6-2021

A Quantitative Argument for Autonomous Aerial Defense Overembedded Missile Systems to Thwart Cruise Threats

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A QUANTITATIVE ARGUMENT FOR AUTONOMOUS AERIAL DEFENSE OVER EMBEDDED MISSILE SYSTEMS TO THWART CRUISE THREATS

THESIS

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AFIT-ENG-MS-21-J-007

DEPARTMENT OF THE AIR FORCE
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Wright-Patterson Air Force Base, Ohio

AFIT-ENG-MS-21-J-007

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Presented to the Faculty
Department of Electrical and Computer Engineering
Graduate School of Engineering and Management
Air Force Institute of Technology
Air University
Air Education and Training Command
in Partial Fulfillment of the Requirements for the
Degree of Master of Science in Computer Science

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Spring 2021

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AFIT-ENG-MS-21-J-007

Abstract

Research into missile defense is a high DoD priority [1][2]. Due to rising tensions between the U.S. and adversaries who have the capability to overwhelm current systems and destroy U.S. air bases vital in a great power struggle. An adversary's capability to overwhelm missile defense systems, combined with the high cost of maintaining and fielding those systems, warrants research into a new type of missile defense system. Specifically, we focus on the Autonomous Aerial Defense Against Missiles Autonomous Aerial Defense Against Missiles (AADAM) system. This system tests the viability of a conceptual, relatively lower-cost missile defense system which employs small-scale unmanned aerial vehicles Unmanned Aerial Vehicle (UAV) in place of existing and other proposed means, such as missiles and high-energy weapons. This system is tested against a modeled Patriot system. Rather than a complete replacement of current missile defense systems, the AADAM system is intended to be integrated as an addition to the layered missile defense system against cruise missile threats. The AADAM system allows for flexible and reusable missile interceptors, leading to potentially more intercepts across the system compared to existing missile defense systems. Results indicate the AADAM system is a comparable system that can be inte grated into the layered cruise missile defense system.

Acknowledgments

I would like to thank God in giving me the patience and confidence needed to accomplish this research during unprecedented times. His guidance in spirit and thought ensured successful completion of this research. I would also like to thank my wife for standing with me the entire time, sacrificing winters at home in Hawaii. A special thanks is given to both of my parents for encouraging me when times seemed tough. To my advisor, Lieutenant Colonel David King, I thank for all the patience and understanding at each step in accomplishing this endeavor.

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A QUANTITATIVE ARGUMENT FOR AUTONOMOUS AERIAL DEFENSE OVER EMBEDDED MISSILE SYSTEMS TO THWART CRUISE MISSILE THREATS

I. Introduction

As tensions in the Indo-Pacific region rise, U.S. missile defense must adapt to protect air bases. The proliferation of ballistic and non-ballistic missile threats from countries such as China and the Democratic People's Republic of Korea requires innovation to keep pace with missile defense goals laid out by the Department of Defense (DoD) in the 2019 Missile Defense Review (MDR) [5]. Specifically, a goal of the MDR is to undermine the confidence of adversaries to successfully launch large salvos of missiles at U.S. air bases [5][6]. One way to undermine this confidence is to develop missile defense systems that impose less cost to deploy than it does for adversaries to launch attacks, known abstractly as a cost-imposition strategy [7][8].

Currently, the cost of missile defense in the U.S. is extremely high [8][9]. While systems today are successful against individual missile threats, they can easily be overwhelmed by large salvos of missiles [8]. The potential number of missile threats coupled with the number of assets to be protected (ranging from aircraft to the defense systems themselves) paints a picture in which the U.S. cannot protect all of its key infrastructure [8]. For the United States Air Force (USAF), this problem is compounded by the fact that deployable active missile defense systems, such as aircraft tasked with missile interception, are expensive and take away from other vital fighter missions. These issues warrant research into developing systems to protect air bases in the Indo-Pacific region that perform well, at a lower cost. A goal of this

research is to investigate such a system using unmanned aerial vehicles (UAVs).

UAVs provide comparatively lower-costs to current systems, rapid response times, reusability, the ability to loiter, and be deployed further ahead of protected assets. The proposed system for this research, the Autonomous Aerial Defense Against Missiles (AADAM) system, leverages small, fast, autonomous UAVs to defend air bases. In this system, UAVs rely on a base radar system to detect incoming threats. The radar system relays this information to a command and control (C2) unit which maintains the view of the entire battlespace and coordinates target acquisition. This C2 component calculates target allocation, which is given to the fleets via the radar system. The fleets then move to intercept. The goal of the AADAM system is to provide a cost effective solution to air base defense against cruise missiles for the USAF without overstepping inter-service assignments.

1.1 Problem Statement

The problem today lies in three key points: the current cost of missile defense, the ability for current defensive systems to be overwhelmed, and the large number of possible assets to be protected by current systems.

The price of research, development, maintenance, modernization, and operation for existing missile defense systems reach staggeringly high levels that do not seem sustainable [9][6][10]. For example, the operational and supporting costs for the Army's current Patriot systems (15 Battalions) is roughly $800 million (USD) [6]. A single missile launched from the Patriot system costs, roughly, between $2 million and $5.38 million (USD) [6]. These estimates do not take into account modernization, missile replacement, or interceptor upkeep, which adds additional costs [6]. For example, the cost to upgrade Patriot Advanced Capability-2 Patriot Advanced Capability-2 (PAC-2) missiles to the PAC-2 Guidance Enhanced Missile-Tactical Guidance En-

hanced Missile-Tactical (GEM-T) missiles was awarded to Raytheon in 2012 for $51.3 million (USD) [11]. The cost of upgrading the radar system used by the Patriot system in 2019 initially cost $384 million (USD) [12]. The cost of missile defense grows significantly when looking at more than a single missile defense system.

While cost plays a large role, a secondary problem is the potential for the systems to be overwhelmed by large salvos of missile attacks. Missile defense system are inadequate under large salvos of attacks due to their need to reload their interceptors and their requirement to be strictly emplaced to ensure adequate coverage of the airspace. Reloading is a great limiting factor in quick, reactive defense due to the means of reloading. For example, the Patriot system cannot reload individual missile interceptors, but must replace the entire launch canister via forklift or a small crane [3]. This process is made worse by the fact that a single canister can hold, at most, 16 missile interceptors, resulting in 4-8 threats intercepted at once before a new canister must be loaded [3]. A RAND Corporation study shows the reality of large salvos of missile threats destroying air bases through numerous simulations [13], exposing current missile defense systems weaknesses. They found that the projected number of cruise and ballistic missiles maintained by China have the ability to overwhelm U.S. air bases in the Indo-Pacific region [13].

Finally, protecting air bases across the world with the combined capacity of current missile defense systems is not possible. The Center for Strategic and Budgetary Assessments Center for Strategic and Budgetary Assessments (CSBA) found that the Patriot is "insufficient" in defending air bases and military infrastructure deemed vital by the U.S. and allies in the face of a great power struggle [6]. This problem is magnified when looking at the Indo-Pacific region. Here, "fielding sufficient systems" to defend air bases and military infrastructure against an attack by China is, "cost prohibitive," [7].

A solution would require a system that defends at significantly lower costs than current systems. Additionally, this new system needs to intercept threats at a cost that greatly undermines the adversary's confidence in launching expensive missiles (ideally, the interceptors would be cheaper than the adversary's missiles)[7][8]. The proposed system must also perform just as well as, if not better, than existing systems. Finally, the system must be easily deployable in any direction around the area of coverage to ensure flexible response to new threats.

1.2 Hypothesis

The pillar of this research is to model and test a flexible and affordable air base missile defense system. The research hypothesizes that the AADAM system, which employs fleets of relatively inexpensive, small, fast, autonomous UAVs will provide better coverage from incoming missile threats than the Patriot system at a substantially lower cost. It also hypothesizes that the AADAM system will provide a higher, if not equal, probability-to-kill Probability-to-Kill (Pk) ratio when compared directly against current Patriot system capabilities.

1.3 Research Objectives

Several research objectives are developed to test the hypotheses:

1. Model fast, lightweight, autonomous drone fleets to support the AADAM system.

2. Develop relevant simulation using the Unreal Engine

3. Construct missile defense scenarios to evaluate the modeled AADAM system and Patriot system.

4. Evaluate UAV fleets against cruise missile-based defense when compared to today's systems.

1.4 Methodology

We modeled the AADAM system to accomplish the research goals outlined in Section 1.3. This system differs from existing ones, such as the Patriot system, in a number of new and unique ways. First, the AADAM system leverages multiple UAVs in the form of a drone fleet, unlike today's missile defense systems which use missiles. These aerial vehicles can act as a kinetic kill vehicle in which the fleet is placed in such a way so that the threat flies through a cloud of drones, or the vehicle can be equipped with explosives for proximity detonation interception. Second, interceptors within the AADAM system maintain the ability to make decisions mid-flight. They are not launched and forgotten as missile interceptors today are. Rather, fleets are able to alter their flight path, be re-tasked to more imminent threats, and even return to base upon missed interception or the end of the fleets operating time. Finally, these fleets are able to loiter over a battle space. They do not require strict emplacement, such as the Patriot system, but can loiter at a distance potentially further than interceptors can travel or be placed directly above key assets.

This research models the AADAM system and compares its performance against the Patriot system using the Unreal Engine. The Patriot system is modeled due to its ability to intercept cruise missiles, and its proliferation as the primary air-base defense tool used for U.S. air bases. Key infrastructure (the radar system and C2 unit) modeled after the Patriot system is used for both Patriot interceptors and UAV fleets. This implies the integration of a new interceptor into existing systems, eliminating the potential need to develop new infrastructure.

Multiple salvo scenarios are launched at the simulated missile defense system

with data gathered on successful intercepts for both the Patriot interceptors and the AADAM system. This data draws comparisons between both aiming to accomplish goals and validate the hypothesis of this research.

1.5 Assumptions/Limitations

The AADAM system is intended to be the first step in developing affordable, flexible air-to-air missile defense techniques. The UAVs within an AADAM system fleet are theoretical in nature due to the current state of small-scale drones. It is assumed that UAV technology today is not fully sufficient based on limitations in speed, altitude ceilings, and flight/loiter time. Therefore, within simulations, fleets are assumed to have a loiter time sufficient to withstand a large, fast salvo of missile threats. Additionally, it is assumed that the speed of the fleets provide adequate time to move to intercept, through they are still much slower than the threats themselves. Finally, the number of UAVs within a fleet that warrant a successful intercept are wholly unknown. Therefore, it is assumed that a single fleet has the same killing capacity of a single Patriot system. As such, the same number of fleets will be deployed to intercept as Patriot missiles. These assumptions are carried out in simulations using the Unreal Engine. As the engine models physics and interaction between components, data gathered can provide support for the given hypothesis but not reflect a level of realism that ought to be used as real-world implementations of such systems.

Beyond fleets within the AADAM system, assumptions of the Patriot system are made to provide a baseline comparison between an existing missile defense system and the proposed solution. Processes related to the flow of communication in a Patriot battery, emplacement, and engagement protocols are gathered from *Patriot Battalion and Battery Operations* [3]. Performance of the system, including Pk ratios, ranges,

and speeds of missile interceptors are deduced from multiple sources. Success of the system (tied to Pk ratios of a single interceptor) ranges from roughly 25% - 90% success rate over the last 30+ years [14][15][16][17]. Similarly, range and speed vary based on source and the type of interceptor being used, requiring an assumption on the interceptors abilities [18][19][20]. Beyond the performance of the Patriot system, a key assumption is made about the target of incoming threats. The system prioritizes protection of itself, automatically engaging threats that post a risk [3]. To eliminate the decision making process in determining which assets to protect (which is ultimately left up to the commander of each battery and/or battalion), the simulation launches all missile threats towards the Patriot system, requiring this engagement. Beyond the specific assumptions of the Patriot and AADAM systems, broader limitations are applied to the simulation to gather data.

Communication and radar tracking between all entities within the simulation is assumed to be 100% reliable. This research does not set out to test processes related to such matters, but rather test the efficacy of integrating drone fleets into existing (though simulated) missile defense systems. Proposed threats are limited to "dumb" cruise missiles which do not have the capability to change or alter course in the terminal phase. This limitation prevents the need to develop more expensive UAVs that would be required to intercept ballistic missiles at higher altitudes. Additionally, the parameters of the adversaries proposed threats (cruise missiles) are unknown. Speeds are assumed to be subsonic based on publicly available sources [21][22][23].

With these assumptions in mind, the goal of this research is not to develop high-fidelity Patriot batteries or UAV fleets. Rather, it is to compare a new system of UAV fleet interceptors as closely as possible to existing systems with readily available information.

1.6 Thesis Overview

The remainder of this thesis will discuss current missile defense measures in the U.S., specifically the Patriot system. Additionally, necessary UAV fleet protocols as they pertain to the AADAM system are outlined in Chapter II. Chapter III covers the processes and functionality used in the Unreal Engine to simulate missile defense scenarios. Chapter IV analyzes data and compares the Patriot system scenarios against the AADAM system. Finally, conclusions and future work are laid out in Chapter V.

II. Background

The rapid technological advancement and proliferation of ballistic and non-ballistic missile threats requires research into defense in order to maintain global stability [5]. The 2019 Missile Defense Review Missile Defense Review (MDR) places more emphasis on the Indo-Pacific region as China expands their military influence in the region [5]. For this reason, the DoD gives high priority to strengthening the United States' missile defense capabilities by modernizing current systems and creating new ones [5].

This chapter provides an outline of priorities set in place by the DoD through the MDR and the Missile Defense Agency (MDA). Systems used to meet these objectives are discussed at a high-level, with emphasis on the Patriot system, modeled in this research. Shortfalls of current missile defense measures are defined as they pertain to cruise missile threats in the Indo-Pacific region in order to shed light on the need for new, innovative, and cost-efficient systems. Finally, components of multi-agent systems important to the development of the AADAM system are detailed so as to provided a level of insight sufficient to understanding the implementation of the system. Each of these details is intended to give a full picture into the need for a system such as the AADAM.

2.1 U.S Missile Defense Priorities

Today, the missile threat environment is, "markedly more dangerous than in years past," warranting an increased effort into developing defensive systems for the U.S. at home and abroad [5]. These systems must, according to the DoD, be, "robust, ready, and fit for our times," as well as cost-efficient [5]. Each of these goals is difficult given the limiting constraints on current systems. These constraints, recognized by the DoD, has led to a push for, "a vigorous science and technology research program

in addition to the exploration of innovative concepts and advanced technologies that have the potential to provide more cost-effective U.S. defense," [5].

The MDA outlines three budget requests that cover the priority of U.S. missile defense research endeavors. The MDA requested $20.7 million to seek, "emerging technology" and "advance future missile capabilit[ies]," [2] to be directed to small businesses and universities. Additionally, $14.2 million was requested to assess, "government, university, and industry technology concepts," that look into interceptor technology concepts along with other defense assessments. These numbers show the priorities placed not just on advancing existing systems, but on innovating new ones. The third budget item that covers DoD research is to look into Multi-Objective Kill Vehicles Multi-Objective Kill Vehicles (MOKCs). MOKVs are interceptors which can intercept multiple threats using a single interceptor. In 2020, the budget request was $13.6 million for MOKVs. Though the proposal of the AADAM system is not strictly one interceptor to multiple threats, its conception of a collective UAV fleet can be viewed as achieving such a goal.

Ultimately, the priorities laid out conceptually by the DoD and substantiated by budget requests show the requirement to develop innovative systems and relatively low costs. The AADAM system serves as the first step in potentially developing such a system.

2.2 Current Threat Environment

Threats facing air bases abroad, specifically those in the Indo-Pacific region, have grown substantially through military modernization. This modernization has taken the form of advancement of technologies (such as cruise missiles), the expansion of territory, reorganization of military components, and the proliferation of ballistic and non-ballistic missiles [24][10][6][25][26]. Currently, the U.S. lacks the ability to defeat

large numbers of ballistic and cruise missiles [6]. This failure comes from a number of reasons, with cost-per-interceptor and intercept capability of current systems being, perhaps, the most limiting factor. To understand the importance of current systems being overwhelmed, one must look into nations that pose the largest threat, the missile threats as they stand, and scenarios providing insight into the capability to destroy U.S. air bases.

2.2.1 Regional Threats

The Indo-Pacific region contains a number of nations that aim to destabilize and subvert the United States' ability to project power in the region. Namely, Chinese influence poses a notable, rising threat. A major part of China's initiative in accomplishing this goal is through the deployment of ballistic and cruise missiles within range of U.S. air bases [10]. This is seen in the reorganization of the People's Liberation Army's (PLA) Rocket Force over the last five years [24]. PLA doctrine outlines the use of ballistic and cruise missiles to deny a, "more capable adversary the ability to generate combat sorties," [13]. Chinese observers also note that a flood of ballistic and cruise missiles would be a part of opening salvos of a war in order to overwhelm U.S. air bases and missile defense systems [6][13].

The RAND Corporation validated and published such claims in *The U.S.-China Military Scorecard* [13]. These claims validated in simulations run by the RAND Corporation [13]. In their simulations, missile attack scenarios were run against Kadena and Andersen Air Bases. The study found that the deployment of 36 ballistic missiles against Kadena AB could shut down fighter operations for four days, and tanker operations for 11 days. Additionally, a salvo of 60 Chinese cruise missiles could target every identified fuel tank, hangar, and hardened hanger (those reinforced with material) such that each target has a 90% chance of being hit [13]. Andersen AB

fared somewhat better due to its location to the potential adversary. In this scenario, it was found that 20 missiles at a 33% fail rate would be able to destroy all hangars. The caveat with this portion of the study is the means of deployment of attacking missiles. The location of Andersen AB requires cruise missiles to be deployed via aircraft. These enemy aircraft could be intercepted by U.S. fighters, but this would potentially take away from offensive operations vital to the region in such a conflict. Additionally, potential failure to intercept even a small number of bomber aircraft or cruise missiles could render U.S. fighters incapable of landing back at their base [27].

The threat environment in the Indo-Pacific region stems from calculated inventory of potential adversaries, as well as current posturing outlining the intended use of their missile inventory. While current systems are capable of successfully intercepting a limited number of missiles, the simple act of overwhelming these systems in their current state is achievable [10]. Missile threats are outlined in the following section.

2.2.2 Missile Threats

As discussed, missile threats to U.S. air bases can come in the form of ballistic and non-ballistic missiles. Non-ballistic threats can take the form of cruise missiles, UAVs, guided-rockets, artillery, mortars, and missiles (G-RAMMs), and more advanced systems such as hypersonic glide vehicles (HGVs). This research focuses on cruise missiles for a number of reasons.

First, ballistic missiles are defended against with a wide range of measures under the MDA. Most systems under the MDA are tasked with ballistic missile defense, though the Aegis and Patriot system are able to intercept cruise missiles as well. This limited concentration on non-ballistic threats, such as cruise missiles, warrants research into the defense of these prolific systems. Secondly, cruise missiles are studied due to the limiting technological capabilities of intelligent UAVs and HGVs. Cur-

rently, UAVs do not possess the capabilities to do much more than fly towards a target with a bomb attached to them. Additionally, HGVs are largely under development, making research into this threat less immediate than into those such as cruise missiles. Finally, the scope of this research focuses on more advanced threats than G-RAMMs. To understand the cruise missile threat, one must also look into behavior and proliferation of the missiles by threats such as China.

Cruise missiles are affordable weapons that allow for rapid production and deployment. They can pose a significant threat due to their low radar cross section and ability to flow at low altitudes. These characteristics make cruise missiles difficult to detect [28][3]. This difficulty to detect, combined with supersonic speeds and the maneuverability of cruise missiles, creates a system with a very limited window to detect and engage. The relatively low cost of cruise missiles allows for rapid proliferation of these systems. As of 2017, China possess somewhere between 450-1,250 cruise missile in their arsenal [13]. The potential for large salvos of cruise missiles develops an almost impossible defensive situation for air base defense. Ideally, a system would be in place that maintains multiple windows for interception, is positioned in precaclulated locations, and intercepts cruise missiles as low cost. This rationale leads to comparative testing of the AADAM system to cruise missile capable interceptors such as the Patriot system.

2.3 Current Technologies

Missile defense in the U.S. is heavily weighted towards ballistic missile defense. This is clearly seen in the MDA's mission statement, "to develop and deploy a layered Ballistic Missile Defense System to defend the United States..." [2]. The lack of focus on cruise missiles, as touched on in Section 2.2.2, scopes this research to focus on these threats over others. As this research aims to combat cruise missiles with drone fleets,

technology being studied today is discussed to differentiate between other work and this research. Additionally, missile defense systems that are capable of intercepting cruise missiles are discussed here, with an in-depth description of the Patriot system as modeled in this research.

2.3.1 Current Fleet Technology

Both the idea and development of UAV fleet technology is not new. The Defense Advanced Research Projects Agency (DARPA) and each military service agency are all working on developing UAV fleet technology for specific missions [29]. As the development of such technology is being widely undertaken, the AADAM system aims to outline a specific use of UAV fleet technology in cruise missile defense.

DARPA is perhaps pushing UAV fleet research more so than other agencies through their OFFensive Swarm-Enabled Tactics (OFFSET) program. This program forsees infantry forces using drone fleets (up to 250) and/or unmanned ground systems (UGSs) to accomplish missions in urban environments [30]. To accomplish this vision, DARPA is researching fleet autonomy and human-fleet teaming. The latter goal is disjoint from this research, as fleets in the AADAM system are autonomous. Therefore, DARPA's research for autonomy can provide insight and guidance into further development of the AADAM system. Fleet autonomy by DARPA has been implemented in real-world systems through a number of research implementations [31]. As there are agencies working on the autonomous aspect including details abstracted away in this research (such as inter-drone communication and formation flying), this research differs primarily from others in its core mission: cruise missile defense.

As stated, DARPA's OFFset program aims at human-fleet interaction for infantry over-watch. The U.S. Marine Corps is also searching for small-scale UAVs to leverage

in combat zones. These drones are aimed to act as loiter munitions which are able to be launched via a portable launcher [32]. This mission set is most closely related to the AADAM system, in which drones loiter above protected assets. The Marine's request differs in its offensive mission, where drones are leveraged to attack targets rather than defend assets from missiles, as in the AADAM system.

Overall, the research done into UAV fleets aims at offensive use, whether providing support for Marines on the ground in battle or used against ships at sea by the U.S. Navy [33]. The AADAM system aims to take the idea of fleets and leverage them for defensive measures, specifically for cruise missile defense.

2.3.2 Current Missile Defense Systems

Currently, cruise missile defense systems are deployed on sea, land and in air. On sea, the Aegis Ballistic Missile Defense (BMD) is able to defend against cruise missiles as well as ballistic ones. There are a number of systems in place aboard an Aegis vessel, including missile interceptors and the Phalanx system, a rapid-fire gun with radar sensors. While most Aegis BMD vessels are restricted to the seas, there is currently an operational Aegis Ashore system stationed in Romania, with a second system being worked on in Poland. On land, the Patriot system is deployed by the U.S. Army. Its surface-to-air design was originally created to combat aircraft. This evolved over its lifetime, making it capable of aircraft, ballistic, and cruise missile interception. Finally, in the air domain, the USAF has combat aircraft that can target cruise missiles via Advanced Medium-Range Air-to-Air Missiles (AMRAAMs) [5]. Currently, the aircraft being looked at and pushed for this mission is the F-35 [5]. Though each of these systems has more or less proven their capabilities in cruise missile defense, there come fatal flaws that must be addressed.

2.3.3 Shortfalls of Current Systems

All current systems share similar shortfalls that can lead to detrimental damage to air bases in the Indo-Pacific region. These flaws can be outlined in three main points: too many missions exist for each system, the low capacity of missile interception for each system, and geographical limitations on each.

Aegis BMD capable ships are tasked primarily with ballistic missile defense [34]. Though they are capable of intercepting cruise missiles, these scenarios often come when the ship, or its assigned fleet, are under direct attack. Systems, such as the Phalanx Weapon System, has limited range on Aegis ships, requiring them to be positioned along the flight path of cruise missile threats. Additionally, there are only 38 operational multi-mission Aegis BMD capable ships that must be spread across the Pacific and Atlantic ocean, and across different naval strike groups. This limiting factor, along with the fact that the Aegis system belongs to the U.S. Navy, creates a situation in which air base defense is a difficult mission to fulfill. Finally, the Aegis system is mainly sea-based, again limiting its ability to intercept threats too far inland. There is an alternative to the sea-based Aegis system, called Aegis Ashore. Currently, there is only one system deployed to Romania, with another being built in Poland [5]. The positioning of these systems is not ideal to cruise missile defense in the Indo-Pacific region, and gives the idea that the Aegis Ashore system is tasked mainly with ballistic missile defense. The shortfalls of this system can be mitigated by adding another, such as aircraft interceptors.

The USAF has cruise missile interceptor missions via fighter aircraft. Here, jets simply takeoff, and launch an interceptor at the threat, hoping for success. In doing so, fighters are taken away from other vital missions during a conflict such as close air support, air superiority, interdiction missions, and others. The wide array of missions already tasked to fighter aircraft outlines the problem of also tasking them with

missile interception. Additionally, each mission requires extensive training. Time taken to train for intercepting cruise missiles is time taken away from training for air superiority missions [27].

Per the 2019 MDR, F-35s are being looked at to intercept missiles. These are extremely expensive multi-role air frames, which have developmental issues of their own. Their stealth capabilities are hindered with too many AMRAAMs attached as well, rendering all the research put into them pointless. In a large salvo scenario, many F-35s would be required to defend against all missiles. In this scenario, there exists the potential for a very small number of missile threats to be missed by interceptors, rendering runways inoperable. This would require the F-35s to land somewhere else, should fuel allow [27]. Additionally, the use of F-35s as missile defense systems by the USAF has become seemingly less likely given political pressures on the system [35].

Finally, the Patriot system provides means to intercept cruise missiles. Similar to the Aegis BMD and fighter systems, the Patriot system is tasked with multiple missions: aircraft interception, ballistic missile interceptions, and cruise missile interception. The wide array of jobs tasked to the Patriot is made more difficult due to the potential number of assets it must protect. While ensuring the survival of airfields, fuel storage, personnel, and other assets, it must also ensure its own survival. As the Patriot system is modeled in this research, its components are described in detail for implementation.

2.3.4 Patriot System

The Patriot system is designed to defend against airborne threats such as ballistic missiles, cruise missiles, and aircraft. Currently, the U.S. Army operates approximately 15 battalions, with 50 batteries, 480 launcher stations and more than 1,200 interceptors [36]. Patriot systems are typically deployed in battalions. Each battalion

consists of five fire units. Every fire units contains an electronic power plant (EPP), a radar system, an engagement control station (ECS), eight launcher stations, the antenna mast group (AMG), and other various support equipment. These components are recommended to be employed in specific configurations as seen in Figure 4 and Figure 2 Not shown in these figures are the launcher stations. These must be stationed between 120 and 1,200 meters from the radar system.

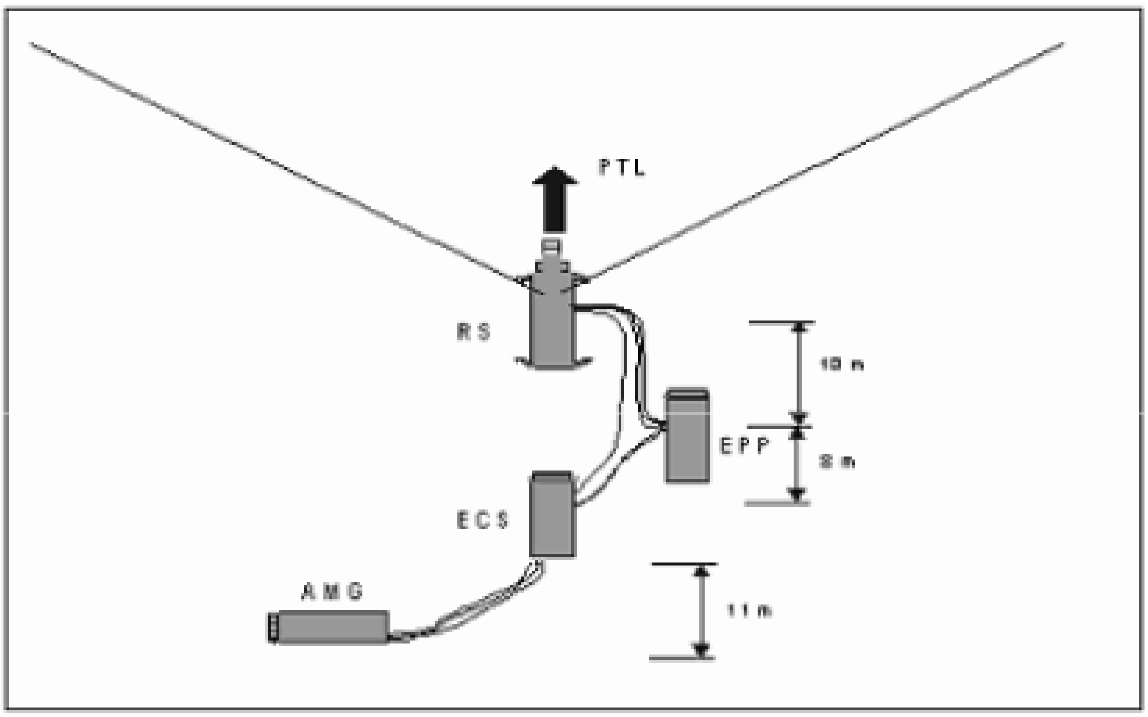

Figure 1: The Patriot emplacement according to Army Field Manual 3-01.85 not including the Launcher systems [3]

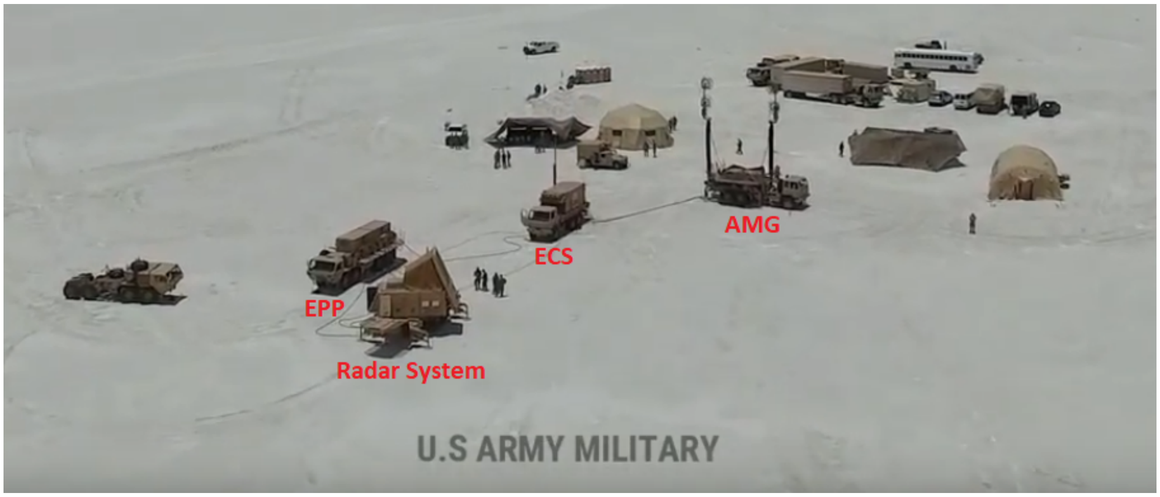

Figure 2: The Patriot emplacement in deployment, not including the Launcher Systems.

2.3.4.1 Radar System

The AN/MPQ-65 radar system implemented by the Patriot system is responsible for target detection, classification, identification, tracking of the threat, and tracking of the interceptors for guidance capabilities [3]. The radar system utilizes multiple beams to track targets with the ability to prioritize already detected targets to reduce latency between each radar sweep [37][38]. The radar system is capable of 360 degree detection, or 90 degrees for tailored search areas [39]. Modifications on the AN/MPQ-65 are currently being made allowing for further coverage with the U.S. Army developing a new system entirely [40][41]. The radar system is the initial entry point for missile threat data and interceptor data, guiding interceptors for more accurate defense.

2.3.4.2 Launcher Stations

Launcher stations are capable of being armed with four PAC-2 or sixteen PAC-3 missiles, exclusively. A combination of the two is used in a Patriot battery to al-

low for a wider range of target coverage, meaning a fire unit often contains a mix of PAC-2 and PAC-3 missiles. Launcher stations must be, "precisely emplaced and aligned prior to launch. Proper emplacement and alignment is critical for engagement of any threat," [3]. That is, flexibility in launching positions does not exist, requiring multiple stations to be employed in strategic positions for desired levels of coverage. Launcher units are placed close to assets under the assumption that this increases Pk ratios [3]. There are a number of emplacement guidelines to be considered when positioning the launching systems due to their inability to quickly alter their positioning.

Balanced fire requires an equal amount of firepower in all directions. Given a battalion, five launcher units would need to be positioned to cover 360 degrees of coverage. Weighted coverage coordinates fire power towards a predetermined heading. Early engagement places the launcher units far enough from critical assets to provide early interception, such as engaging aircraft before they can deploy their armament. Defense in depth creates a staggered approach which aims to intercept targets at different distances to lessen the threats as they approach the assets. Mutual support positions launchers in a way where the dead zone of one launcher is covered by another. Finally, overlapping fires positions launchers so their area of coverage overlaps with others, allowing more robust intercept areas. Each of these must be taken into consideration when employing the launcher systems.

2.3.4.3 Interceptors

The primary missiles used by the Patriot system are the Patriot Advanced Capability (PAC) -2 and -3 missiles. They differ by interception means. The PAC-2 utilizes proximity detonation to destroy the target while the PAC-3 is a kinetic kill vehicle. The missiles travel 3,500-5,000 km/h with a range of 60 km and a flight ceil-

ing of more than 20km [42][34]. Upon use of all missiles in a launcher device, reload time is estimated to take between five and a half to six and a half minutes [43].

2.3.4.4 Operations and Emplacement

The operations of Patriot systems are carried out by a combination of automation and human interaction [3]. For the purpose of this research, all operations are automated, eliminating the need for user input in determining intercept targets. This approach is justified by fire doctrine used in Patriot operations. Patriot doctrine also outlines the emplacement and interaction of components in the system.

In each missile attack scenario, all interceptors are deployed to intercept threats. This is done to simulate three principles outlined in Patriot operations [3] First, the Patriot systems conforms to the principle of, "self-defense is never denied," [3]. This means that theater ballistic missiles threatening the fire unit directly are automatically engaged. Though there is no direct information on cruise missiles in this capacity, this research makes the assumption that such threats are also automatically engaged so as to preserve the integrity of the fire unit. Second, the system does not hold any interceptors in reserve if they are immediately needed for the current battle [3]. As such, all missile threats target the fire unit, meaning they are all engaged and all interceptors are used to defend. Finally, the number of missiles launched depends upon the scenario. This level of decision making is built upon experience and training, but the standard guidance is two interceptors per one threat [3]. As such, two interceptors are used per threat. The means of firing takes on multiple forms as well, such as a ripple method in which there is a three to four second delay between each missile launch [3]. This research launches the missiles in a salvo approach in which the LSs launch interceptors as soon as they receive launch orders. The emplacement of components in the fire unit allow for a small impact radius by the missile threats,

but is required for effective engagement.

Figure 3 roughly outlines the emplacement of a single Patriot battery with 360° coverage. In real-world application, this figure differs only in the LS placement, which is carefully selected to obtain optimal coverage of the battlespace. The setup is centered around the radar system, shown as a blue circle. The radar system determines distance of LSs, as well as emplacement of the other four components in the figure. The EPP connects to the radar system and the ECS via wire, while the AMG connects to the ECS to provide inter-battery communication. Each LS wirelessly communicates with the ECS awaiting orders to launch interceptors. Once launched, the interceptors then communicate with the radar system while within range. In Figure 3, the first red circle shown indicates the minimum distance a LS may be positioned from the radar system, 120 meters. The second red circle shown, 1,200 meters from the radar system, marks the maximum distance a LS may be positioned from the radar system. The blue circle represents an arbitrary range the radar system can scan. This range varies based on radar capability, but is limited to 100km for this research. In this figure, all components and boundaries will remain the same in every scenario except the LSs. That is, the radar system (and its ranges), ECS, AMG, and EPP will all maintain the same positioning while the LSs can be adjusted to better protect the battle space on changing threats. Additionally, this research limits the the engagement angle to 90°, assuming a tailored-search area [3].

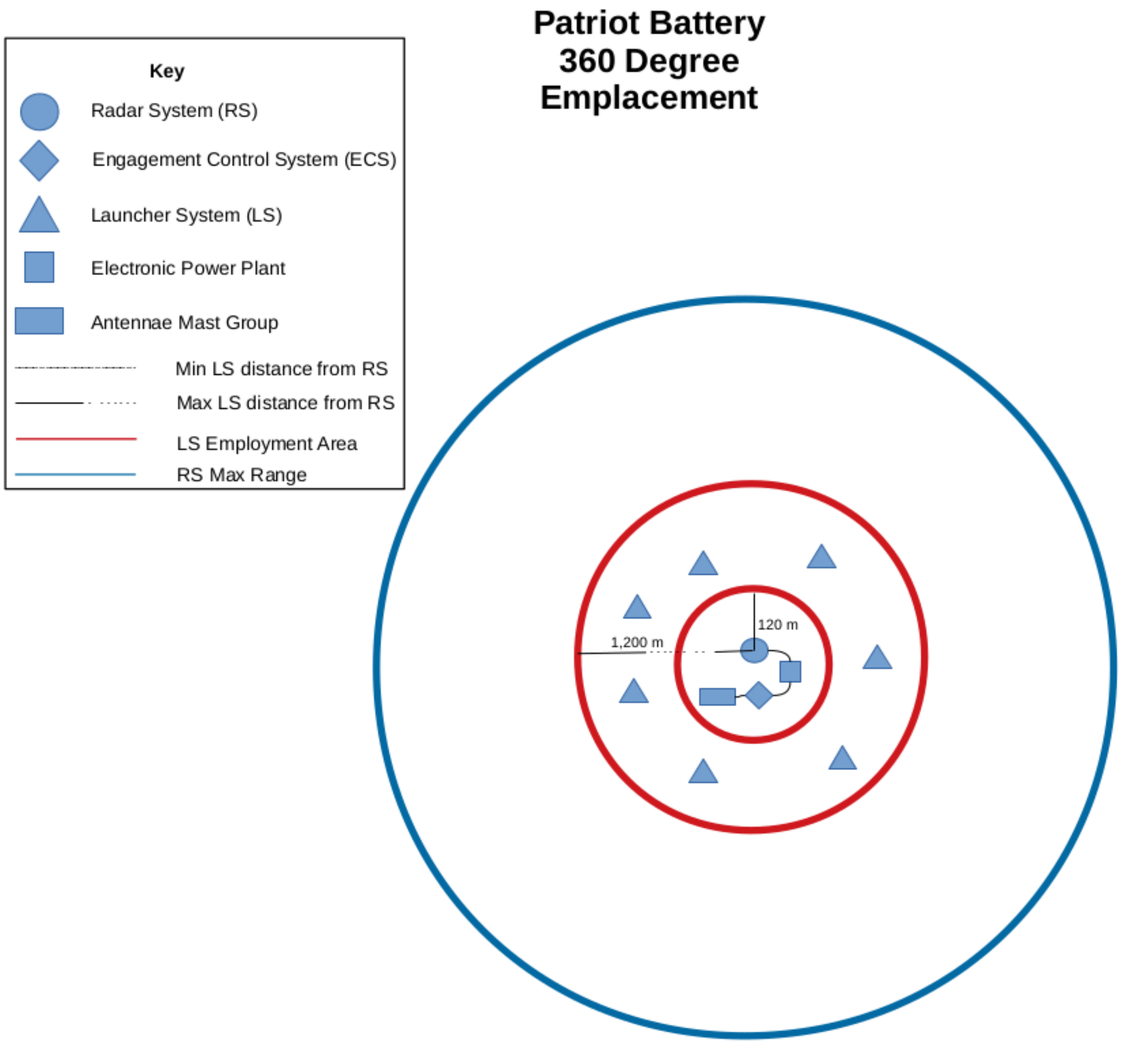

Figure 3: The Patriot emplacement according to Army Field Manual 3-01.85. This shows the positioning of key infrastructure within the battery, potential positioning of the launcher systems, and an arbitrary radar range [3]

2.4 Multi-Agent Systems

Given the rigidity, careful planning requirements, and one-time-use of Patriot system interceptors, drone fleets are looked at for cost-effective, reusable, flexible alternatives. Drone fleets are classified as a type of Multi-Agent System (MAS).

MASs are a collection of simpler agents (UAVs, software components, etc.) that can potentially divide larger tasks into smaller, more efficient ones than a single agent can [44]. Over the next few sections, we outline key aspects of MASs that can be investigated in their modeling in the AADAM system.

2.4.1 Cost of MASs

Each individual component of a MAS has the potential to operate at lower cost than a single agent equivalent to the whole MAS. [44]. For example, multiple agents searching an area, under the right circumstances, could cover more ground than a single agent. These individual agents could expend less energy as they would not be required to traverse the entire search area, unlike the individual agent. A MAS may also cost less, monetarily, than its single-agent counterpart. This is exemplified by the intent of this research. A UAV fleet, acting as the MAS, is made up of small-scale drones that potentially cost less than a single interceptor missile, the single-agent system. Cost is lessened through the replacement of components of each systems as well. Should the MAS fail catastrophically, replacement is limited to a single agent within the system. Should the single-agent equivalent fail catastrophically, the entire system must be replaced. For example, the destruction of a single missile interceptor due to reasons other than successful interception requires an entire missile to be replaced, eliminating all capability that came with that missile. The destruction of a single UAV within a fleet may lower the effectiveness of the fleet as a whole, but the system is still able to accomplish its mission while replacement is limited to a comparatively lower-cost interceptor, the UAV. Finally, MASs are reliable due to the redundant nature they hold. Should an agent fail for any reason, others are able to continue working where the failed agent left off.

While it is not guaranteed, MASs carry the strong potential to save cost through

operational and monetary means, providing a driving force to their use in the AADAM system [44].

2.4.2 Features of MASs

Each of the following features are used in developing and implementing an effective UAV fleet to combat missile threats. Leadership within the fleet limits communication between the tasking components and the fleet themselves. Heterogeneity allows for the same system to be used, but with different means of interception. For example, a drone swarm could follow suit with PAC-2 and -3 missiles, mixing radial blast interceptors and kinetic kill vehicles. Agreement metrics are required for the different swarms in the battlefield to come to an agreement on who targets which missile so as not to waste resources or miss a target completely. Finally, the data transmission frequency is important to note due to the frequency of communication between updating the swarms' targets ensuring the best results for defense. Though there exist other important features in describing MASs, these are a subset as they pertain directly to the modeling of the AADAM system [44].

2.4.2.1 Leadership

MASs must have their goals and tasks defined. This can be done in a leaderless fashion (decentralized), or a leader-oriented one (centralized). In a leaderless capacity, each agent in the system determines its own task in order to reach individual goals, with the intent to reach the goal of the entire system. These tasks are decided by each agent dependent on information it perceives from its surrounding environment. Here, the action of each agent is taken independently of others, resulting in a changed environment for others. In the existence of a leader, an agent, group of agents, or some central entity is designated to steer the system in the direction of the goal.

Followers (agents that are not the leader) must communicate information relevant to the system, such as position, velocity, heading, etc. to the leader so they can further coordinate future action among other followers.

The AADAM systems takes a centralized approach, in which fleets are the followers, and the ECS of the Patriot system is the central leader. Followers share their information with the leader via the radar system. The ECS determines the actions of each fleet, and transmits taskings to them.

2.4.2.2 Heterogeneity

Heterogeneity reflects the similarity or differences of agents within a MAS. These differences can be based on hardware, software or functionality. A heterogeneous system is one in which hardware, software, and/or functionality is different across all agents or subsets of agents. For example, a swarm that consists of UAVs and unmanned land systems to work towards a common goal is a heterogeneous MAS. Conversely, a homogeneous system in which these components are the same across all agents. An example here would be a UAV system in which all drones are the same in both hardware and software.

The AADAM system models MASs after Patriot interceptors. There are two types of fleets, making the AADAM system heterogeneous. One fleet consists of UAVs that intercept via impact, model after PAC-3 missiles. The other fleet type intercepts via proximity explosion, modeling the PAC-2 missiles.

2.4.2.3 Agreement Metrics

Often times, agents within a MAS must collectively agree on common variables of interest. When a system comes to an agreement, it is known as a consensus [45]. The consensus of MASs can be categorized as first-, second-, and higher-order systems

[44]. In a first-order system, there is a single metric that must be agreed upon. For example, a drone swarms whose goal is to intercept a missile will share the same trajectory for intercept. Intuitively, a second-order system shares two metrics. For example, the formation of a drone swarm must agree on position and velocity to maintain a uniform formation. Finally, higher-order systems maintain consensus of three or more variables. As an example, the flocking of birds often consider three values for agreeing on movement: position, velocity, and acceleration [44][45].

Within this iteration of the AADAM system, consensus is limited to a first-order system. Fleets are given intercept targets, as agreed upon by a task allocation scheme performed by the ECS. It is hoped that future iterations of the AADAM system will reach higher-order systems, as UAVs within fleets will be required to share and agree on information.

2.4.3 Task Allocation

Within any MAS, there is the explicit need for agents to select tasks to complete as individuals, or as groups. In the existence of a leader, task allocation is handled in a centralized setting where the leader determines the course of action for each agent or group. In the absence of a leader, allocation is handled in a decentralized manner in which each agent must decide on their own course of action. Task allocation, hereafter referred to as target allocation, is further exemplified in missile interception as multiple incoming missiles require smart allocation of defending resources.

The AADAM system allocates fleets to targets using a modified contract net protocol (CNP) [46][47]. The CNP is a task allocation method in which disjoint agents bid on tasks shared by a central auctioneer. Whichever agent has the highest bid is awarded the contract to complete the task.

2.5 Background Summary

This chapter outlined a brief summary of components within the U.S. missile defense system as they pertain to cruise missiles. This is done to present a look into what this research will be evaluating against. It described agents in the context of artificial intelligence providing information on components that agents are developed on. This is expanded to multi-agent systems in which the benefits are looked at as well as notable characteristics required in order to describe the design of a MAS. A distributed target allocation method is discussed to provide insight into future alterations in the following sections. This thesis aims to investigate the use of drone fleets as defensive measures against aerial threats that, historically, have not been prioritized to levels others have.

III. Methodology

Through the development of the AADAM system, this research tests the effectiveness of small-scale UAVs as a means of missile defense using the Unreal Engine (UE). This is done by testing the effectiveness of drone fleets against cruise missiles in numerous missile defense scenarios. Results are compared against a simulated Patriot system to gain insight into whether the implemented drone fleet will perform as good as, or better than the Patriot system. In each scenario, missiles are launched towards the Patriot battery and must be intercepted before hitting any key infrastructure. As per the Army Field Manual guiding Patriot operations, the battery will automatically engage threats that target it [3]. This eliminates the need to take into account protection of other assets such as aircraft and runways when determining which targets to intercept. Both the drone fleets of the AADAM system and the Patriot LSs utilitize the same infrastructure for interception means, meaning they share the radar system and ECS. Therefore, the factors this study is looking at for analysis is performance between traditional missile interceptors and new drone fleet interceptors.

This chapter begins with a description of the UAV fleets as implemented in simulation. This is given due to real-world constraints of small-scale drones, leading to the development of a theoretical, yet not unrealistic system to be used in the fleets. Next is a brief system overview to provide literacy in sections that follow. The Unreal Engine is described as it applies to this research, including built in functionality that is used throughout the system. Next, component emplacement and communication as they relate to this research are covered to provide an overview of the battlefield. Component implementation is covered in depth so as to provide a means for future replication of the components. Finally, experiments are setup to transition to results.

3.1 UAV - Fleet Design

The AADAM system employs small-scale UAVs en masse, known as a fleet. Each UAV is abstracted out of this research so as to lessen the complexity of implementation by avoiding focus on items such as drone-to-drone communication, inter-fleet communication, and the topology of fleets. Additionally, as this research focuses on testing the viability of UAV *fleets* as a means of missile interception, not necessarily individual UAVs acting independently, fleets are taken as the entire unit. Though the smallest unit in the fleet, the individual drone, is abstracted away for implementation purposes there are still requirements the drones must meet, and thus the fleet as a whole.

UAVs in the AADAM system are intended to be small-scale drones as opposed to large UAV airframes the USAF uses today, such as the MQ-9. As all fleets that successfully intercept a target are destroyed, the use of large drones, such as the MQ-9, is arguably wasteful given their production cost [48]. At the same time, consumer drones today are largely insufficient in successfully intercepting missiles in the AADAM system. They are restricted by speed, range, flight time, altitude limits, and payload limits. As such, a drone in the AADAM system, and ultimately in each fleet within the system, has specs that fall between consumer drones today and the military drones such as the MQ-9. This leads to the theoretical description of each UAV and requirements of fleets to meet the standards of the AADAM system.

Perhaps the most limiting factor of UAVs to be used in the AADAM system is their speed. Fleets as a whole must be fast enough to intercept targets at a safe enough distance from protected assets to allow for a second volley of interceptors to launch should the first one fail. At the same time, fleets must be slow enough to allow for fast maneuverability and re-tasking if their original targets are destroyed. The balance here is largely unknown and beyond the scope of this research, but it

is safe to assume the fleets must be slower than missile interceptors to allow for the aforementioned maneuverability, but faster than current consumer drones. One consumer drone today, the Wingcopter, claims to be able to reach speeds of 240 km/h, or 67 m/s [49] (note, this is not an endorsement of the drone for use by the AADAM system or the DoD, but an example of drone capabilities).

Figure 4: The Wingcopter whose speed is modeled in the AADAM system [4].

While this speed potentially was reached under very specific circumstances, it shows the development of faster UAVs is growing. As such, the AADAM system tests fleets which can collectively reach speeds of at least 67 m/s.

Ideally, fleets will be able to be deployed far enough away from protected assets to allow more time for secondary defense on failed interceptions. If the fleets are stationed nearer to the assets, then their range must extend far enough out for the same reason, again mentioned under speed discussion. Additionally, the flight time

of the fleets must be long enough to allow for a successful re-tasking. This means potentially distant targets from the asset will not render the fleet useless due to flight-time that is too short to be limit fleets to single-use, rather than multi-use. In this research, the UAVs, and collectively the fleets, have range capabilities similar to the missile interceptors used by the Patriot system. They also maintain the ability to fly for as long as each scenario takes. Given the setup of each scenario modeling a fast-paced attack intent on overwhelming the missile defense system, this flight time is not unrealistically long. To further hone the theoretical fleets employed in the AADAM system, one must consider altitude ceilings of the drones.

Consumer drones are limited in how high they can fly by how well they can handle the potential for strong winds and other atmospheric issues. This, and the altitude at which cruise missiles fly are important considerations in determining altitude limits of AADAM system fleets. Within the AADAM system, fleets intercept cruise missiles in their terminal phase, meaning they are in a descent towards the target. Therefore, the theoretical UAVs within each fleet are not required to fly at heights reaching 11,000 feet (roughly 3,350 meters) as some have reported [50]. Instead fleets are positioned at roughly 1,650 feet (500 meters) to simulate patrolling at a reasonable altitude and are expected to intercept cruise missiles lower to earth.

Finally, the payload limits of each UAV, and therefore the fleet as a whole, is an important consideration to detail. The payload on a drone is either an explosive, to mirror PAC-2 missiles, or the mass of the drone, to mirror kinetic impact of PAC-3 missiles. It is assumed that there is one UAV per fleet, and each fleet has the intercept capability and success rate as the modeled Patriot interceptors.

With the individual UAVs of the described AADAM system, it is important to remember that collections of UAVs in the forms of fleets are tested an analyzed. Therefore, the remainder of this chapter discusses AADAM system interceptors in

terms of fleets.

3.2 System Overview

The simulation comprises of seven components that operate sequentially:

- missile threats
- missile and fleet interceptors
- a database that holds missile and fleet component information, and serves as the communication mediator between the radar system and the Engagement Control System (ECS)
- a Radar System that simulates missile and fleet tracking
- an ECS that allocates targets to interceptors using updated information from the radar system
- Launcher Systems that receive launch orders from the ECS and command missile interceptors

A Patriot battery, as described in Section 2.3.4 also includes an Antenna Mast Group (AMG) and an Electronic Power Plant (EPP). The EPP is omitted functionally from the simulation under the assumption that there is sufficient power to operate the other components for the duration of each simulation. The EPP is included in simulation to simulate its potential destruction, resulting in failed powering of the system as a whole. The AMG is omitted both functionally and in placement under the assumption that there is only one battery operating, eliminating the need to communicate with other Patriot batteries. The placement of all components loosely follows figure Figure 5, with the area of engagement limited to 90° rather than 360°.

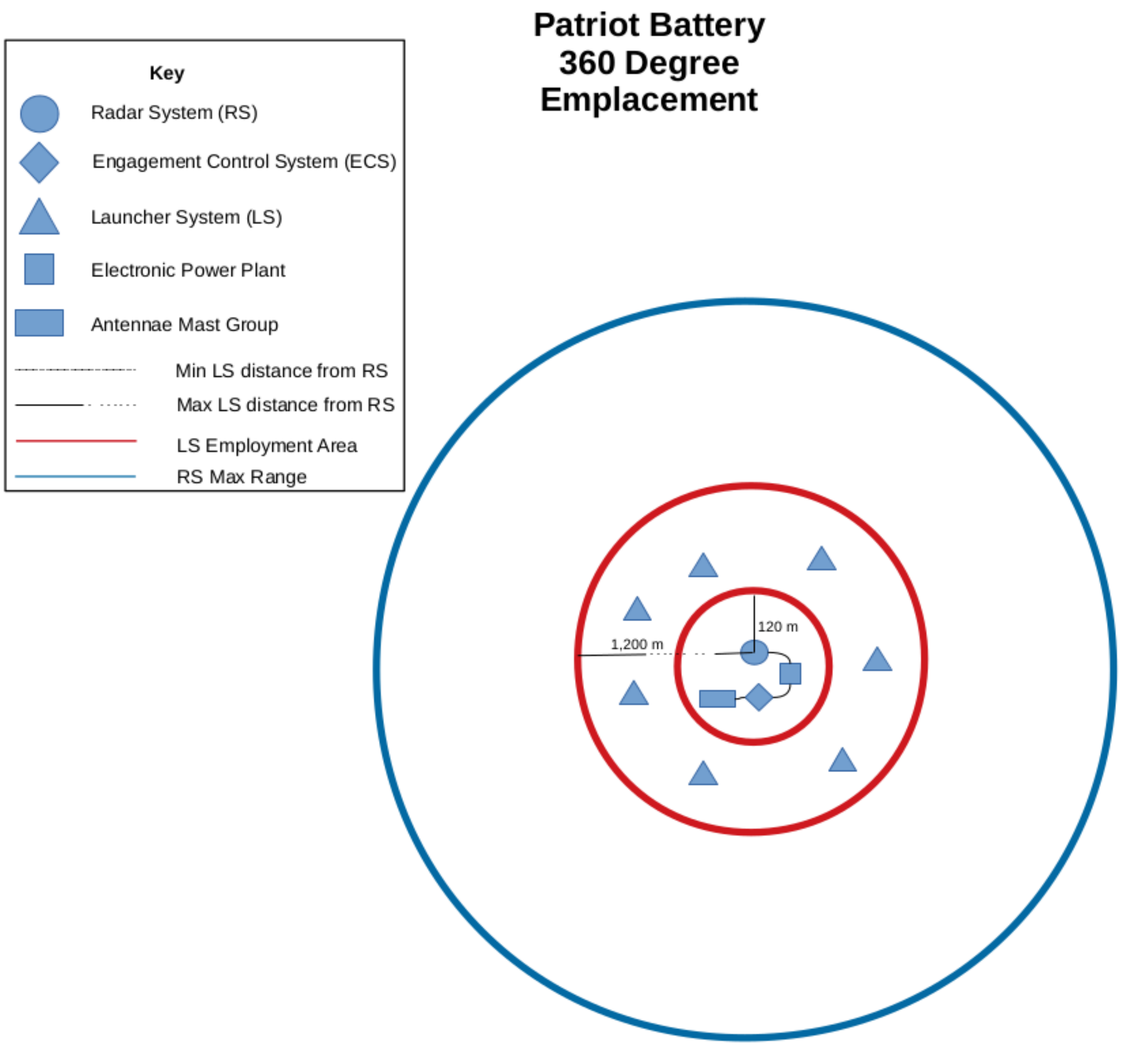

Figure 5: The Patriot emplacement according to Army Field Manual 3-01.85. This shows the positioning of key infrastructure within the battery, potential positioning of the launcher systems, and an arbitrary radar range.

3.3 Unreal Engine

The Unreal Engine is an open source, 3D simulation engine used for game development, simulation, and training. Both DARPA and the U.S. Navy have used the engine for training scenarios [51]. Documentation for the UE is provided by EPIC

Games (the owning company) and the UE community given its wide use and popularity. It provides the key features needed in implementing and testing the AADAM system against a modeled Patriot system. This section includes a brief overview of the engine with details as they pertain to this research, including key functionality from the engine used in implementation.

All interacting components in the simulation are implemented as Unreal Engine *actors.* These are entities that can be placed in the world, interact with other actors, and can be created and destroyed during run-time. Their behavior defined by scripts called blueprints, a visual tool within the UE. The UE provides additional functionality that simplifies implementation via blueprint nodes. Specifically, the engine's *projectile movement component.* This is a component that can be attached to an actor which then updates the position of the actor every time step (i.e., frame). The *projectile movement component* has a homing capability in which the desired actor is set as the target, and the moved to by the projectile. To use the *projectile movement component* in this fashion, there are a number of parameters to set. The specific values for each of these values will be covered in Section 3.7, but their roles will be covered here.

Homing functionality in the *projectile movement component* can be turned on and off during simulation using a Boolean. True activates the acceleration of the compononet which begins omvement towards the target. This target is stored in the *HomingTargetComponent*, which is simply the object in the world to move toward. Movement is handled by setting three speed variables. The *HomingAccelerationMagnitude* is simply the magnitude of acceleration towards the target. The acceleration here is capped by the next variables, *MaxSpeed.* This variable is the upper speed limit on any specified object in the world. Finally, the *InitialSpeed* sets the objects speed at launch. For the purposes of this simulation, cruise missile threats are spawned

mid-air, simulating they are already launched. As such, all speed variables are set to be the same.

All component setup including positioning and scaling, as well as implementation is described in the remainder of this chapter.

3.4 Simulation Emplacement

With the EPP included in the simulation, Figure Figure 6 provides the setup for a Patriot system, with LS. Per this setup, it is expected that threats will come from the north-easterly direction. Limiting the direction of coverage is a strategy employed in real-life application of the Patriot system, and is carried out here to limit the complexity of LS emplacement due to considerations unknown to those who do not command Patriot units [3]. In the figure, the radar system, ECS, and EPP are positioned in the south-eastern corner with the radar system scanning at 90 degrees. The first set of LSs is positioned 500 meters from the radar system, and the second is 1,200 meters, both falling under the guidelines outlined in Section 3.7. To provide as close to a one-to-one comparison between missile interceptors and the AADAM system, UAV fleets patrol near key assets (the radar system) until they are tasked with an intercept target. These patrol points simply follow the arc of the LS so as not to give the fleets a significant upper hand simply by being placed closer to the targets (though this is a potential advantage of the AADAM system). This setup can be seen in Figure Figure 7. Here, the white circles represent way-points for the fleets to hit. They move from one to the next, staying within their designated arc, until launch orders are received. Given the two different means of interception (missiles vs. fleets), two outlined configurations are required. This differentiation also requires separate descriptions for each interceptor, though all other operations remain generally the same throughout the system.

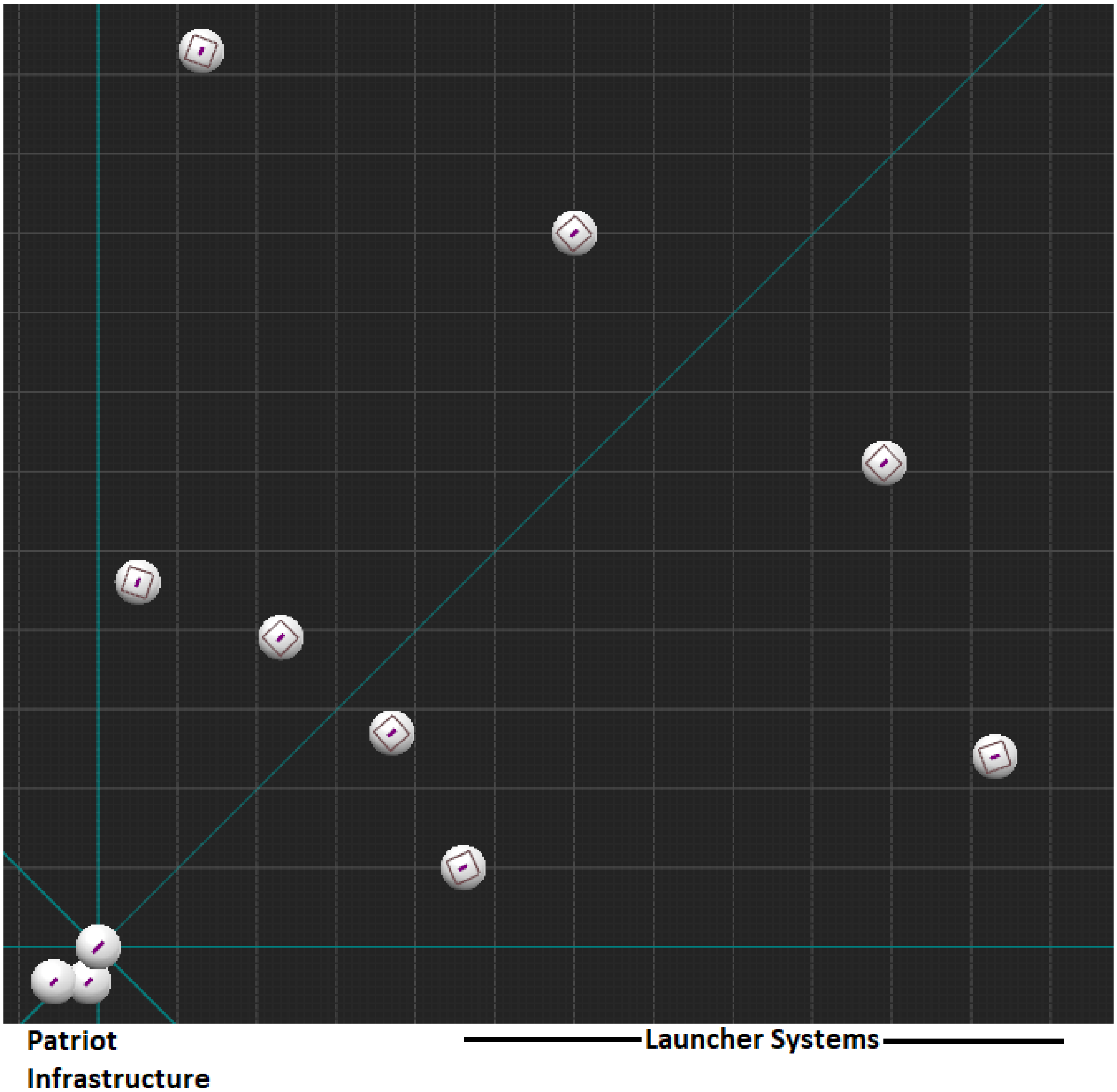

Figure 6: The Patriot emplacement modified to cover a 90° area of defense with LS placement. LSs are seen in a 90° arc around the Patriot infrastructure, each outlined with a box. Infrastructure is positioned according Army Field Manual 3-01.85 in the South-West corner of the image [3]. Incoming missile threats originate from the North-East quadrant.

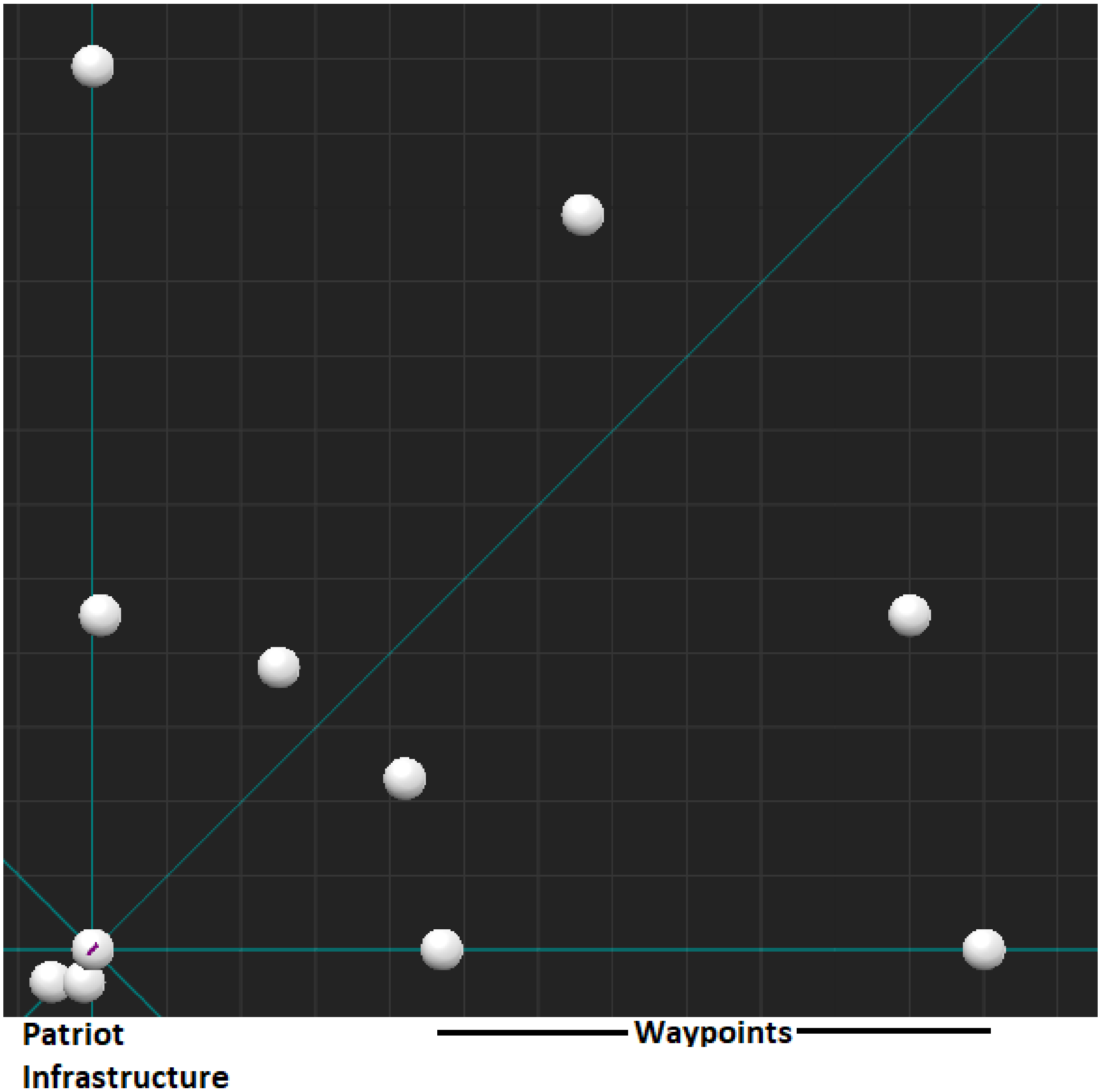

Figure 7: The Patriot emplacement modified to cover a 90° area of defense with fleet waypoints. Waypoints are seen in a 90° arc around the Patriot infrastructure, positioned roughly over LSs in Figure 6. Infrastructure is positioned according the [3] in the South-West corner of the image. Incoming missile threats originate from the North-East quadrant.

3.5 Component Execution Ordering

The components in simulation execute sequentially, as seen in Figure Figure 8. This provides a high-level overview of communication as component details are described later in this chapter. First, red missiles update their location in flight towards their designated targets. Next, interceptors, whether missiles or UAV fleets, update their location in flight to intercept. The database then performs all necessary calculations to determine which missiles can be seen by the radar system. The radar system looks at those threats that are in range and determines if they are able to be intercepted, passing on operation to the ECS. Once the ECS makes its determinations, LSs are given launch orders in the missile scenario and fleets are updated during the radar systems phase in the AADAM system scenario.

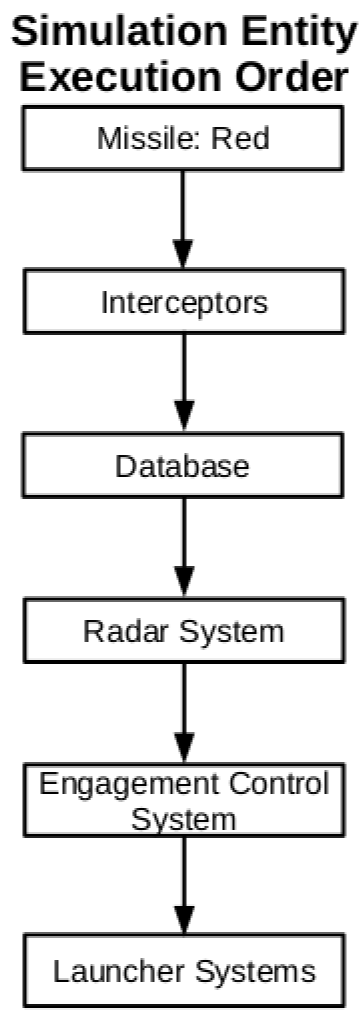

Figure 8: The execution order of all components in the UE.

3.6 System Communication

Communication in a Patriot battery starts at the radar system and ends at the interceptor. Upon threat detection, the radar system transmits necessary information to classify and defend against the threat to the ECS. Here, target allocation is determined via automation or human input by the ECS. These decisions are sent to the optimal LS, which then launches their missiles for intercept. While flying to intercept, missiles are also tracked and remotely guided by the radar system until success

or failure. This final step, remote guidance of missile interceptors, is omitted from simulation. This is due to functionality within the UE in moving towards targets, covered in Section 3.7.1.2 and the limited capability of simulated cruise missiles in maneuverability. The flow of communication is similar to that of the AADAM system to provide smooth integration into Patriot infrastructure. The only differences are the elimination of physical LSs (fleets are patrolling, eliminating the need for a LS) and fleets are used in lieu of missiles. This means the AADAM system still receives launch orders from the ECS, and the radar system still remotely guides fleets to new or re-tasked cruise missile threats.

The real-world flow of information is shown in Figure 9. Here, purple connectors outline missile interceptor communication while blue outlines drone fleets. As can be seen on the drone fleet side, there is no LS to launch the fleets, as they are already launched, just in a patrolling mode. Another key difference is the passing of updated target information from the ECS to the radar system, to be transmitted to the drone fleets. Similar information is not passed to missile interceptors, and changing course is difficult and unrealistic given speed constraints. Additionally, once a missile interceptor is launched, it is locked onto its designated target. Should that target be destroyed before it is reached, by a specific interceptor, the interceptor simply flies until impact with the ground, eliminating the ability to be re-tasked with another target.

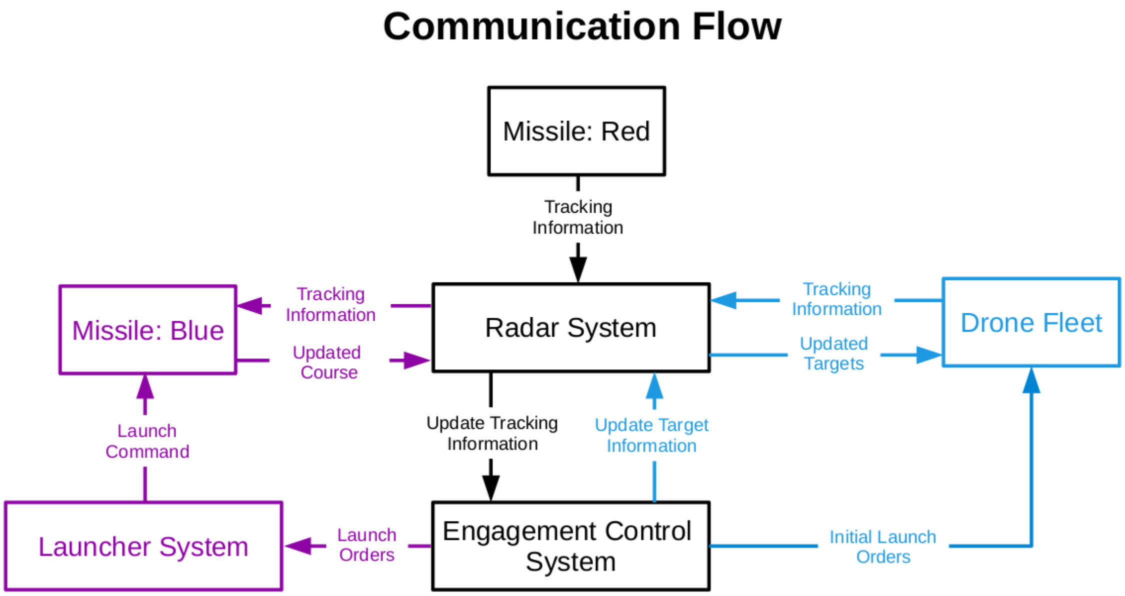

Figure 9: The communication flow between components within the simulation. Blue labels and connectors outline a drone fleet scenario, and purple outline a missile interceptor scenario. Both are used in the case of a hybrid missile defense scenario.

In simulation, communication differs slightly for implementation purposes. First, the radar system does not guide the missile interceptors, eliminating the two connectors between the radar system and the Missile: Blue box in Figure Figure 9. This is due to functionality in moving world actors towards others used in the UE, described further in Section 3.7.1.2. Additionally, as outlined in Section 1.5, cruise missile threats do not maintain the ability to maneuver in terminal flight. This somewhat eliminates difficulty in tracking by the radar system, and the potential for missed interceptions due to incorrect tracking data. Another difference between real-world flow of communication and implementation is the addition of a central database in simulation. This database serves as a mediator between the radar system and the ECS, limiting direct communication. A database is added to provide easier data collection and clearer implementation. Figure Section 3.6 shows this communication

update. It can be seen that the general flow of communication remains, maintaing the integrity of the system. Again, blue symbols indicate UAV fleet implementation and purple indicates missile interceptor implementation.

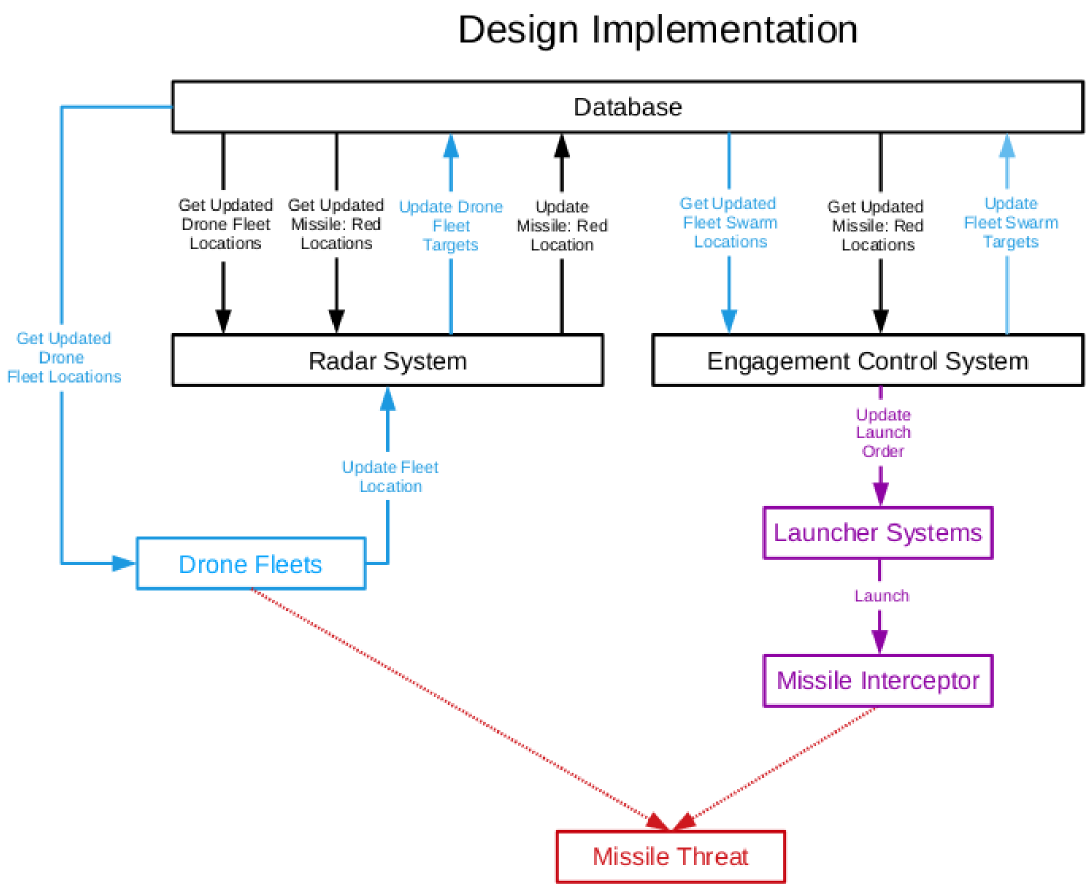

Figure 10: The communication is facilitated throgh an intermediary database within the UE. Similar to Figure 9, blue labels and connectors outline drone fleet processes and purple outlines missile interceptor scenarios.

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From Figure Section 3.6, UAV fleets first update their target information from the database, simulating receiving this information from the radar system. Then, the radar system reads tracking information about the missile threats including its current location, target, and deployed UAV fleets including their current targets. This

data is parsed, and stored back in the database. The ECS then pulls this data from the database to determine interceptor allocations. In missile interception scenarios, the ECS passes launch orders directly to the LSs while fleet updates are stored in the database. Details of each component, including how they handle data, are outlined in the remainder of this chapter.

3.7 Component Implementation

There are seven components implemented in simulation, first mentioned in Section 3.2: the missile threats, interceptors (missiles and fleets), the database, the radar system, the engagement control system, and the launcher systems. All flying components, the missile threats, missile interceptors, and fleet interceptors share functionality in movement towards their target. They differ in how those targets are determined and behavior when components are not moving to defend or attack. Interceptors receive orders to attack via the radar system, which receives this information from the ECS. Given the difference in interceptor target allocation, there are two processes ran by the ECS. As such, component description covers both missile interceptor scenarios and fleet interceptor scenarios when pertinent.

3.7.1 Flying Components

As outlined in Section 3.3, all flying components utilize the engine's homing functionality in the *projectile movement component* with all speed variables equal. Once a target is assigned to the component, whether missile threat or interceptor, the component moves towards that target until it either successfully or unsuccessfully impacts its target. The behavior before and after target assignment differs, and is explained with regards to each individual component.

3.7.1.1 Cruise Missile Threats

All threats spawn in random locations within a set area just outside of the radars range, shown in Figure Figure 11. This is done to simulate a realistic scenario in which all threats will most likely not be detected by the radar system at the same time, but come in from different ranges. When each threat is spawned into the world, it randomly selects a target from the radar system, ECS, and EPP with equal chance. In addition to a randomly set target, each missile selects a random time to launch so as to avoid all missiles moving towards their target at the same time. This time is set to a 15-second interval over all scenarios, meaning all missile threats begin their attack between 0-15 seconds. Once this time is reached, missile threats set the *isHomingProjectile* boolean under the *projectile movement component* to true and begin flying to its target. All speed variables outlined in Section 3.3 are set on spawn. Missile threats are destroyed on two triggers: impact with its target, or impact with an interceptor. When the missile threat comes within range (set to 1 meter in simulation), the system registers as successfully destroying its target and ending the scenario under the assumption that each of the three components listed (the radar system, ECS, and EPP) are vital for operation. The range of missiles threats can be altered, but is set to 1 meter to enforce the idea that all spawned missiles are a direct threat to the Patriot fire unit, requiring defense. Speeds for cruise missile targets vary between sub-sonic and super-sonic. This research looks at the former, setting the speed to 300 m/s or mach 0.88. When the missile threat comes within range of an interceptor, mechanics are handled by the interceptors.

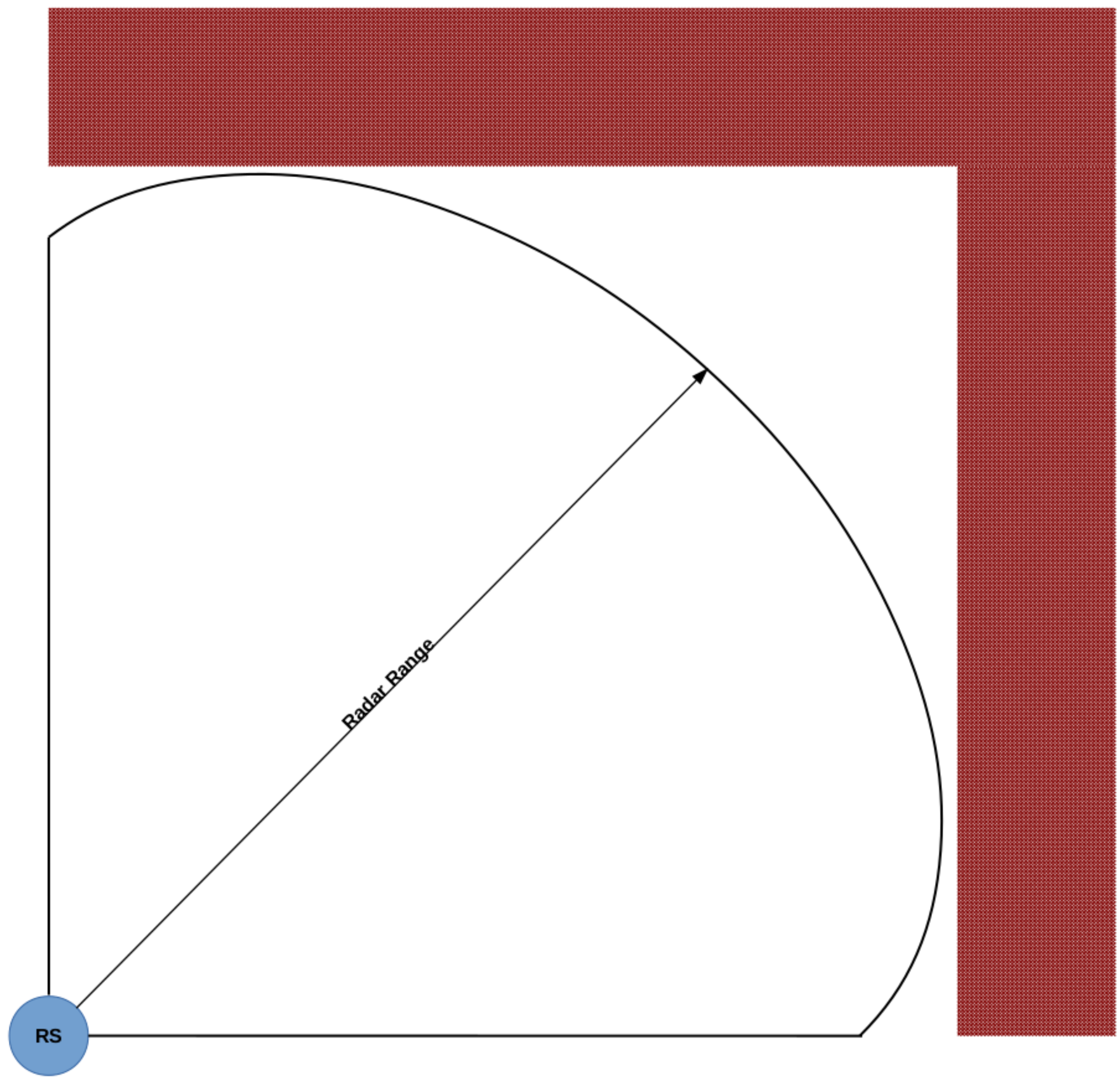

Figure 11: Outlines the spawn location options for missile threats. The red boxes, just outside of range for the radar system, are all valid spawn locations for enemy missiles.

3.7.1.2 Missile Interceptors

Missile interceptors are modeled after the PAC-2 and PAC-3 Patriot missiles, taking into account intercept methods, speed, and range. As each missile must be launched from a LS, each scenario begins with them spawning at the LSs. The

combination of PAC-2 and PAC-3 missiles is a 50/50 split across the LSs. That is, half of the LSs in each scenario hold PAC-2 missiles and half hold PAC-3 missiles. This is the default distribution of missile interceptors due to ambiguity that comes with deciding the composition of the LS as outlined in [3]. Since half of the interceptors model PAC-2 missiles and half model PAC-3 , and there are eight LSs total per battery, there is a total of 16 PAC-2 missiles and 64 PAC-3 missiles, resulting in 80 total missile interceptors in each scenario.

Each scenario spawns missile interceptors at LSs, alternating which missile is assigned. When spawned, homing functionality is turned off until launch orders are received by the ECS. When a launch order is received from the LS, the missile is assigned the target as determined by the ECS and homing functionality is turned on. The missiles moves towards the target until they are within range of interception. Here, the threat is intercepted using the Pk ratios to determine success or failure. On success, the missile threat and the interceptor are destroyed and removed from the simulation. As two missiles are launched for every one threat, and missiles are not recoverable or reusable after launch, the second missile is destroyed as well, but not counted as a successful intercept, but rather a wasted missile. Should the first missile fail, the second missile calculates success rate when within range. If both fail, and there are additional interceptors, it is possible for the missile threat to have another intercept attempt.

The speed, range, and Pk ratio are set on spawn as well. These parameters are seen in Section 3.7.1.2. All of these values are not readily available for the public, so values were estimated based on open-source information. The maximum values were used in simulation to give the Patriot missile interceptors the best performance, though these values may still underestimate or overestimate real-world performance. The used values for each of these can be seen in table. Speed and range for the PAC-2 are pulled

from the Smithsonian, while a range of Pk ratios are used in the three scenarios [52]. The explosion radius of the PAC-2 is inferred given no public information is available. The speed of the PAC-3 is set to match the PAC-2 given a lack of public information as well, while the range is found in multiple sources [18][19]. The Pk ratios are similar to the PAC-2, though the last two ratios are switched to account for the potential for one system to outperform the other when use in conjunction with one another, seen in *Pk Ratios (%)* in Section 3.7.1.2. As the PAC-3 is a kinetic kill vehicle, there is no associated explosion radius. Due to many missing data points about the interceptors themselves, the most important aspect of each scenario is their individual Pk ratio. This determines if a threat is successfully intercepted when interceptors come within appropriate range. The speeds and ranges simply determine how far or how close the threats are intercepted from the assets. Functionality between missile interceptors and fleets are similar only in homing targets, while all other behavior is different.

Table 1: Patriot Missile Parameters

Missile Type	Speed (m/s)	Range (km)	Pk Ratios (%)
PAC-2	1,565	60	80-75-90
PAC-3	1,565	20	80-90-75

3.7.1.3 Fleet Interceptors

Each fleet is spawned in a similar fashion to the missiles. That is, at a designated point, with homing functionality turned off, and speed and Pk ratios set. There are 80 fleets per scenario due to the use of 80 interceptor missiles. Additionally, half of the fleets are modeled after the PAC-2 missiles and half after the PAC-3, meaning some fleets intercept via impact and others via proximity explosion. Every fleet is tasked with one of two jobs at any given point: patrolling and intercepting. At the

beginning of each scenario, all fleets are patrolling the sky at some distance from the radar system. For the purposes of this research and to gain as close as a comparison between interceptors and fleets, the AADAM system places the patrol points for each fleet along the arc of the LSs.

Fleets are spawned at each patrol point. This is done by splitting up the fleets evenly among the 8 patrol points, meaning there are 10 fleets per point. They then select the next neighboring patrol point to be the next destination, in a clock-wise fashion. If a fleet reaches the final patrol point on either end, they simply switch directions. This behavior is not complicated, and is not intended to develop or solve any patrolling problems, but simply to exhibit the behavior the AADAM system can employ in using fleets. These patrol points can be expanded well beyond the LSs, within range of the radar system, allowing for wider coverage or better positioning.

Once a fleet receives launch orders from the radar system, as this is the primary communicator, homing functionality is turned on and the fleets move toward their target. Similar to the missiles, when a fleet is within range of a threat (0 meters for kinetic kill vehicles and 10 for proximity explosion), Pk ratios are used to determine success of failure on intercept. If a fleet successfully intercepts, both the fleet and the missile are destroyed. If not, the second fleet has a chance to intercept. A key difference is on the success of the first fleet to intercept the target. In the missile scenario, this leads to both missiles being destroyed as a secondary launched missile cannot be recovered or reused. In the fleet scenario, this allows the second fleet to be re-tasked to another threat, allowing for more missile threats to be destroyed. Therefore, if the first assigned fleet successfully intercepts the threat, the second marks its availability to be rerouted by the ECS. Until a new threat is assigned, the fleet resumes its patrol path. While it may seem obvious that this will lead to the AADAM system intercepting more missiles, is has previously been untested and not

conceptualized in open-source materials.

Task allocation schemes for both the missile interceptors and AADAM system fleets are handled by the ECS. The infrastructure of the Patriot system is utilized by both missile interceptors and fleets.

3.7.2 Database

The database maintains all missile and drone fleet components within the world. This provides clear and efficient communication between all components as well as a means to easily collect data in the UE. The database interacts only with the radar system and the ECS. It holds a number of lists to be accessed and used by the radar system and ECS. Additionally, the database performs a single process to simulate a missile attack, used by the radar system.

- *Missile Red List, Missile Blue List, and Fleet List*: these hold all corresponding components in the simulation, regardless of status or location (launched, destroyed, etc.). Each list is populated at the beginning of each scenario.

- *Missiles Red Launched, Missiles Blue Launched, and Fleets Launched*: these hold all corresponding components that have been launched from their staging area. These lists are populated upon launch signals from the components themselves.

- *Missile Red Within Range*: this hold all targets that are within range of the radar system. This list is populated with the only process in the database. *Get Distance To* function. If the return is less than or equal to the radar system's range, the missile is added to this list.

- *Missiles Red Targetable*: This list holds all targets that are both within range,

and have been successfully tracked. This criteria is specified in *section Section 3.7.3*.

- *Missiles Red Destroyed, Missiles Blue Destroyed, and Fleets Destroyed*: these hold all corresponding components that have been destroyed in the scenario via impact with another component or the ground. This list is populated by signals received on impact.

- *Fleet Updated by radar system, and Fleet Updated by ECS*: these hold all data filled by the respective components. The radar system and ECS update fleet information to be used by the other. This loosely acts as, "old targets" vs. "new targets"

The database performs a single operation, updating the world-view to allow for the radar system to accurately carry out operations. Since all missile threats spawn outside of the radar system's range, the database checks each missile to determine if it is is within range of the radar system. If it is, it is stored in *Missiles Red Within Range* which is then accessed by the radar system.

3.7.3 Radar System

In real-world application, the radar system is responsible for detection, classification, identification, tracking, missile tracking, and missile guidance [3]. The radar system detects airborne entities, classifies their type (missile, aircraft, other), identifies whether they are friend or foe, maintains tracking for successful interception, and tracks and guides interceptor missiles. It acts as the central communicator between all airborne object and the ECS.

In simulation, the radar system maintains the same responsibilities with the exception of missile (blue) tracking and guidance. This is swapped out with fleet tracking

and guidance while missile interceptors are launched and forgotten. Detection is done explicitly with help of the database. As the scenario focuses on a cruise missile attack, it is assumed all threats are airborne and all threats are missiles, eliminating the need for classification. Identification is handled implicitly as all airborne objects are maintained in separate lists in the database. Overall, the simulated radar system differs from the real-world radar system by the aforementioned processes only.

3.7.3.1 Simulated Radar System

As stated, the radar system interacts with all tracking information via the database. First, the radar system updates the drone fleet targets with new targets from the ECS using *Fleet Updated by ECS and Fleets Launched.* Here, the radar system iterates over each of these lists comparing the current target of each fleet from *Fleets Launched* against the updated targets from *Fleet Updated by ECS*. This step simulates the priority fleets have in moving to their new target for successful interception. This step is only taken in missile defense scenarios in which UAV fleets are used.

Second, the radar system processes target missile data. It uses the *Missiles Red Within Range and Missiles Red Targetable* lists. As the missiles are always available to be seen by the radar system, there must be a means to simulated this tracking. To accomplish this, the radar system specifies a required number of scans before allowing the ECS to process any information with that missile. It is assumed that at least three scans by the radar system are needed to provide accurate tracking data. Thus, after the counter has hit a threshold, the missile is added to *Missiles Red Targetable* and shared with the ECS. Once done, the ECS is able to pull the target from the missile component and calculate interception.

Finally, the radar system gets each fleet's targets and sends them to the ECS via the database. This assumes the ECS does not maintain long-term memory of the

battle-space, while allowing the flexibility of drone fleets to select targets without an ECS. It uses the *Fleet Updated by radar system and fleets Launched* lists to perform this task. The radar system changes each fleets' target in *Fleet Updated by radar system* from the fleets in *Fleet Launched*. This is done last to exhibit the behavior of tracking fleets in flight and passing the information to the ECS to perform calculations in altering interception targets. Upon completion of the radar system processes, the ECS computes targets for blue missiles and/or drone fleets.

3.7.4 Engagement Control System

The ECS is responsible for determining which LSs launch their interceptors, target allocation, and target re-allocation (for fleets). In real-world implementation, the ECS is manned. Target allocation can be performed manually by soldiers actively analyzing incoming threats and determining a prioritized list of targets to be intercepted. This process can also be automated. In the case of missiles that are a direct threat to the battery, targets are automatically engaged [3].

3.7.4.1 Simulated Engagement Control System

In each scenario, red missiles are launched towards the Patriot system to spur automatic engagement, eliminating the need for the ECS to prioritize protection across a broad spectrum of assets. The ECS must determine targets for both missiles and fleets, requiring different task allocation schemes due to the fleets' ability to alter targets. The final difference between missile and fleet interceptors is which components receive target information. Upon target allocation, information for missiles is sent to LS whereas fleets received their updates via the radar system.

Fleet Interceptor Assignment Fleets are assigned to missile threats using a modified Contract Net Protocol (CNP). There are key factors to keep in mind with

fleet-to-missile interceptors. First, the goal in the AADAM system is to intercept threats as far from the protected assets as possible to allow for additionally volleys if necessary. This goal is made more difficult due to the speed restrictions of the fleets. That is, not every fleet will be able to reach every missile due to the potential for the calculated point of interception being too close, or at the missile threat's target. Second, the bid value of the fleets in the AADAM system takes into account distance from missile threats to targets. Therefore, task allocation utilizes a sorted list of missile threats based on distance to assets. Finally, as two interceptors are initially used for every single threat, the ECS maintains a list of which fleets are assigned to which missiles, adjusting when a higher bid is calculated. This differs from the missile interceptor scenario in that fleets must be maintained in memory rather than simply communicating to a LS to launch multiple missiles at once. With these factors in mind, task allocation in the AADAM system is outlined.

Target assignment with fleets leverages a modified CNP [47]. In the CNP, target assignment is a decentralized process in which each fleet receives information on the missile target from a central node (the ECS), calculates its bid with local information, submits this bid to the central node, and is awarded the contract if it has the optimal bid. The AADAM system abstracts some autonomy away from the fleets, leaving the target allocation scheme solely to the ECS. This means the ECS calculates the bid values for each missile threat to each fleet and assigns those that have the highest value per missile. Key to the CNP is the bid value calculated by the AADAM system.

There are three values incorporated in determining the goodness of assigning any fleet to a specific missile: the cost of intercept, the reward of intercept, and the value of the target. The cost to intercept is calculated as the distance between the fleet and the intercept point for each target. This is done under the idea that a fleet that has to travel a lesser distance than another will cost less fuel and time. The intercept

point is calculated using the distance between the interceptor and target D, the time for the threat to travel that distance Equation (1), the fleet's current position P_f, and the fleet's current velocity V_f.

$$T = D/\text{Missile Threat Speed} \tag{1}$$

With these three pieces, the intercept point is calculated with Equation (2). This calculation can be optimized, but follows this format given the availability of data within the UE, such as the positions and distances to targets for both interceptors and targets.

$$\text{Intercept Point } IP = (T * V_f) + P_f \tag{2}$$

Once found, Section 4.3 outlines the cost of assigning the current missile threat to the fleet i.

$$\text{Cost}(F_i) = \text{Distance}(F_i, \text{IP}) \tag{3}$$

Next, the intercept reward is set as the distance between the intercept point and the threat's target Equation (4). This is done under the assumption that a greater reward is given to the fleet that can intercept the threat's target, allowing for future engagement upon failed intercept.

$$\text{Reward}(F_i) = \text{Distance}(\text{Threat's Target, IP}) \tag{4}$$

Finally, the value of the threat is the distance between the threat and its target Equation (5). This assumes that a threat that is closer to its target is higher value, requiring a more immediate response than threats that are further from their targets.

$$\text{Value}(F_i) = \text{Distance(Threat, Threat's Target)} \tag{5}$$

With these values defined, the final bid value of fleet i for each missile is calculated with

$$\text{Bid}(F_i) = (\text{Reward}(F_i) \text{ - } \text{Cost}(F_i)) \text{ - } \text{Value}(F_i) \tag{6}$$

With the value used by fleets (via the ECS) to bid on missile threats outlined, the full ECS process is discussed next.

As there exists the potential for fleets to be unassigned after their designated threat is targeted, only fleets that are unassigned are incorporated in this process. First, the ECS sorts all unassigned missile threats based on distance to their target in ascending order. That is, the closest missile threat is first while the furthest in last in the list. This is done by first calculating the distances of all missile threats, then adding the closest missile to a list for reference (selection sort). This runs in $O(n^2)$, but that runtime relies on all n missiles to be in range of the radar system at once and all unassigned at the time of sorting. Next, each fleet calculates its bid value for each missile using Equation (6). During this calculation, it is vital that the fleet is able to reach the calculated intercept point in time to hit the threat. Therefore, this is determined by comparing the time it takes the fleet to reach the intercept point against the time it takes for the threat to reach it. If the fleet reaches it first, the full bid is calculated. If the fleet does not reach it first (due to speed differentials), than the current fleet is not considered as an interceptor for that missile. Assuming the fleet is tagged as a potential good interceptor, its bid value is then compared against its previous bid. A higher value indicates potential reassignment of the fleet from its previous missile to the current one. This reassignment is contingent on the bid

being higher than all fleet bids assigned to that missile. As each missile is initially assigned two interceptors, the fleet's bid must be higher than one of those two. This assignment process can be seen in Algorithm 1.

Algorithm 1 Modified CNP for ECS

Result: Assigned AADAM fleet to missile

Data: sort(targetable missiles) → sorted target list

```
for each sorted missile do
    for each unassigned fleet do
        intercept point ← calculate intercept point(current fleet, current missile)
        if current missile reaches intercept point first then
            break
        current bid ← calculate bid(current fleet, current missile)
        if current fleet.bid ¡ current bid AND current missile.bid ¡ current bid then
            current fleet.bid = current bid current fleet.target = current missile
```

When a fleet is assigned to a missile, this information is passed to the radar system via the database, then to the fleet via the radar system. This process continues so long as there is a missile within range of the radar system (it can be seen) and is unassigned.

As missile interceptors are unable to be re-tasked and must be launched from a LS, their assignment is handled differently.

Missile Interceptor Assignment In the missile interceptor scenario, the ECS uses the *Missiles Red Targetable* list. It builds launch orders which contains the target, and the number of missiles to launch. The ECS iterates over each LS in the simulation. In this simulation, there are eight LSs as each battery usually contains this many [3]. Next, the closest unassigned missile threat is selected from all targetable missiles. To determine which missile is closest to the LS, the range of

each missile (PAC-2 or PAC-3) according to the payload the LS has is used. Here, if the missile threat is within range of the missile, it is assigned to the LS and a launch order is built. This process is for all missiles until the closest, unassigned one is selected. Once selected, the missile is designated as assigned so other interceptors are not launched towards it beyond the required two. Finally, the missile threat, along with the number of interceptors to launched, is packaged into a launch order that contains these two pieces of information using a struct. The remainder of the process is handled by each LS. Fleet interceptor assignment is handled differently, via a modified CNP.

3.7.5 Launcher Systems

The LSs simulate the Patriot components which launch the missile interceptors. It communicates directly with the ECS receiving launch orders and updating armament count. Once launch orders are received, the LS communicates with the interceptors to begin interception. The means of launch, including direction and frequency, are different based upon interception method.

In the missile interceptor scenario, the launch orders are first unpacked. The targets are then passed to the appropriate number of interceptors. That is, if the order calls for two missiles, then two missiles are given their targets. This research launched two missile interceptors for every single missile threat as the normal engagement protocol utilized by the Patriot system [3]. The LS then decrements the number of missiles it has launched, resulting in count of how many missiles are available in the system. When any LS has zero interceptors remaining, it becomes inoperable in this simulation. Avoiding reload logic allows for a more direct comparison between the same number of missile and fleet interceptors, avoiding arbitrary number of interceptors being spawned into each simulation. Once a missile is launched, it no longer

communicates with any other component.

3.8 Experimental Setup

The intent of this research is to test the AADAM system against a modeled Patriot system. Given the high likelihood of current missile defense systems being overwhelmed in a strategic cruise missile attack, there are more missile threats than there are missile interceptors. This means that protected assets will eventually be destroyed. In the setup, there are 100 missile threats launched at the Patriot infrastructure, and 80 interceptors. Each simulation runs until an end condition is met. Once key infrastructure is destroyed by a missile threat, or all interceptors are destroyed, the simulation ends.

There are three total scenarios ran, each on Patriot interceptors and AADAM fleets, with 500 simulations per, resulting in 1,500 simulations total for the Patriot system and the AADAM system. Each scenario is similar in the used Pk ratios, as seen in Table 2. Important to not is that each scenario uses either Patriot interceptors (PAC-2 *and* PAC-3 missiles) or AADAM fleets, exclusively. For example, scenario one sets the Pk ratios as 80% across every interceptor, but this scenario is ran once on Patriot interceptors, and once on AADAM fleets.

Table 2: Experimental Parameters for Each Scenario

Scenario Setup				
Scenario #	**PAC-2 Pk**	**PAC-3 Pk**	**40 Fleets' Pk**	**40 Fleets' Pk**
1	80	80	80	80
2	75	90	75	90
3	90	75	90	75

IV. Results and Analysis

This chapter describes results gathered in testing the AADAM system against a modeled Patriot system in missile defense scenarios. Multiple scenarios were ran, testing different probability-to-kill ratios for UAV fleets and missile interceptors. The first scenario looked at a constant Pk ratio across all PAC-2 and -3 missiles as well as the fleet counterparts. The second scenario differentiated between PAC-2 and -3 missiles (and their fleet counterparts), giving a higher Pk ratio for PAC-2 missiles. The third scenario kept these Pk values, but flipped their assigned missiles, seen in 2. All experiments found that the AADAM system performed at least as well as the Patriot missiles for calculated Pk ratios, fulfilling the hypothesis laid out in this research. That is, the number of missiles intercepted by the AADAM system was at least as many as the Patriot system.

4.1 Performance Metric

Looking at the expected number of missiles to be successfully intercepted provides a baseline of interceptors against themselves. For example, if scenario has 80 interceptors, one missile is used to intercept one target, and the interceptor has a 100% chance of successfully shooting down the target, then one can expect 80 successful intercepts. This metric is used to test the performance of the Patriot battery given the potential for wildly varying results due to design being limited to open-source data, and therefore subject to error.

The expected number of successful Patriot interceptions is calculated differently than the expected of fleet interceptors. This is due to the assumption that missiles that are launched to intercept are not able to be re-tasked should their target be destroyed before being reached. Since two missiles are launched for every one threat,

the maximum number of threats that can be intercepted in any scenario is the total number of interceptor missiles divided by two. For example, there are 40 possible interceptions given the use of 80 missile interceptors in each scenario. Additionally, half of the interceptor missiles in each scenario are PAC-2 and half are PAC-3 missiles. This affects the expected number of intercepts as Pk ratios differ between both missiles in the last two scenario. The expected value of missiles intercepted, $E[y]$, is calculated with Equation (7). Here, |PAC-2| and |PAC-3| represent the number of PAC-2 and PAC-3 missiles, respectively.

$$E[y] = \left(\frac{|\text{PAC-2}|}{2} * \text{PAC-2 Pk Ratio}\right) + \left(\frac{|\text{PAC-3}|}{2} * \text{PAC-3 Pk Ratio}\right) \tag{7}$$

As the number of PAC-2 and PAC-3 missiles is split among eight LSs, there are 16 PAC-2 missiles (4 missiles * 4 LSs) and 64 PAC-3 missiles (16 missiles * 4 LSs). The expected number of threat intercepts (rounded down) is, using the above information, seen in Table 3. The expected intercept values are outlined specifically for the Patriot system, to provide a baseline to compare the models performance against. Therefore, the Patriot system ought to intercept roughly as many missiles as described in Table 3.

Table 3: The expected intercept results for a Patriot battery with the Pk ratios used in simulation.

Expected Patriot Intercepts			
Scenario	**PAC-2 Pk Ratio (%)**	**PAC-3 Pk Ratio (%)**	**Expected Threats Intercepted**
1	80	80	32
2	75	90	34
3	90	75	31

As stated, these values are different for UAV fleets within the AADAM system. Is this system, two fleets are used for a single threat, like the Patriot system. The ability for a fleet to be re-tasked increases the total number of potential intercepts. For example:

- 80 fleets are able to intercept 40 missiles per the 2-to-1 ratio
- Given 100% Pk ratio, 40 missiles are intercepted by 40 fleets, leaving 40 to be re-tasked
- 40 fleets remaining are able to intercept 20 missiles per the 2-to-1 ratio
- Given 100% Pk ratio, 20 missiles are intercepted by 20 fleets, leaving 20 to be re-tasked

This logic is followed until there is at least one fleet remaining, with the expected values outlined in Table 4. Since the fleets model their Pk ratios against the PAC-2 and PAC-3 in this research, their values are incorporated into the table. Incorporating Pk ratios yields expected intercepts in the form of *number of fleets * Pk ratio*, with the remaining fleets able to be re-tasked. It is important to note that the maximum number of possible intercepts for 80 total missile interceptors is 40, given the 2-to-1 ratio set by the Patriot system in this implementation.

Table 4: The expected intercept results for a Patriot battery with the Pk ratios used in simulation.

Expected Fleet Intercepts			
Scenario	**PAC-2 Pk Ratio (%)**	**PAC-3 Pk Ratio (%)**	**Expected Threats Intercepted**
1	80	80	39
2	75	90	39
3	90	75	39

To compare expected results to actual results, and therefore the AADAM system to the Patriot system, analysis is performed.

4.2 Data Analysis

The performance of each system is determined by two factors: how many missile threats are successfully intercepted and how many interceptors are expended and rendered unusable. The first factor is looked at in this section, while the second focuses on a cost-analysis of the Patriot vs the AADAM system. Initially, the performance of the model must be evaluated to show that the baseline comparison for the AADAM system is sound. This analysis looks at the calculated expected values for compared against the performance of the model. Once it is established that the Patriot system is implemented accurately, the AADAM system is compared against it. The significance of this comparison is checked using a two-sample t-test with unequal variance.

4.2.1 Model Evaluation

Performance of the Patriot model is outlined in Table 5. Here, all values are rounded down so as to avoid partial interceptions. That is, a missile is either successfully intercepted, or not. It can be seen that the implemented model of the Patriot system outperforms the expected results. This difference may be attributed to the number of PAC-2 and PAC-3 missiles in each scenario and their Pk ratios. In each scenario, there are 16 PAC-2 and 64 PAC-3 missiles. Scenario two assigns a 75% chance of successful interception for PAC-2 missiles, compared to scenario three in which there is a 75% chance of successful interception PAC-3 missiles. Since there are 48 more PAC-3 missiles in each scenario, there is a higher chance of failure (15%) in scenario three than there is in scenario two. Overall, the difference in values should be kept in mind for analysis of the AADAM system so as to provide a level comparison.

Table 5: The expected intercept results for a Patriot battery compared against the implemented system.

Patriot Model Comparison			
Scenario	**Patriot Implementation**	**Patriot Expected Value**	**Difference**
1	32	32	0
2	36	34	2
3	37	31	6

4.2.2 AADAM System Comparison

The AADAM system outperforms the modeled Patriot system in the number of missile threats intercepted and the number of interceptors saved for later use. This claim is further substantiated by the ability of drones to be reused. This validates

the hypothesis that the AADAM system will perform as well as, or better, than the modeled Patriot.

The AADAM system outperforms the modeled Patriot system in average number of threats intercepted over 500 simulations in three scenarios, and the frequency of intercept values, as seen in Table 6. Given the fact that a single missed cruise missile can render an entire Patriot battery inoperable in battle, the AADAM system's consistently high intercept rates versus the modeled Patriot system saves both protected assets and money.

The AADAM system is compared against the modeled Patriot system using the two-sample t-test. In each test, the null hypothesis states that there is no significant statistical difference between performance of the AADAM system and the modeled Patriot system. While the results do not follow a normal-distribution, the sample size (500 data points for each scenario) warrants the use of the t-test. For each scenario, the α value for the t-test is set to 0.05. Therefore, the t-test aims to indicate that any statistical difference is due to chance only 5% of the time. Each calculated p-value fell below the α value. Therefore, the null hypothesis is rejected, meaning the AADAM

Table 6: Results of the AADAM system and the modeled Patriot system in a missile defense scenario looking at average intercepts and most common scenarios across 500 simulations.

AADAM-Patriot Comparison			
Scenario 1	**AADAM System**	**Modeled Patriot System**	**Difference**
Mean	38	32	6
Mode	49	39	10
Scenario 2	**AADAM System**	**Modeled Patriot System**	**Difference**
Mean	43	36	7
Mode	50	40	10
Scenario 3	**AADAM System**	**Modeled Patriot System**	**Difference**
Mean	40	37	3
Mode	49	38	11

system did perform better than the modeled Patriot for reasons not attributed to random chance.

The modeled Patriot system seems to barely outperform the AADAM system in consistency, though all performance values are lower than fleet implementation. That is, looking at Table 6 and Table 7, there are key points given the maximum number of missiles the modeled Patriot system can intercept: 80. In Table 7, the minimum and maximum number of missiles intercepted for all three scenarios are the same. The minimum value mostly likely is a result of a single threat destroying key infrastructure before any other missiles are intercepted, ending that simulation run. This end condition is present in the AADAM system implementation as well, resulting in low (though higher than the modeled Patriot system) intercept numbers. The maximum value is capped at 40, as this is the most missiles than can be intercepted by the system. This means 100% of the interceptors destroyed their target. Additionally, the mean and mode of each scenario in Table 6 are consistently near the systems maximum values, while the AADAM system appears to have more variance. This type of consistency is important in a missile defense system, as is present in the AADAM system, though not to the same degree. Despite this slight difference, the AADAM system consistently interceptors more threats in every metric than the modeled Patriot system.

The greater number of threat intercepted by the AADAM system is most likely due to a fleets ability to re-allocate to new threats. The system inherently has more opportunity to defend. The number of interceptions could most likely be increased under higher fleet speeds and further deployment. In doing so, fleets would be better positioned to allow for secondary interception to target threats that are missed. Additionally, faster fleet systems would allow for more target allocations given the systems ability to reach further distance faster.

Table 7: Results of the AADAM system and the modeled Patriot system in a missile defense scenario looking at best and worst case scenarios.

AADAM-Patriot Comparison II			
Scenario 1	**AADAM System**	**Modeled Patriot System**	**Difference**
Minimum	6	1	5
Maximum	58	40	18
Scenario 2	**AADAM System**	**Modeled Patriot System**	**Difference**
Minimum	10	1	9
Maximum	59	40	19
Scenario 3	**AADAM System**	**Modeled Patriot System**	**Difference**
Minimum	8	1	7
Maximum	60	40	20

Though the AADAM system outperforms the modeled Patriot system, resulting in more threats intercepted and by extension, more assets protected, the cost difference between each system is another critical point to consider.

4.3 Cost Analysis of AADAM System vs Patriot System

Cost analysis of the AADAM system versus the modeled Patriot system is done in two parts: the number of missile interceptors wasted by the Patriot system, and the estimated number of AADAM fleets that can be purchased based on the modeled Patriot cost.

As stated in Section 1.1, the cost of a single PAC-2 missile is roughly \$2 million, while the cost for a PAC-3 missile is roughly \$5.38 million (USD). Based on these values, the estimated cost of the modeled Patriot system on missile interceptors alone is \$376,320,000 (USD). This cost takes into account interceptor cost only. Additionally, the fact that Patriot missiles are unable to be reused ultimately results in a launched missile, that does not intercept, as wasted. According to this, Table 8 outlines the average number of missiles wasted in each scenario, as well as the lowest potential cost (assuming all PAC-2 missiles) and the highest potential cost (assuming all PAC-3

missiles). As the intent of each scenario is to overwhelm the modeled missile defense systems, it is assumed that all interceptors are launched. Therefore, waste is calculated as any interceptor that is launched, but does not successfully intercept a target.

Conversely, as an AADAM system fleet is able to be retasked and reused for future encounters. Here, if a fleet's initial target is destroyed, it misses its target, or any other reason that results in the fleet remaining operational, it is able to move to another target (unlike the Patriot system). Fleets are able to return to bases, allowing for later use. These factors result in the waste of the modeled AADAM system being $0, as not UAVs are wasted.

Table 8: Estimated waste for each scenario at $2,000,000 per PAC-2 missile and $5,380,000 per PAC-3 missile (USD).

Scenario #	Wasted Missiles	PAC-2 Cost	PAC-3 Cost
1	48	$92 Million	$258.2 Million
2	44	$88 Million	$236.7 Million
3	43	$86 Million	$231.3 Million

Next, estimated AADAM system acquisition is given in Table 9 based on the amount spent on PAC-2 and PAC-3 missiles in the simulation. This table looks at the estimated cost of 16 PAC-2 missiles ($32 Million USD) and 64 PAC-3 ($344.3 Million UDS). The potential number of AADAM UAVs are given assuming the prices in the leftmost column. These values are largely estimates in order to give an idea of the purchasing power associated with relatively lower-cost intereptors, with one exception. $60,000 is the rough cost of a single Wingcopter, the drone modeled in this simulation [49].

Table 9: Estimated number of UAVs to be purchased for the equivalent PAC interceptor acquisitions, assuming $32 Million USD (PAC-2) and $344.3 Million (PAC-3).

UAV Cost (USD)	PAC-2 Equivalent	PAC-3 Equivalent
$60,000	533 UAVs	5,738 UAVs
$100,000	320 UAVs	3,443 UAVs
$250,000	128 UAVs	1,377 UAVs
$500,000	64 UAVs	688 UAVs
$750,000	42 UAVs	459 UAVs

These analyses are not intended to advocate for the replacement of Patriot interceptors, but to outline the strong ability to develop a more cost efficient addition to layered missile defense. That is, integrating a UAV missile defense system such as the modeled AADAM system as a final layer of defense can potentially ensure more successful missile defense scenarios when paired with a missile interceptor system.

4.4 Summary

The success of the AADAM system in defending against more missile threats than the modeled Patriot system outlines a route to take in developing new missile defense systems. The successful intercept of just one more missile threat in the AADAM system over the Patriot system exhibits a number of advantages. This can be the difference between wasting a $2 million to $5.38 million (USD) missile interceptor to the potential destruction of an entire radar system to the rendering of an airfield inoperable. The AADAM system exhibited significantly better results than the modeled Patriot system, ranging from three additional missile threats intercepted to six, saving between $6 million and $37.66 million (USD) on single missile interceptors alone. This value is higher given the AADAM system's ability to allow for fleets to

land safely after their mission timeline has ended.

V. Conclusions

The rising threats of cruise missiles in the Pacific warrant research into developing new, cost-effective missile defense systems in order to maintain regional peace. These new systems must not only be lower-cost than current missile defense systems, but perform at a level that ensures the protection of designated assets. Replacing current missile defense systems is unrealistic given the amount of money poured into their development, modernization, and acquisition today. Therefore, a system ought to be developed to add a low-cost, flexible, and successful system to be incorporated into layered cruise missile defense. The idea is made apparent through numerous DoD initiatives and budgetary responses.

This research set out to be the first stepping stone in accomplishing this goal. It developed and tested the Autonomous Aerial Defense Against Missiles system. UAV fleets, comprised of individual drones, are placed on simple patrol routes until missile threats are detected. Upon successful missile defense, unused fleets are re-tasked to intercept a new threat, increasing the killing power of the missile defense system over the modeled Patriot. The AADAM system outperformed the modeled Patriot system by defending against more missiles, at lower-cost. The potential acquisition of hundreds to thousands more interceptors provides reason to pursue arguably simpler, more prolific means of missile defense to increase the defense of vital air base assets.

5.1 Future Work

As this research is the first proposal of the AADAM system, there is a wide array of future work to test the viability of the system further. The following suggestion propose avenues to pursue:

- Given the general hype around UAV fleets, inter-agency collaboration can (and

should) be leveraged so as to avoid unnecessary redundancy in research. With this in mind, the development of the AADAM system should be focused on cruise missile defense.

- Individual UAVs that makeup fleets can be looked at, with aspects such as topology and communication researched to provide a higher fidelity look into how many drones are needed to effectively intercept a cruise missile.
- The Patriot system and the AADAM system can be used in conjunction with one another to outline the increase in cruise missile interceptions with an added layer to the missile defense umbrella. Here, Patriot systems can focus on targets further from the RS or other protected assets, or even ballistic missile threats, while the AADAM system focuses on protecting the missile defense system itself.
- The implementation of fleets can be removed, allowing for individual UAVs to patrol their own path with the development of intelligent AI in which UAVs near each other communicate their intent to move to intercept. This approach outlines a decentralized manner in target allocation in which every drone makes its own decision with the help of those around it.
- The fleets in the AADAM system can be positioned further out, with speeds increased, to allow further interception and thus more response time in case of missile targets for other missile defense systems to engage.
- The concept of fleet interceptors can be expanded to test viability against non-cruise missile, non-ballistic missile threats such as G-RAMMs and radar suppression threats such as the Harpy system. This emphasizes smaller scale protection of personnel or specific assets rather than a large-scale battlespace.

- The modeled Patriot system can be made more realistic through proper information acquisition by those with clearance to do so. This would provide a better look at the AADAM system against a real-world missile defense system.

The search for new and cost-effective missile defense system is one undertaken by multiple DoD agencies. Many propositions have been made, ranging from high-energy weapons to aircraft used as interceptors. The AADAM system proposed and proved itself as a viable option against cruise missile threats when compared to a modeled Patriot systems. Its ability to save interceptors through re-tasking to new threats, as well as it s ability to be reused outlines a system in which cost is greatly lowered for better missile defense.

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Acronyms

AADAM Autonomous Aerial Defense Against Missiles. iv

AMG Antenna Mast Group. 33

CNP Contract Net Protocol. 53

CSBA Center for Strategic and Budgetary Assessments. 3

ECS Engagement Control System. 33

EPP Electronic Power Plant. 33

GEM-T Guidance Enhanced Missile-Tactical. 2

MAS Multi-Agent System. 23

MDR Missile Defense Review. 9

MOKCs Multi-Objective Kill Vehicles. 10

PAC-2 Patriot Advanced Capability-2. 2

Pk Probability-to-Kill. 4

UAV Unmanned Aerial Vehicle. iv

UE Unreal Engine. 29

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704–0188

1. REPORT DATE *(DD–MM–YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From — To)*
15–03–2021	Master's Thesis	Sept 2019 — Mar 2021

4. TITLE AND SUBTITLE

A QUANTITATIVE ARGUMENT FORAUTONOMOUS AERIAL DEFENSE OVEREMBEDDED MISSILE SYSTEMS TOTHWART CRUISE THREATS

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Andrew R. Davis

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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WPAFB OH 45433-7765

8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT-ENG-MS-21-J-007

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFXX/XXXX
Building XXX
WPAFB OH 45433-7765
DSN XXX-XXXX, COMM 937-XXX-XXXX
Email: first.last@us.af.mil

10. SPONSOR/MONITOR'S ACRONYM(S)

XXXX/XXXX

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A:
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Given the high cost of missile defense systems, their ability to be overwhelmed, and rising tensions between the U.S. and adversaries in the Indo-Pacific region, a new modeled is proposed to investigate a new approach to missile defense. The Autonomous Aerial Defense Against Missiles (AADAM) system leverages reusable, small-scale UAVs to propose a cheaper, more effective system in defending against cruise missile threats. The aim of this system is to provide and additional layer in current missile defense strategies at lower-cost. This modeled system is found to outperform a modeled Patriot system in close-range interception of designated assets, with no waste given UAVs' abilities to be reused and recoverable.

15. SUBJECT TERMS

Missile Defense, UAVs, Patriot System, Multi-Agent Systems, Fleets, Swarms

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Lt Col David King, AFIT/ENG
					19b. TELEPHONE NUMBER *(include area code)*
U	U	U	UU	91	(937) 255-3636; david.king@afit.edu