
11	1	22	0	2	16
12	1	24	0	1	14
13	1	24	0	1	20
14	1	23	0	1	21
15	1	23	0	1	20
16	1	21	0	1	23
17	1	25	0	0	12
18	1	22	0	0	20
19	1	20	0	3	28
20	1	23	0	0	13
21	1	25	0	0	20
22	1	22	0	1	26
23	1	21	0	1	21
24	1	24	0	0	21
25	1	22	0	2	21
26	1	23	0	2	18
27	1	22	0	2	22
28	1	21	0	1	21
29	1	23	0	1	19
30	1	22	0	2	17
31	1	22	0	1	24
32	1	23	0	1	18
33	1	22	0	2	23
34	1	24	0	1	21
35	1	22	0	2	18
36	1	24	0	0	19
37	1	23	0	1	17
38	1	23	0	0	19
39	1	24	0	0	22
40	1	23	0	1	18
41	1	19	0	1	30
42	1	22	0	2	17
43	1	25	0	0	18
44	1	21	0	1	20
45	1	22	0	2	21
46	1	24	0	1	23

Table 14: Simulation Experiment Results, Runs 47-92

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
47	1	21	0	1	22
48	1	20	0	3	16
49	1	21	0	2	18
50	1	24	0	1	16
51	1	23	0	0	24
52	1	23	0	0	23
53	1	21	0	1	21
54	1	21	0	2	13
55	1	22	0	2	18
56	1	23	0	1	24
57	1	23	0	1	23
58	1	24	0	0	17
59	1	21	0	3	24
60	1	23	0	2	19
61	1	21	0	1	22
62	1	22	0	2	22
63	1	21	0	0	20
64	1	22	0	1	24
65	1	24	0	1	18
66	1	23	0	1	18
67	1	22	0	1	19
68	1	24	0	0	21
69	1	21	0	1	20
70	1	23	0	1	25
71	1	22	0	2	19
72	1	22	0	1	22
73	1	22	0	0	26
74	1	24	0	1	19
75	1	20	0	1	22
76	1	24	0	0	22
77	1	21	0	1	23
78	1	25	0	0	20
79	1	22	0	1	16
80	1	24	0	0	21
81	1	23	0	1	21
82	1	24	0	1	21
83	1	24	0	0	19
84	1	24	0	0	18
85	1	23	0	0	15
86	1	24	0	1	13
87	1	21	0	2	19
88	1	22	0	1	20
89	1	20	0	1	22
90	1	21	0	1	22
91	1	20	0	1	26
92	1	22	0	1	13

Table 15: Simulation Experiment Results, Runs 93-138

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
93	1	22	0	1	21
94	1	25	0	0	19
95	1	24	0	1	16
96	1	21	0	1	17
97	1	21	0	1	22
98	1	20	0	1	23
99	1	24	0	1	17
100	1	23	0	1	13
101	2	21	0	1	21
102	2	23	0	0	22
103	2	21	0	2	15
104	2	24	0	1	17
105	2	23	1	1	17
106	2	24	0	0	16
107	2	22	0	2	21
108	2	24	0	0	22
109	2	20	0	3	21
110	2	20	0	1	16
111	2	22	0	2	16
112	2	24	0	1	14
113	2	24	0	1	20
114	2	23	0	1	21
115	2	22	0	1	20
116	2	21	0	1	23
117	2	24	0	0	11
118	2	22	0	0	20
119	2	19	0	3	29
120	2	23	0	0	13
121	2	25	0	0	20
122	2	22	0	1	26
123	2	19	1	2	12
124	2	24	0	0	21
125	2	22	0	2	21
126	2	23	0	2	18
127	2	21	0	2	25
128	2	21	0	1	21
129	2	23	0	1	19
130	2	22	0	2	17
131	2	22	0	1	24
132	2	22	0	1	17
133	2	22	0	2	23
134	2	24	0	1	21
135	2	22	0	2	18
136	2	24	0	0	19
137	2	22	0	1	21
138	2	23	0	0	19

Table 16: Simulation Experiment Results, Runs 139-184

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
139	2	24	0	0	22
140	2	23	0	1	18
141	2	19	0	1	30
142	2	22	0	2	17
143	2	25	0	0	18
144	2	21	0	1	20
145	2	22	0	2	21
146	2	22	0	2	24
147	2	21	0	1	22
148	2	20	0	3	16
149	2	21	0	2	18
150	2	24	0	1	16
151	2	23	0	0	24
152	2	22	0	0	19
153	2	21	0	1	21
154	2	21	0	2	13
155	2	22	0	2	18
156	2	21	0	1	30
157	2	23	0	1	23
158	2	24	0	0	17
159	2	21	0	3	24
160	2	22	0	2	17
161	2	21	0	1	22
162	2	22	0	2	22
163	2	21	0	0	20
164	2	22	0	1	24
165	2	24	0	1	18
166	2	22	0	1	15
167	2	22	0	1	19
168	2	23	0	0	22
169	2	21	0	1	20
170	2	23	0	1	25
171	2	22	0	2	19
172	2	21	1	1	22
173	2	22	0	0	26
174	2	24	0	1	19
175	2	18	1	2	22
176	2	23	0	0	19
177	2	21	0	1	23
178	2	25	0	0	20
179	2	21	0	1	18
180	2	24	0	0	21
181	2	23	0	1	21
182	2	24	0	1	21
183	2	24	0	0	19
184	2	24	0	0	18

Table 17: Simulation Experiment Results, Runs 185-230

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
185	2	23	0	0	15
186	2	24	0	1	13
187	2	21	0	2	19
188	2	22	0	1	20
189	2	19	1	1	22
190	2	20	0	1	21
191	2	20	0	1	26
192	2	22	0	1	13
193	2	22	0	1	21
194	2	25	0	0	19
195	2	24	0	1	16
196	2	21	0	0	20
197	2	21	0	1	22
198	2	20	0	0	20
199	2	24	0	1	17
200	2	22	0	1	12
201	3	20	0	2	21
202	3	24	0	1	12
203	3	23	0	0	13
204	3	22	0	2	10
205	3	24	0	0	22
206	3	22	0	1	16
207	3	23	0	1	23
208	3	24	0	1	19
209	3	25	0	0	20
210	3	19	0	1	26
211	3	25	0	0	17
212	3	24	0	1	13
213	3	24	0	1	21
214	3	22	0	0	17
215	3	23	0	0	18
216	3	19	0	1	19
217	3	22	0	1	17
218	3	17	0	2	23
219	3	22	0	1	18
220	3	22	0	0	17
221	3	21	0	3	20
222	3	21	0	1	23
223	3	20	0	2	22
224	3	22	0	1	24
225	3	24	0	0	22
226	3	24	0	1	13
227	3	23	0	1	21
228	3	21	0	2	20
229	3	22	0	1	15
230	3	20	0	2	18

Table 18: Simulation Experiment Results, Runs 231-276

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
231	3	22	0	1	27
232	3	23	0	2	20
233	3	21	0	1	25
234	3	24	0	1	19
235	3	21	0	2	23
236	3	22	0	2	22
237	3	21	0	2	20
238	3	21	0	2	24
239	3	24	0	1	24
240	3	20	0	3	21
241	3	19	0	3	25
242	3	23	0	1	23
243	3	24	0	0	19
244	3	21	0	1	20
245	3	22	0	1	25
246	3	22	0	2	21
247	3	21	0	2	23
248	3	20	0	2	22
249	3	23	0	1	16
250	3	21	0	2	15
251	3	24	0	0	18
252	3	21	0	2	20
253	3	20	0	1	24
254	3	23	0	0	19
255	3	23	0	1	17
256	3	22	0	2	26
257	3	22	0	2	26
258	3	22	0	2	17
259	3	21	0	1	23
260	3	23	0	1	21
261	3	19	0	3	16
262	3	20	0	3	26
263	3	19	0	1	27
264	3	20	0	1	22
265	3	23	0	1	19
266	3	21	0	2	21
267	3	20	0	2	21
268	3	21	0	2	15
269	3	19	0	3	14
270	3	22	0	2	28
271	3	21	0	1	24
272	3	23	0	0	19
273	3	20	0	1	15
274	3	25	0	0	9
275	3	20	0	0	24
276	3	24	0	0	24

Table 19: Simulation Experiment Results, Runs 277-322

Run #	Treatment	Red Killed	PopUp Killed	Blue Killed	Bomber Hit
277	3	22	0	0	25
278	3	25	0	0	22
279	3	21	0	1	22
280	3	21	0	2	27
281	3	22	0	1	22
282	3	22	0	2	17
283	3	22	0	0	24
284	3	22	0	1	22
285	3	21	0	1	17
286	3	21	0	2	19
287	3	21	0	2	21
288	3	22	0	1	22
289	3	20	0	1	20
290	3	22	0	0	23
291	3	20	0	0	22
292	3	20	0	1	22
293	3	21	0	2	16
294	3	23	0	2	22
295	3	23	0	1	21
296	3	19	0	1	19
297	3	18	0	2	22
298	3	18	0	2	23
299	3	24	0	1	11
300	3	23	0	1	19
301	4	19	0	2	25
302	4	23	1	1	12
303	4	22	0	0	10
304	4	22	0	2	10
305	4	23	1	0	24
306	4	22	0	1	16
307	4	22	1	1	23
308	4	23	1	1	19
309	4	24	0	0	20
310	4	18	1	1	22
311	4	25	0	0	17
312	4	22	1	1	19
313	4	23	1	1	19
314	4	21	0	0	19
315	4	19	0	2	24
316	4	19	0	1	19
317	4	22	0	1	17
318	4	15	0	2	27
319	4	21	1	1	16
320	4	21	1	0	15
321	4	21	1	2	18
322	4	19	0	2	28

Table 20: Simulation Experiment Results, Runs 323-368

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
323	4	20	0	2	22
324	4	22	1	1	24
325	4	23	1	0	22
326	4	22	0	2	18
327	4	22	0	1	21
328	4	19	0	3	20
329	4	20	0	2	26
330	4	20	0	2	18
331	4	20	0	2	26
332	4	22	0	2	20
333	4	19	1	1	26
334	4	24	0	1	19
335	4	19	0	2	23
336	4	21	0	2	22
337	4	21	1	1	22
338	4	20	1	2	24
339	4	23	1	1	21
340	4	19	1	2	19
341	4	19	0	1	26
342	4	22	1	1	21
343	4	23	0	0	16
344	4	20	0	1	21
345	4	22	0	1	25
346	4	23	0	0	22
347	4	21	0	2	23
348	4	19	0	2	20
349	4	22	0	1	22
350	4	20	0	2	15
351	4	23	0	0	18
352	4	20	1	2	18
353	4	20	0	1	24
354	4	21	0	1	18
355	4	22	1	1	17
356	4	22	1	0	28
357	4	21	1	2	25
358	4	20	0	2	17
359	4	19	0	2	22
360	4	22	0	2	23
361	4	19	0	2	19
362	4	20	0	3	26
363	4	17	0	2	24
364	4	19	1	1	22
365	4	22	1	1	19
366	4	21	0	2	21
367	4	20	1	1	23
368	4	21	1	1	17

Table 21: Simulation Experiment Results, Runs 369-414

Run #	Treatment	Red Killed	PopUp Killed	Blue Killed	Bomber Hit
369	4	19	0	3	14
370	4	22	0	1	26
371	4	21	0	1	20
372	4	21	0	1	19
373	4	19	1	1	25
374	4	25	0	0	9
375	4	19	0	0	23
376	4	23	0	0	23
377	4	19	1	1	27
378	4	23	1	1	23
379	4	20	0	1	22
380	4	18	1	4	24
381	4	21	1	1	22
382	4	22	1	1	19
383	4	20	1	1	27
384	4	21	1	1	23
385	4	21	0	1	17
386	4	20	0	2	15
387	4	21	0	1	21
388	4	20	0	2	19
389	4	19	0	1	20
390	4	20	1	1	23
391	4	20	0	0	24
392	4	20	0	1	22
393	4	22	0	0	22
394	4	22	1	1	29
395	4	22	0	1	27
396	4	18	0	1	21
397	4	18	0	2	22
398	4	16	1	3	22
399	4	23	0	1	8
400	4	22	1	1	19
401	5	21	0	1	17
402	5	22	1	1	20
403	5	22	1	1	13
404	5	24	0	1	17
405	5	23	1	1	12
406	5	23	1	0	20
407	5	21	0	3	22
408	5	24	0	0	17
409	5	22	1	1	23
410	5	20	0	1	13
411	5	23	1	0	17
412	5	23	1	1	19
413	5	24	0	1	21
414	5	23	0	1	18

Table 22: Simulation Experiment Results, Runs 415-460

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
415	5	23	1	0	22
416	5	21	0	0	16
417	5	24	1	0	14
418	5	22	0	0	18
419	5	21	1	1	26
420	5	22	0	1	17
421	5	25	0	0	20
422	5	22	0	1	16
423	5	21	1	0	20
424	5	23	0	1	21
425	5	22	1	1	20
426	5	22	0	3	21
427	5	23	1	0	23
428	5	20	0	2	19
429	5	23	0	1	20
430	5	23	0	1	16
431	5	22	0	1	25
432	5	23	0	0	22
433	5	23	0	1	25
434	5	24	0	1	20
435	5	22	1	1	14
436	5	21	0	2	19
437	5	22	0	1	22
438	5	22	1	0	17
439	5	24	0	0	21
440	5	22	1	1	17
441	5	19	0	0	18
442	5	23	0	1	16
443	5	25	0	0	18
444	5	20	1	1	14
445	5	23	0	1	22
446	5	23	1	1	24
447	5	22	0	0	20
448	5	21	0	1	25
449	5	22	0	1	20
450	5	24	0	1	16
451	5	22	0	1	25
452	5	20	1	2	19
453	5	23	0	0	16
454	5	22	0	1	15
455	5	24	0	0	15
456	5	21	0	2	26
457	5	23	0	1	23
458	5	24	0	0	13
459	5	22	0	2	23
460	5	23	0	1	18

Table 23: Simulation Experiment Results, Runs 461-506

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
461	5	21	1	0	23
462	5	23	0	1	19
463	5	19	0	1	21
464	5	22	0	1	22
465	5	24	0	1	19
466	5	23	1	0	23
467	5	23	0	0	16
468	5	23	1	0	18
469	5	21	1	0	15
470	5	23	0	1	21
471	5	22	0	2	16
472	5	22	0	1	21
473	5	20	0	1	16
474	5	24	0	1	19
475	5	19	0	1	21
476	5	23	0	0	19
477	5	22	0	0	20
478	5	24	1	0	22
479	5	21	0	1	18
480	5	23	0	1	21
481	5	23	0	1	13
482	5	24	0	1	21
483	5	23	0	1	21
484	5	23	0	1	18
485	5	22	0	1	18
486	5	24	0	1	16
487	5	21	0	2	16
488	5	21	0	2	17
489	5	19	1	1	22
490	5	20	1	1	20
491	5	21	0	0	24
492	5	22	0	1	18
493	5	22	1	0	24
494	5	25	0	0	19
495	5	24	0	1	16
496	5	21	0	0	20
497	5	22	0	0	11
498	5	19	0	1	17
499	5	24	0	1	17
500	5	22	1	1	15
501	6	21	0	1	17
502	6	22	1	1	20
503	6	22	1	1	13
504	6	24	0	1	17
505	6	23	1	1	15
506	6	23	1	0	20

Table 24: Simulation Experiment Results, Runs 507-552

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
507	6	21	0	3	22
508	6	24	0	0	17
509	6	22	1	1	23
510	6	20	0	1	13
511	6	23	1	0	17
512	6	23	1	1	17
513	6	24	0	1	21
514	6	23	0	1	18
515	6	23	1	0	22
516	6	21	0	0	17
517	6	24	1	0	14
518	6	22	0	0	18
519	6	21	1	1	26
520	6	23	0	0	18
521	6	25	0	0	20
522	6	22	0	1	16
523	6	20	1	1	20
524	6	23	0	1	21
525	6	22	1	1	20
526	6	22	0	3	22
527	6	23	1	0	23
528	6	20	0	2	20
529	6	23	0	1	20
530	6	23	0	1	16
531	6	22	0	1	25
532	6	23	0	0	22
533	6	23	0	1	25
534	6	24	0	1	20
535	6	21	1	2	14
536	6	21	0	2	17
537	6	21	0	2	22
538	6	22	1	0	17
539	6	24	0	0	21
540	6	22	1	1	17
541	6	19	0	0	18
542	6	23	0	1	16
543	6	25	0	0	18
544	6	20	1	1	19
545	6	23	0	1	22
546	6	23	1	1	24
547	6	22	0	0	20
548	6	21	0	1	25
549	6	22	0	1	20
550	6	24	0	1	16
551	6	22	0	1	25
552	6	20	1	2	19

Table 25: Simulation Experiment Results, Runs 553-598

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
553	6	23	0	0	16
554	6	22	0	1	15
555	6	24	0	0	15
556	6	20	0	3	26
557	6	23	0	1	23
558	6	24	0	0	13
559	6	22	0	2	24
560	6	23	0	1	18
561	6	21	1	0	23
562	6	23	0	1	21
563	6	19	0	1	21
564	6	22	0	1	21
565	6	24	0	1	19
566	6	23	1	0	23
567	6	23	0	0	16
568	6	23	1	0	18
569	6	21	1	0	15
570	6	23	0	1	23
571	6	22	0	2	16
572	6	22	0	1	22
573	6	20	0	1	16
574	6	24	0	1	19
575	6	19	0	1	21
576	6	22	0	1	21
577	6	22	0	0	20
578	6	24	1	0	22
579	6	21	0	1	19
580	6	23	0	1	21
581	6	23	0	1	13
582	6	24	0	1	21
583	6	23	0	1	21
584	6	23	0	1	18
585	6	22	0	1	18
586	6	24	0	1	16
587	6	20	0	3	17
588	6	21	0	2	17
589	6	19	1	1	22
590	6	20	1	1	20
591	6	21	0	0	24
592	6	22	0	1	18
593	6	22	1	0	25
594	6	25	0	0	19
595	6	24	0	1	16
596	6	21	0	0	20
597	6	22	0	0	11
598	6	19	0	1	17

Table 26: Simulation Experiment Results, Runs 599-644

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
599	6	24	0	1	17
600	6	22	1	1	15
601	7	20	1	1	22
602	7	24	1	0	14
603	7	20	1	2	17
604	7	22	1	1	12
605	7	23	1	0	23
606	7	21	1	1	24
607	7	21	1	1	22
608	7	23	1	1	22
609	7	24	1	0	21
610	7	19	1	0	21
611	7	23	1	1	18
612	7	23	1	1	15
613	7	23	1	1	25
614	7	19	1	2	16
615	7	20	1	2	11
616	7	20	1	1	19
617	7	20	0	2	13
618	7	20	1	0	25
619	7	19	1	2	17
620	7	19	1	1	20
621	7	22	1	0	18
622	7	19	1	1	19
623	7	20	0	1	19
624	7	23	1	0	24
625	7	21	1	2	22
626	7	24	0	0	14
627	7	23	1	0	19
628	7	21	1	1	13
629	7	21	1	1	21
630	7	21	1	1	16
631	7	20	1	2	27
632	7	23	1	1	22
633	7	19	1	3	23
634	7	22	1	1	26
635	7	21	1	1	23
636	7	22	1	1	24
637	7	20	1	1	25
638	7	21	1	1	22
639	7	24	1	0	23
640	7	22	1	0	15
641	7	20	1	1	21
642	7	21	1	2	27
643	7	22	1	1	21
644	7	20	1	1	19

Table 27: Simulation Experiment Results, Runs 645-690

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
645	7	21	1	1	25
646	7	22	1	1	23
647	7	22	1	0	16
648	7	21	1	1	25
649	7	23	1	0	15
650	7	22	1	1	18
651	7	22	1	1	23
652	7	22	1	0	26
653	7	19	1	0	20
654	7	21	1	1	19
655	7	23	1	0	24
656	7	23	0	0	24
657	7	21	1	1	26
658	7	22	1	1	24
659	7	20	1	1	24
660	7	23	1	1	25
661	7	21	1	0	19
662	7	22	1	0	20
663	7	19	1	1	25
664	7	21	0	0	14
665	7	22	1	1	19
666	7	20	0	2	18
667	7	20	1	1	21
668	7	22	1	0	24
669	7	18	1	2	20
670	7	21	1	1	27
671	7	21	0	1	21
672	7	21	1	1	20
673	7	20	1	0	21
674	7	23	1	0	16
675	7	19	0	1	22
676	7	23	1	0	20
677	7	21	1	1	23
678	7	24	1	0	23
679	7	20	0	1	23
680	7	21	1	1	28
681	7	22	1	1	17
682	7	22	1	1	24
683	7	20	1	1	24
684	7	21	1	1	19
685	7	19	1	1	23
686	7	21	1	1	19
687	7	21	1	1	16
688	7	22	1	0	24
689	7	20	1	0	21
690	7	19	1	2	23

Table 28: Simulation Experiment Results, Runs 691-736

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
691	7	16	1	1	24
692	7	19	1	1	19
693	7	20	1	2	24
694	7	21	1	3	28
695	7	21	1	2	21
696	7	19	1	1	22
697	7	18	1	1	18
698	7	19	1	1	15
699	7	23	0	1	12
700	7	21	1	1	21
701	8	20	1	1	22
702	8	24	1	0	14
703	8	20	1	2	17
704	8	22	1	1	12
705	8	23	1	0	23
706	8	21	1	1	24
707	8	21	1	1	22
708	8	23	1	1	22
709	8	24	1	0	21
710	8	19	1	0	21
711	8	23	1	1	18
712	8	23	1	1	17
713	8	23	1	1	25
714	8	19	1	2	16
715	8	19	1	2	10
716	8	18	1	3	11
717	8	20	0	2	13
718	8	19	1	0	23
719	8	19	1	2	17
720	8	19	1	1	20
721	8	22	1	0	18
722	8	19	1	1	20
723	8	20	0	1	19
724	8	23	1	0	24
725	8	22	1	1	24
726	8	24	0	0	14
727	8	23	1	0	19
728	8	21	1	1	13
729	8	21	1	1	21
730	8	21	1	1	16
731	8	20	1	2	25
732	8	23	1	1	22
733	8	19	1	3	23
734	8	22	1	1	26
735	8	21	1	1	23
736	8	22	1	1	24

Table 29: Simulation Experiment Results, Runs 737-782

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
737	8	20	1	1	24
738	8	21	1	1	24
739	8	24	1	0	23
740	8	22	1	0	15
741	8	20	1	1	21
742	8	21	1	2	27
743	8	22	1	1	23
744	8	20	1	1	19
745	8	21	1	1	25
746	8	22	1	1	23
747	8	22	1	0	16
748	8	21	1	1	25
749	8	23	1	0	15
750	8	22	1	1	18
751	8	22	1	1	20
752	8	22	1	0	26
753	8	19	1	0	20
754	8	21	1	1	19
755	8	23	1	0	24
756	8	23	0	0	24
757	8	21	1	1	26
758	8	21	1	2	24
759	8	20	1	1	25
760	8	23	1	1	25
761	8	21	1	0	19
762	8	22	1	0	20
763	8	19	1	1	25
764	8	21	0	0	14
765	8	22	1	1	19
766	8	20	0	2	18
767	8	20	1	1	24
768	8	22	1	0	24
769	8	18	1	2	20
770	8	21	1	1	27
771	8	21	0	1	21
772	8	21	1	1	20
773	8	20	1	0	21
774	8	23	1	0	16
775	8	19	0	1	22
776	8	22	1	1	22
777	8	21	1	1	23
778	8	24	1	0	23
779	8	20	0	1	23
780	8	21	1	1	28
781	8	20	1	3	11
782	8	22	1	1	24

Table 30: Simulation Experiment Results, Runs 783-828

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
783	8	20	1	1	23
784	8	21	1	1	19
785	8	18	1	1	25
786	8	21	1	1	19
787	8	21	1	1	16
788	8	22	1	0	24
789	8	20	1	0	21
790	8	19	1	2	23
791	8	16	1	1	24
792	8	19	1	1	18
793	8	20	1	2	24
794	8	21	1	3	30
795	8	21	1	2	21
796	8	19	1	1	22
797	8	18	1	1	20
798	8	19	1	1	15
799	8	23	0	1	8
800	8	21	1	1	21
801	9	22	0	0	24
802	9	23	0	1	17
803	9	22	0	2	14
804	9	24	0	1	15
805	9	24	0	1	15
806	9	23	0	1	20
807	9	24	0	0	22
808	9	24	0	0	22
809	9	24	0	1	19
810	9	20	0	1	16
811	9	22	0	2	16
812	9	24	0	1	15
813	9	24	0	1	10
814	9	23	0	1	21
815	9	23	0	1	20
816	9	21	0	1	26
817	9	25	0	0	13
818	9	22	0	0	20
819	9	22	0	1	26
820	9	22	0	1	19
821	9	25	0	0	19
822	9	22	0	1	27
823	9	21	0	1	22
824	9	24	0	0	24
825	9	22	0	2	18
826	9	24	0	1	18
827	9	23	0	1	24
828	9	20	0	2	22

Table 31: Simulation Experiment Results, Runs 829-874

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
829	9	24	0	0	24
830	9	23	0	1	15
831	9	22	0	1	23
832	9	23	0	2	19
833	9	22	0	2	22
834	9	24	0	1	19
835	9	24	0	0	16
836	9	24	0	0	18
837	9	23	0	1	17
838	9	23	0	0	22
839	9	24	0	0	24
840	9	23	0	1	18
841	9	18	0	2	28
842	9	23	0	1	17
843	9	25	0	0	18
844	9	22	0	0	21
845	9	23	0	1	20
846	9	24	0	1	22
847	9	22	0	1	22
848	9	21	0	2	20
849	9	22	0	1	25
850	9	24	0	1	14
851	9	23	0	0	25
852	9	22	0	1	19
853	9	21	0	1	23
854	9	21	0	2	20
855	9	22	0	2	19
856	9	22	0	2	24
857	9	23	0	1	21
858	9	24	0	0	19
859	9	23	0	1	23
860	9	23	0	2	16
861	9	21	0	1	22
862	9	24	0	0	26
863	9	21	0	0	23
864	9	21	0	2	20
865	9	24	0	1	19
866	9	23	0	1	20
867	9	22	0	1	19
868	9	24	0	1	20
869	9	22	0	1	17
870	9	24	0	0	22
871	9	24	0	0	15
872	9	22	0	1	22
873	9	22	0	0	26
874	9	24	0	1	19

Table 32: Simulation Experiment Results, Runs 875-920

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
875	9	19	0	2	22
876	9	24	0	0	22
877	9	22	0	1	24
878	9	25	0	0	18
879	9	22	0	1	16
880	9	24	0	0	20
881	9	23	0	1	21
882	9	24	0	1	19
883	9	24	0	0	20
884	9	24	0	0	17
885	9	23	0	0	15
886	9	24	0	1	19
887	9	20	0	3	18
888	9	23	0	0	17
889	9	18	0	3	22
890	9	21	0	1	20
891	9	20	0	1	27
892	9	22	0	1	11
893	9	22	0	1	21
894	9	24	0	1	23
895	9	25	0	0	16
896	9	22	0	0	18
897	9	21	0	1	20
898	9	20	0	1	23
899	9	24	0	1	17
900	9	23	0	1	15
901	10	22	0	0	24
902	10	22	1	1	22
903	10	21	1	2	14
904	10	24	0	1	15
905	10	24	0	1	15
906	10	23	0	1	20
907	10	23	0	0	22
908	10	24	0	0	22
909	10	22	0	2	23
910	10	20	0	1	16
911	10	22	0	2	16
912	10	24	0	1	15
913	10	24	0	1	10
914	10	23	0	1	21
915	10	21	0	2	20
916	10	21	0	1	26
917	10	24	0	0	12
918	10	22	0	0	20
919	10	21	0	1	28
920	10	22	0	1	19

Table 33: Simulation Experiment Results, Runs 921-966

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
921	10	25	0	0	19
922	10	22	0	1	27
923	10	20	1	1	22
924	10	24	0	0	24
925	10	22	0	2	18
926	10	24	0	1	18
927	10	22	0	1	26
928	10	20	0	2	22
929	10	24	0	0	24
930	10	23	0	1	15
931	10	22	0	1	23
932	10	23	0	1	18
933	10	22	0	2	22
934	10	24	0	1	19
935	10	24	0	0	16
936	10	24	0	0	18
937	10	22	0	1	21
938	10	23	0	0	22
939	10	23	0	0	24
940	10	21	0	2	23
941	10	18	0	2	28
942	10	23	0	1	17
943	10	25	0	0	18
944	10	22	0	0	21
945	10	23	0	1	20
946	10	23	0	1	21
947	10	21	0	1	18
948	10	21	0	2	20
949	10	22	0	1	25
950	10	24	0	1	14
951	10	23	0	0	25
952	10	21	0	1	20
953	10	21	0	1	23
954	10	21	0	2	20
955	10	22	0	2	19
956	10	20	0	2	28
957	10	23	0	1	21
958	10	24	0	0	19
959	10	23	0	1	23
960	10	23	0	1	18
961	10	21	0	1	22
962	10	24	0	0	26
963	10	21	0	0	23
964	10	21	0	2	20
965	10	24	0	1	19
966	10	22	0	1	20

Table 34: Simulation Experiment Results, Runs 967-1012

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
967	10	22	0	1	19
968	10	24	0	1	20
969	10	23	0	0	17
970	10	24	0	0	22
971	10	24	0	0	15
972	10	22	0	1	22
973	10	22	0	0	26
974	10	24	0	1	19
975	10	19	1	1	22
976	10	23	0	0	22
977	10	22	0	1	24
978	10	24	0	0	19
979	10	21	0	1	19
980	10	24	0	0	20
981	10	23	0	1	21
982	10	24	0	1	19
983	10	24	0	0	20
984	10	24	0	0	17
985	10	23	0	0	15
986	10	24	0	1	19
987	10	20	0	3	18
988	10	23	0	0	17
989	10	19	1	1	21
990	10	20	0	1	22
991	10	20	0	1	27
992	10	22	0	1	11
993	10	22	0	1	21
994	10	24	0	1	23
995	10	25	0	0	16
996	10	21	0	0	20
997	10	21	0	1	20
998	10	19	1	1	22
999	10	24	0	1	17
1000	10	22	0	1	14
1001	11	19	0	4	24
1002	11	23	0	2	12
1003	11	21	0	2	17
1004	11	24	0	1	19
1005	11	24	0	0	22
1006	11	23	0	1	20
1007	11	23	0	1	22
1008	11	24	0	1	17
1009	11	24	0	1	18
1010	11	20	0	1	24
1011	11	25	0	0	18
1012	11	24	0	1	15

Table 35: Simulation Experiment Results, Runs 1013-1058

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
1013	11	24	0	1	21
1014	11	23	0	0	23
1015	11	22	0	2	17
1016	11	21	0	1	13
1017	11	24	0	1	19
1018	11	19	0	1	26
1019	11	22	0	1	13
1020	11	23	0	0	23
1021	11	23	0	1	20
1022	11	22	0	1	23
1023	11	19	0	2	25
1024	11	22	0	1	21
1025	11	24	0	0	20
1026	11	23	0	2	15
1027	11	23	0	1	19
1028	11	22	0	1	16
1029	11	24	0	0	28
1030	11	22	0	1	20
1031	11	20	0	2	19
1032	11	24	0	1	15
1033	11	21	0	1	25
1034	11	24	0	1	21
1035	11	24	0	0	20
1036	11	23	0	1	24
1037	11	22	0	1	16
1038	11	20	0	3	22
1039	11	24	0	1	22
1040	11	20	0	3	20
1041	11	19	0	3	26
1042	11	23	0	1	21
1043	11	25	0	0	18
1044	11	22	0	0	20
1045	11	24	0	0	23
1046	11	23	0	1	23
1047	11	23	0	1	22
1048	11	22	0	1	21
1049	11	23	0	1	17
1050	11	23	0	2	14
1051	11	24	0	0	18
1052	11	22	0	1	20
1053	11	22	0	1	22
1054	11	22	0	1	20
1055	11	23	0	1	18
1056	11	23	0	1	20
1057	11	22	0	2	28
1058	11	22	0	2	18

Table 36: Simulation Experiment Results, Runs 1059-1104

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
1059	11	21	0	2	23
1060	11	23	0	2	23
1061	11	22	0	1	18
1062	11	21	0	3	23
1063	11	18	0	2	24
1064	11	23	0	1	18
1065	11	22	0	2	20
1066	11	22	0	2	20
1067	11	21	0	1	24
1068	11	22	0	2	12
1069	11	21	0	2	14
1070	11	23	0	1	23
1071	11	22	0	2	17
1072	11	23	0	0	22
1073	11	21	0	1	29
1074	11	25	0	0	15
1075	11	19	0	2	24
1076	11	23	0	1	26
1077	11	23	0	1	20
1078	11	25	0	0	20
1079	11	23	0	0	16
1080	11	22	0	2	23
1081	11	23	0	1	16
1082	11	23	0	2	17
1083	11	23	0	0	18
1084	11	23	0	0	22
1085	11	22	0	1	16
1086	11	24	0	1	14
1087	11	22	0	1	13
1088	11	21	0	1	22
1089	11	20	0	1	20
1090	11	22	0	0	22
1091	11	20	0	1	22
1092	11	20	0	2	22
1093	11	20	0	2	16
1094	11	25	0	0	19
1095	11	24	0	0	19
1096	11	19	0	2	18
1097	11	19	0	1	21
1098	11	16	0	4	20
1099	11	24	0	1	13
1100	11	23	0	0	20
1101	12	18	0	3	27
1102	12	22	1	2	13
1103	12	21	0	2	17
1104	12	24	0	1	19

Table 37: Simulation Experiment Results, Runs 1105-1150

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
1105	12	23	0	0	21
1106	12	23	0	1	20
1107	12	22	1	1	21
1108	12	23	0	1	19
1109	12	23	0	1	19
1110	12	19	1	1	21
1111	12	25	0	0	18
1112	12	21	1	2	23
1113	12	23	1	1	21
1114	12	21	1	1	20
1115	12	20	1	2	21
1116	12	20	0	2	13
1117	12	24	0	1	19
1118	12	17	0	2	23
1119	12	21	1	1	20
1120	12	22	0	1	22
1121	12	22	1	1	20
1122	12	21	0	1	22
1123	12	19	0	2	25
1124	12	22	1	1	23
1125	12	23	1	0	24
1126	12	22	0	2	13
1127	12	22	0	1	19
1128	12	21	0	1	16
1129	12	24	0	0	28
1130	12	22	0	1	20
1131	12	20	0	2	21
1132	12	23	0	1	17
1133	12	19	1	1	28
1134	12	24	0	1	21
1135	12	23	0	0	18
1136	12	21	0	1	21
1137	12	22	1	1	17
1138	12	19	1	3	24
1139	12	23	1	1	21
1140	12	19	1	2	22
1141	12	18	0	3	24
1142	12	22	0	1	21
1143	12	24	0	0	13
1144	12	20	0	0	21
1145	12	23	1	0	21
1146	12	22	0	1	21
1147	12	21	0	2	22
1148	12	21	0	1	18
1149	12	22	0	1	22
1150	12	22	0	1	17

Table 38: Simulation Experiment Results, Runs 1151-1196

Run #	Treatment	Red Killed	PopUp Killed	Blue Killed	Bomber Hit
1151	12	23	0	0	19
1152	12	22	1	0	23
1153	12	22	0	1	22
1154	12	21	0	1	17
1155	12	22	1	1	18
1156	12	21	1	0	36
1157	12	21	1	1	25
1158	12	21	0	1	19
1159	12	21	0	1	22
1160	12	22	0	2	24
1161	12	20	1	2	20
1162	12	21	0	3	23
1163	12	17	0	2	33
1164	12	22	0	1	16
1165	12	21	1	2	19
1166	12	22	0	1	19
1167	12	20	0	1	19
1168	12	21	0	1	17
1169	12	21	0	2	14
1170	12	23	0	0	23
1171	12	21	0	1	21
1172	12	21	0	1	21
1173	12	20	0	0	26
1174	12	25	0	0	15
1175	12	18	0	2	26
1176	12	22	0	1	21
1177	12	23	0	1	20
1178	12	24	1	0	23
1179	12	22	0	0	18
1180	12	21	1	2	24
1181	12	21	1	2	16
1182	12	23	1	1	20
1183	12	21	1	1	24
1184	12	22	1	0	22
1185	12	22	0	1	16
1186	12	23	1	1	15
1187	12	22	1	0	18
1188	12	20	0	1	20
1189	12	19	0	1	20
1190	12	21	1	0	22
1191	12	18	0	2	20
1192	12	20	0	2	22
1193	12	21	0	1	23
1194	12	23	1	0	29
1195	12	24	0	0	19
1196	12	18	1	2	20

Table 39: Simulation Experiment Results, Runs 1197-1242

Run #	Treatment	RedKilled	PopUpKilled	BlueKilled	BomberHit
1197	12	19	0	1	21
1198	12	17	1	2	25
1199	12	23	0	1	14
1200	12	22	1	0	20
1201	13	21	1	0	23
1202	13	23	1	0	20
1203	13	22	1	1	15
1204	13	24	0	1	16
1205	13	23	1	1	19
1206	13	23	1	0	16
1207	13	23	0	0	22
1208	13	23	0	0	22
1209	13	23	1	1	21
1210	13	20	0	1	13
1211	13	23	1	0	18
1212	13	23	1	1	16
1213	13	25	0	0	14
1214	13	23	0	1	20
1215	13	23	1	0	22
1216	13	21	1	0	13
1217	13	24	1	0	13
1218	13	22	0	0	18
1219	13	21	0	1	23
1220	13	22	0	1	17
1221	13	24	1	0	20
1222	13	22	0	1	18
1223	13	21	1	0	21
1224	13	24	0	0	18
1225	13	22	0	2	22
1226	13	24	0	1	18
1227	13	23	0	0	13
1228	13	20	0	2	22
1229	13	23	0	0	19
1230	13	23	0	1	16
1231	13	23	0	0	23
1232	13	24	1	0	14
1233	13	22	0	1	24
1234	13	24	0	1	19
1235	13	24	0	0	12
1236	13	21	0	2	21
1237	13	22	0	1	17
1238	13	22	1	0	17
1239	13	23	1	0	26
1240	13	22	1	1	18
1241	13	19	1	0	20
1242	13	23	0	1	17

Table 40: Simulation Experiment Results, Runs 1243-1288

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
1243	13	25	0	0	18
1244	13	21	0	1	14
1245	13	23	0	1	23
1246	13	22	1	2	23
1247	13	21	0	1	23
1248	13	21	1	1	21
1249	13	21	0	2	24
1250	13	24	0	1	16
1251	13	22	0	1	23
1252	13	21	1	1	23
1253	13	22	1	0	18
1254	13	22	0	1	15
1255	13	24	0	0	17
1256	13	22	0	1	24
1257	13	23	0	1	26
1258	13	24	0	0	13
1259	13	23	0	1	20
1260	13	23	0	1	18
1261	13	20	1	1	24
1262	13	23	0	1	18
1263	13	19	1	1	23
1264	13	21	0	1	21
1265	13	24	0	1	19
1266	13	22	1	1	22
1267	13	22	0	1	19
1268	13	23	1	1	20
1269	13	23	0	0	19
1270	13	24	0	0	20
1271	13	24	0	0	19
1272	13	22	0	1	22
1273	13	20	1	1	16
1274	13	23	1	1	19
1275	13	19	0	1	21
1276	13	23	0	0	17
1277	13	23	0	0	21
1278	13	24	1	0	21
1279	13	22	0	0	22
1280	13	22	1	1	21
1281	13	23	1	0	17
1282	13	24	0	1	21
1283	13	22	0	2	19
1284	13	24	0	0	16
1285	13	22	0	1	18
1286	13	24	0	1	20
1287	13	21	0	2	17
1288	13	23	0	0	19

Table 41: Simulation Experiment Results, Runs 1289-1334

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
1289	13	18	1	2	20
1290	13	19	1	2	22
1291	13	20	0	1	25
1292	13	22	0	1	15
1293	13	22	1	0	25
1294	13	23	1	1	24
1295	13	25	0	0	16
1296	13	21	0	0	23
1297	13	21	1	0	9
1298	13	19	1	1	17
1299	13	23	0	1	18
1300	13	22	1	1	15
1301	14	21	1	0	23
1302	14	23	1	0	20
1303	14	21	1	2	15
1304	14	24	0	1	16
1305	14	23	1	1	21
1306	14	23	1	0	16
1307	14	23	0	0	22
1308	14	23	0	0	22
1309	14	23	1	1	21
1310	14	20	0	1	13
1311	14	23	1	0	18
1312	14	23	1	1	16
1313	14	25	0	0	14
1314	14	23	0	1	20
1315	14	23	1	0	22
1316	14	21	1	0	13
1317	14	24	1	0	13
1318	14	22	0	0	18
1319	14	21	0	1	23
1320	14	22	0	1	17
1321	14	24	1	0	20
1322	14	22	0	1	18
1323	14	21	1	0	21
1324	14	24	0	0	18
1325	14	22	0	2	22
1326	14	24	0	1	18
1327	14	23	0	0	13
1328	14	20	0	2	22
1329	14	23	0	0	19
1330	14	23	0	1	16
1331	14	23	0	0	23
1332	14	24	1	0	14
1333	14	22	0	1	24
1334	14	24	0	1	19

Table 42: Simulation Experiment Results, Runs 1335-1380

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
1335	14	24	0	0	12
1336	14	21	0	2	21
1337	14	21	0	2	19
1338	14	22	1	0	17
1339	14	23	1	0	26
1340	14	22	1	1	17
1341	14	19	1	0	18
1342	14	23	0	1	17
1343	14	25	0	0	18
1344	14	21	0	1	21
1345	14	23	0	1	23
1346	14	22	1	2	23
1347	14	21	0	1	23
1348	14	21	1	1	21
1349	14	21	0	2	24
1350	14	24	0	1	16
1351	14	22	0	1	23
1352	14	21	1	1	24
1353	14	22	1	0	18
1354	14	22	0	1	15
1355	14	24	0	0	17
1356	14	22	0	1	24
1357	14	23	0	1	26
1358	14	24	0	0	13
1359	14	23	0	1	20
1360	14	23	0	1	18
1361	14	20	1	1	24
1362	14	23	0	1	20
1363	14	19	1	1	23
1364	14	21	0	1	21
1365	14	24	0	1	19
1366	14	22	1	1	22
1367	14	22	0	1	19
1368	14	23	1	1	20
1369	14	23	0	0	19
1370	14	24	0	0	20
1371	14	24	0	0	19
1372	14	22	0	1	23
1373	14	20	1	1	16
1374	14	23	1	1	19
1375	14	19	0	1	21
1376	14	23	0	0	19
1377	14	23	0	0	21
1378	14	24	1	0	21
1379	14	22	0	0	22
1380	14	22	1	1	21

Table 43: Simulation Experiment Results, Runs 1381-1426

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
1381	14	23	1	0	17
1382	14	24	0	1	21
1383	14	22	0	2	19
1384	14	24	0	0	16
1385	14	22	0	1	19
1386	14	24	0	1	20
1387	14	21	0	2	17
1388	14	23	0	0	20
1389	14	18	1	2	20
1390	14	19	1	2	22
1391	14	20	0	1	25
1392	14	22	0	1	15
1393	14	22	1	0	25
1394	14	23	1	1	24
1395	14	25	0	0	16
1396	14	21	0	0	23
1397	14	21	1	0	11
1398	14	19	1	1	17
1399	14	23	0	1	18
1400	14	22	1	1	15
1401	15	20	1	2	16
1402	15	23	1	1	15
1403	15	21	1	2	21
1404	15	23	1	1	20
1405	15	24	1	0	19
1406	15	22	1	1	20
1407	15	20	1	2	24
1408	15	23	1	1	20
1409	15	23	1	1	21
1410	15	18	1	1	18
1411	15	23	1	0	18
1412	15	23	1	1	14
1413	15	21	1	2	20
1414	15	21	1	1	19
1415	15	23	1	0	21
1416	15	19	1	2	17
1417	15	23	1	1	17
1418	15	21	1	0	27
1419	15	21	1	1	19
1420	15	20	1	1	20
1421	15	21	1	1	17
1422	15	22	1	0	15
1423	15	21	1	0	18
1424	15	22	1	1	23
1425	15	21	1	0	28
1426	15	24	0	0	13

Table 44: Simulation Experiment Results, Runs 1427-1472

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
1427	15	23	1	0	17
1428	15	21	0	1	21
1429	15	21	1	1	25
1430	15	23	1	0	18
1431	15	20	1	2	24
1432	15	23	1	1	16
1433	15	20	1	2	22
1434	15	21	1	1	21
1435	15	23	1	0	20
1436	15	20	1	2	24
1437	15	21	1	1	17
1438	15	21	1	1	25
1439	15	21	1	2	25
1440	15	21	1	1	18
1441	15	21	1	0	17
1442	15	21	1	2	27
1443	15	24	1	0	16
1444	15	21	1	0	18
1445	15	22	1	1	20
1446	15	22	1	1	25
1447	15	22	1	1	26
1448	15	21	1	1	23
1449	15	20	1	2	18
1450	15	22	1	1	16
1451	15	21	1	2	25
1452	15	21	1	0	22
1453	15	21	1	1	21
1454	15	20	1	1	21
1455	15	21	1	2	20
1456	15	23	0	0	25
1457	15	20	1	2	28
1458	15	22	1	1	26
1459	15	22	1	0	21
1460	15	23	1	1	28
1461	15	21	1	1	21
1462	15	23	1	0	15
1463	15	20	1	0	24
1464	15	22	1	1	19
1465	15	22	1	1	23
1466	15	22	1	1	17
1467	15	19	1	1	25
1468	15	23	1	0	25
1469	15	20	1	1	16
1470	15	22	1	0	25
1471	15	22	1	1	23
1472	15	21	1	1	22

Table 45: Simulation Experiment Results, Runs 1473-1518

Run #	Treatment	Red Killed	PopUp Killed	Blue Killed	Bomber Hit
1473	15	21	1	0	22
1474	15	24	1	0	15
1475	15	19	0	1	22
1476	15	22	1	1	19
1477	15	22	1	1	22
1478	15	22	1	2	24
1479	15	21	1	0	16
1480	15	20	1	1	25
1481	15	23	1	0	19
1482	15	23	1	1	17
1483	15	21	1	1	24
1484	15	21	1	1	19
1485	15	21	1	1	22
1486	15	24	1	0	18
1487	15	22	1	0	18
1488	15	21	1	1	19
1489	15	20	1	0	21
1490	15	20	1	1	22
1491	15	18	1	0	18
1492	15	20	1	2	19
1493	15	19	1	2	22
1494	15	24	0	0	21
1495	15	23	1	1	18
1496	15	19	1	2	27
1497	15	16	1	2	26
1498	15	19	1	1	10
1499	15	23	0	1	14
1500	15	22	1	1	22
1501	16	20	1	2	16
1502	16	23	1	1	15
1503	16	21	1	2	21
1504	16	23	1	1	20
1505	16	24	1	0	19
1506	16	22	1	1	20
1507	16	20	1	2	24
1508	16	23	1	1	20
1509	16	23	1	1	21
1510	16	18	1	1	18
1511	16	23	1	0	18
1512	16	23	1	1	14
1513	16	21	1	2	20
1514	16	21	1	1	19
1515	16	23	1	0	21
1516	16	20	1	1	13
1517	16	23	1	1	17
1518	16	21	1	0	27

Table 46: Simulation Experiment Results, Runs 1519-1564

Run #	Treatment	Red Killed	PopUp Killed	Blue Killed	BomberHit
1519	16	21	1	1	19
1520	16	20	1	1	20
1521	16	21	1	1	17
1522	16	22	1	0	17
1523	16	21	1	0	19
1524	16	22	1	1	23
1525	16	21	1	0	28
1526	16	24	0	0	13
1527	16	23	1	0	17
1528	16	21	0	1	21
1529	16	21	1	1	25
1530	16	23	1	0	18
1531	16	20	1	2	24
1532	16	23	1	1	16
1533	16	20	1	2	22
1534	16	21	1	1	21
1535	16	23	1	0	20
1536	16	20	1	2	24
1537	16	21	1	1	17
1538	16	21	1	1	25
1539	16	21	1	2	25
1540	16	21	1	1	18
1541	16	21	1	0	20
1542	16	21	1	2	27
1543	16	24	1	0	16
1544	16	21	1	0	18
1545	16	22	1	1	20
1546	16	22	1	1	25
1547	16	22	1	1	24
1548	16	21	1	1	23
1549	16	20	1	2	18
1550	16	22	1	1	17
1551	16	21	1	2	25
1552	16	21	1	0	22
1553	16	21	1	1	21
1554	16	20	1	1	21
1555	16	21	1	2	20
1556	16	23	0	0	25
1557	16	20	1	2	28
1558	16	22	1	1	26
1559	16	22	1	0	21
1560	16	23	1	1	28
1561	16	21	1	1	21
1562	16	22	1	1	15
1563	16	20	1	0	24
1564	16	22	1	1	19

Table 47: Simulation Experiment Results, Runs 1565-1600

Run #	Treatment	Red Killed	Pop Up Killed	Blue Killed	Bomber Hit
1565	16	22	1	1	23
1566	16	22	1	1	19
1567	16	19	1	1	24
1568	16	23	1	0	25
1569	16	21	1	0	17
1570	16	22	1	0	25
1571	16	22	1	1	23
1572	16	21	1	1	22
1573	16	21	1	0	22
1574	16	24	1	0	15
1575	16	19	0	1	22
1576	16	22	1	1	21
1577	16	21	1	2	22
1578	16	22	1	2	25
1579	16	21	1	0	16
1580	16	20	1	1	23
1581	16	23	1	0	19
1582	16	23	1	1	17
1583	16	21	1	1	24
1584	16	21	1	1	19
1585	16	21	1	1	22
1586	16	24	1	0	18
1587	16	22	1	0	18
1588	16	21	1	1	19
1589	16	20	1	0	21
1590	16	20	1	1	22
1591	16	18	1	0	18
1592	16	20	1	1	19
1593	16	19	1	2	22
1594	16	24	0	0	21
1595	16	23	1	1	20
1596	16	19	1	2	27
1597	16	18	1	1	20
1598	16	19	1	1	10
1599	16	23	0	1	14
1600	16	22	1	1	22

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14. ABSTRACT

Advancements in modern IADS have bolstered A2AD environments and subsequently degraded the advantages that the Air Force once held, prompting a call to reform the nature of warfare in order to challenge these threats. A solution is weapon swarming technology, which has the ability to overwhelm IADS by engagement of a large numbers of low-cost, but lethal air assets that have autonomous functionalities. This research proposes the application of a four dimensional framework for autonomy to a swarm of cruise missiles. A virtual A2AD environment of two opposing forces is constructed using the AFSIM, wherein a manned bomber seeks to penetrate into an enemy IADS. The manned bomber will then release a swarm of autonomous cruise missiles in order to compete within the battle space. Analysis of the experimental results show that autonomy is significant at a 95% level of confidence towards all measures of effectiveness. The ability for intra-swarm communication provides the largest benefit to both offensive and defensive performance of the swarm, most notably with 51.9% increase in the swarm's capacity to detect and destroy new threats.

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Autonomy, Autonomous Systems, Swarm Technology, Manned-Unmanned Teams, Anti-Access Area Denial, Modeling and Simulation, Combat Modeling, Design of Experiments

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