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THESIS

COUNTER-UNMANNED AERIAL VEHICLES STUDY: SHIPBOARD LASER WEAPON SYSTEM ENGAGEMENT STRATEGIES FOR COUNTERING DRONE SWARM THREATS IN THE MARITIME ENVIRONMENT

by

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This thesis studied engagement strategies for countering maritime drone swarm threats using a shipboard laser weapon system (LWS). The thesis examined maritime drone swarm threats to define parameters that characterize the different types of drone swarms expected in the near future. The thesis explored swarm attack formations, defined two potential heterogeneous swarm scenarios, and proposed five engagement strategies involving the order in which a shipboard laser weapon system would fire upon drones in a swarm threat. Modeling and simulation data was collected from the NPS Modeling Virtual Environments and Simulation (MOVES) Swarm Commander Tactics program to study the efficacy of swarm formation and engagement strategies. The results reinforce that the size of the swarm and formations used significantly affect the success rate of the attacking swarm. The complexity of the situation further increases when facing heterogeneous swarms. The results show that the success rate shifts severely in favor of the attacking swarm when using a simple heterogeneous decoy attack. When altering the LWS engagement strategy to counter this, there is a substantial reversal of success rate, which nearly changes the outcome in favor of the defending ship. This information amplifies the need to explore swarm attack and defense tactics that will organically develop with heterogeneous swarms and LWS use.

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COUNTER-UNMANNED AERIAL VEHICLES STUDY: SHIPBOARD LASER WEAPON SYSTEM ENGAGEMENT STRATEGIES FOR COUNTERING DRONE SWARM THREATS IN THE MARITIME ENVIRONMENT

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ABSTRACT

This thesis studied engagement strategies for countering maritime drone swarm threats using a shipboard laser weapon system (LWS). The thesis examined maritime drone swarm threats to define parameters that characterize the different types of drone swarms expected in the near future. The thesis explored swarm attack formations, defined two potential heterogeneous swarm scenarios, and proposed five engagement strategies involving the order in which a shipboard laser weapon system would fire upon drones in a swarm threat. Modeling and simulation data was collected from the NPS Modeling Virtual Environments and Simulation (MOVES) Swarm Commander Tactics program to study the efficacy of swarm formation and engagement strategies. The results reinforce that the size of the swarm and formations used significantly affect the success rate of the attacking swarm. The complexity of the situation further increases when facing heterogeneous swarms. The results show that the success rate shifts severely in favor of the attacking swarm when using a simple heterogeneous decoy attack. When altering the LWS engagement strategy to counter this, there is a substantial reversal of success rate, which nearly changes the outcome in favor of the defending ship. This information amplifies the need to explore swarm attack and defense tactics that will organically develop with heterogeneous swarms and LWS use.

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LIST OF ACRONYMS AND ABBREVIATIONS

ADA	automated decision aid
ANCHOR	Atmospheric Naval Postgraduate School Code for High Energy Laser Optical Propagation
COTS	commercial-off-the-shelf
DOD	Department of Defense
E.M.	electromagnetic
E.O.	electro-optical
GCS	ground control station
I.R.	infrared
LWS	laser weapon system
MOVES	Modeling Virtual Environments and Simulation
SCT	Swarm Commander Tactics
TEWA	threat evaluation and weapon assignment
UAV	unmanned aerial vehicle
UUV	unmanned underwater vehicle

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EXECUTIVE SUMMARY

Swarm is the next evolutionary step in warfare. Laser weapon systems (LWSs) will be a cost-effective method to compete in this new battlespace. UAV systems are being used at every level, from terrorist organizations to world superpowers and inexpensive UAV systems serve as a way to employ swarm warfare. Already, UAV swarms are being used in heterogeneous configurations and have been on display during military demonstrations (Hambling 2021). As a counter, the Department of Defense must develop a cost-effective response, and LWSs offer the benefit of being low-cost per shot and take a short time-to-effect.

UAV systems' capabilities have grown as communication methods, machine-learning, and swarm theory do the same. They are classified by various combinations of weight, range, and speed. UAV systems perform an extensive range of mission types, including surveillance, countermeasures, decoys, sensor neutralization, and payload delivery. They are generally made of high-strength low-weight materials such as aluminum or carbon-fiber-reinforced-polymer; however, there is a recent exploration into using magnesium-based composites for even cheaper manufacturing (Hoeche et al. 2021). Easily accessible and inexpensive UAV systems allow for a cost-effective way to form a swarm. The LWS will be an effective way to prepare for this novel threat.

With the proper employment, LWSs will become invaluable as a proportional and effective response to an inexpensive swarm attack. The proposed $1 per shot will allow the Navy to win the economic attrition in these engagements (Smalley 2014; Perkins 2017). There are, however, some hurdles to be aware of, such as atmospheric effects, turbulence, and thermal blooming. An LWS also requires highly capable sensor and control systems to precisely track long-range targets and maintain a trained beam for the required dwell time. This need is amplified even more in the maritime environment, where a ship's turbulence and motion further complicate the problem. The complex decisions made by the tactical officer are another concern with swarm warfare and LWS employment. In swarm warfare environments, the engagements can be as short as single-digit minutes. Automated decision aids that help decision-makers quickly filter through a large amount of

information will be pivotal in winning these rapid skirmishes. This thesis explored various UAV threat scenarios and LWS engagement strategies to determine some key factors.

UAV swarms may consist of either homogeneous or heterogeneous groups. Using a homogeneous group simplifies the acquisition and employment of a cost-efficient swarm, while heterogeneous groups increase the swarm's complexity and capability. Operators of homogeneous swarms can alter the size and formation of attacks. Heterogeneous swarms can utilize units of various roles, such as fighters, bombers, decoys, jammers, and scouts. Changing the swarm composition could have a considerable impact on the chance of success for the whole.

The LWS engagement strategy used can severely affect the outcome of the engagement. The most straightforward technique is the proximity-based method, where the weapons system prioritizes targets by range only. The "shortest engagement" algorithm provides a model that considers LWS slew time as well. If the incoming threat is a heterogeneous swarm, the LWS can employ more sophisticated strategies that prioritize various functions of the swarm such as sensing or communication. These heterogeneous engagement methods will require that the defenders have significant knowledge of the swarm and thus very capable sensors and data fusion systems.

This thesis used a program called "Swarm Commander Tactics" (SCT) from the Modeling Virtual Environments and Simulation (MOVES) Institute to explore and simulate swarm warfare environments. SCT was used to test various swarm formations, including line, wedge, and waved wedge. Additionally, this thesis developed a heterogeneous swarm formation employing decoy drones to shield the bomber units. For the LWS, this thesis evaluated an engagement strategy to prioritize bomber units over any other.

The primary findings were that swarm formations maximizing the angular displacement between units were more successful than closely clumped groups. These results were due to the increased LWS slew times required between each target. The armored decoy scenario increased overall swarm survival and thus, performance. In simulations where the ship survived, the bombers were able to live longer and get closer to the ship before being destroyed. In simulations where the ship was destroyed, a much greater number of bombers survived. Regarding the LWS engagement strategy, the shift caused an enormous impact on the results. In simulations where the ship survived, the engagement was much shorter, and the bombers were destroyed much farther away. In simulations where the ship was destroyed, the engagement lasted longer, and a much larger portion of the bomber group was destroyed. These results highlight the potential benefits of utilizing various formations, heterogeneous UAV groups, and developing LWS engagement strategies to counter them.

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I. INTRODUCTION

A. MOTIVATION AND BACKGROUND

Unmanned system capabilities are rapidly advancing and proliferating globally. Air, land, and sea all have various forms of autonomous systems navigating their environments. Unmanned systems, and unmanned aerial vehicles (UAVs) in particular, have become a threat of interest to the Navy. A primary concern is the concerted attack of multiple UAVs acting in a swarm. UAV swarms are large numbers of drones working as a collective, and sometimes chaotic, group. As recent as January 2021, the Indian army showed a demonstration of a 75-drone swarm attack in which a “mothership” UAV released smaller “kamikaze” drones with explosive payloads (Hambling 2021). At the same time, other major powers’ drone capabilities have been continuing to rise, especially in China (Hambling 2020). The first of these examples speaks to the move of swarm systems from a homogenous group of clones to a modular heterogeneous group where each UAV may have a unique function that serves the whole swarm. This would be a cost-effective method of swarm design, balancing redundancy with avoiding obsolescence.

The Navy is developing laser weapon systems (LWS) as a cost-efficient weapon system to defend ships against UAVs due to their predicted low-cost per shot and effective range (Michnewich 2018). Determining the best methods in using an LWS in the decision process (or kill chain) will enhance naval warfighters’ ability to defend ships against UAV swarms. This thesis studied the use of the LWS as a weapon to address UAV swarms for ship defense. Figure 1 illustrates a maritime C-UAV mission using a shipboard LWS.

Figure 1. Using shipboard LWS to defend against a UAV swarm threat. Adapted from Lockheed Martin (2020) and Edwards (2021).

The Navy must develop systems to defend its forces against the impending UAV swarm threat. Human operators can become quickly overwhelmed in this situation due to the sheer number of threats that must be detected, tracked, and engaged. Operators of the LWS need to understand potential swarm threat tactics and apply effective counter-UAV engagement strategies. This study explored the maritime drone swarm threat and the use of the LWS as a defense. The thesis studied LWS engagement strategies for prioritizing targets in a swarm to yield the greatest effect. The highlighted portions of Figure 2 show the focus of this effort—concentrating on the "decide," "activate," and "destroy" functions of the counter-UAV neutralization chain.

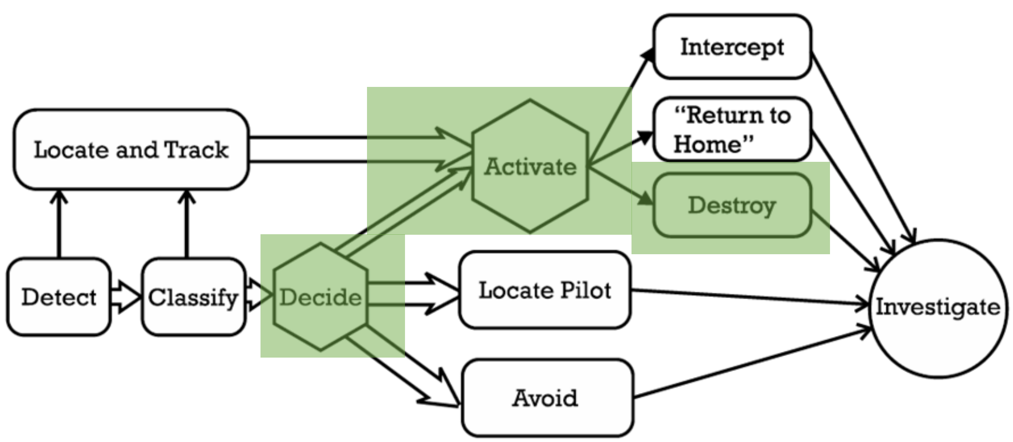


Figure 2. C-UAV neutralization chain. Adapted from Markarian (2020, 161).

B. THESIS STATEMENT AND RESEARCH OBJECTIVES

This thesis studied engagement strategies for using a shipboard laser weapon system to counter UAV swarm threats in the maritime environment. The thesis addressed the following research goals:

1. To identify and characterize maritime UAV threat swarms.
2. To develop and define engagement logic strategies involving the use of an LWS to defend a ship against UAV threat swarms.
3. To evaluate the utility of the different LWS engagement strategies against various maritime UAV swarm threat scenarios.

C. RESEARCH METHOD

This thesis explored shipboard LWS engagement strategies for counter-UAV swarm threats using modeling and simulation to evaluate different strategies against various representative threat scenarios. The research began with a literature review to study potential maritime UAV threats and characterize possible UAV swarm tactics. The literature review also included the study of LWS as a defensive system for use in the maritime environment against UAV threats. The study developed a set of combat scenarios involving different UAV swarms with various capabilities and attack patterns. Next, the study developed a set of LWS engagement strategies based on different threat prioritization tactics. Some scenarios were modeled using the NPS Modeling Virtual Environment and Simulation (MOVES) Institute's Swarm Commander Tactics (SCT) capability. Finally, the different engagement strategies were applied to the combat scenarios within the MOVES SCT software to explore their counter-UAV utility.

D. BENEFIT OF STUDY

This thesis expands the Navy's knowledge concerning the utility of shipboard laser weapons for countering swarms of drones. The study's findings provide an analytical foundation for exploring engagement strategy effectiveness against drone swarm threats—specifically identifying and evaluating various LWS engagement options for different types of swarms. This exploration and foundation are crucial to supporting naval counter-

UAV operations in the future maritime environment. They form the basis for understanding LWS applications, which will support the evaluation of engineering and implementation trade-offs for LWS integration on naval ships.

E. THESIS OVERVIEW

This paper is organized into six chapters: (I) Introduction, (II) UAV Swarm Threat, (III) Shipboard Laser Weapon System for Counter-UAV, (IV) Threat Scenarios and Engagement Strategies, (V) Modeling and Simulation Analysis, and the (VI) Conclusion. This chapter introduced the problem and provided an overview of the thesis objectives, research methodology, and benefits. Chapter II provides background information about the UAV swarm threat in the maritime environment. Chapter III describes the capabilities and limitations of shipboard laser weapon systems for defending against UAV swarm threats. Chapter IV presents maritime C-UAV threat scenarios and LWS engagement strategies. Chapter V describes the thesis modeling and analysis of the simulation. Finally, Chapter VI presents the thesis conclusions and recommendations for future research.

II. UAV SWARM THREAT

This chapter presents the thesis findings on the current state of UAV and UAV swarm development. The primary findings are that the use of drones as military threats is on the rise worldwide and that this technology is advancing rapidly. Key takeaways from this literature review are that: drones are easily obtained, easily weaponized, inexpensive, and are being used widely for a variety of harmful purposes. The findings also indicate that the development of swarms of drones is advancing and will lead to an even more challenging threat to defend against in the near future.

This chapter is organized into four sections. The first section contains the findings concerning recent foreign UAVs and swarm threat development. The second section provides an overview of UAV threat characteristics, applications, and swarms. The third section discusses the potential use of UAV and UAV swarms as threats in the maritime domain. The final section assembles a summary of the entire chapter.

A. RECENT FOREIGN UAV AND SWARM THREAT DEVELOPMENT

The world continues to develop UAV and swarm capabilities. Russia has recently announced a UAV called “Molniya” (Lightning), shown in Figure 3, which seems to be a response to the U.S. Gremlin system (Fedutinov 2021). This UAV is capable of very high speeds of about 700 km/h, expected ranges in the hundreds of kilometers, and expected payloads of about 5 to 7 kgs (Fedutinov 2021). A larger UAV or manned aircraft can deploy and retrieve multiple UAVs to support amassing a large swarm making it especially difficult to defend against, thanks to its high velocity and trim profile. In August, the Russian company ZALA Aero showed a mock-up of the loitering munition modified for naval use, the KUB-UAV, shown in Figure 4 (Novichkov 2021). This system has speeds of up to 130 km/h, an endurance of 30 minutes, carries a warhead of three kilograms, and can be deployed by a deck launcher to form swarms rapidly (Novichkov 2021). An adversary equipped with this system could coordinate an inexpensive and overwhelming attack against a surface target to disable their sensor, communication, or weapon systems, any of which leads to a mission kill.

In 2017, China launched one of the largest swarms, consisting of 119 UAVs showing their commitment to developing their swarm force (Tate 2017). Today, China continues the march forward and has various defense companies focusing on the problem. One company, Zhuhai Ziyan, has been developing cheap and effective rotary-wing UAVs that support a range of missions (Parakala 2021). The Blowfish family, shown in Figure 5, are some such systems that are electrically powered, modular, and capable of operating in wide-ranging environments (Parakala 2021). The payloads are interchangeable depending on the mission and target. From mortar bomb dispensers to light machine guns, these small systems have a range of 20 kilometers and can carry a payload of 12 to 15 kg. China's continued development of ever more capable and cost-effective systems indicates that the next battlefield will require an equally capable and cost-effective response.

Figure 3. Mock-up of the Russian Molniya UAV. Source: Kirill (2021).

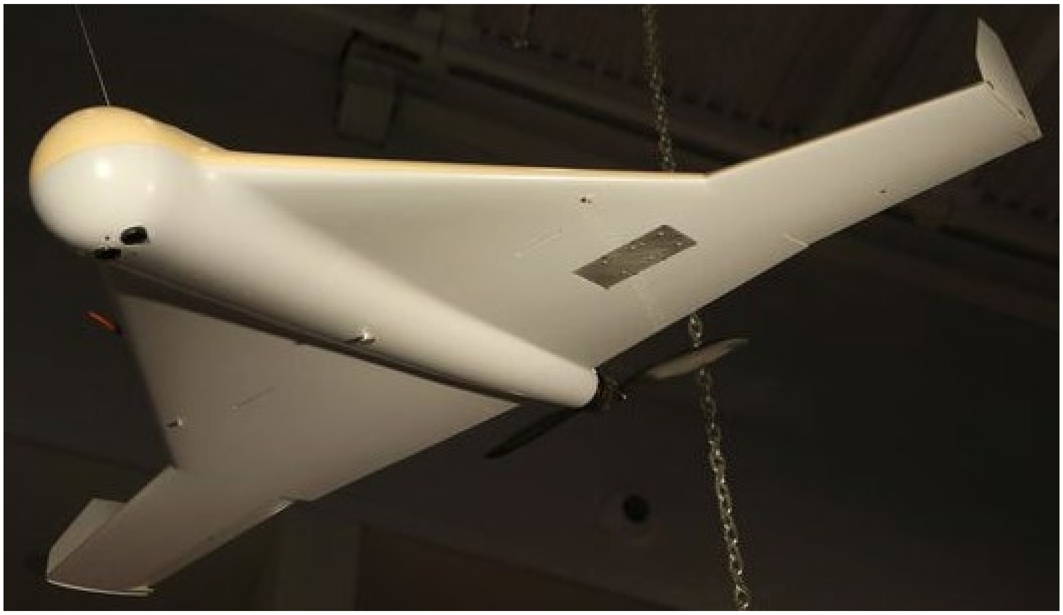


Figure 4. Mock-up of a Russian Naval Variation of the ZALA Aero KUB-UAV Loitering Munition. Source: Fedutinov (2021).

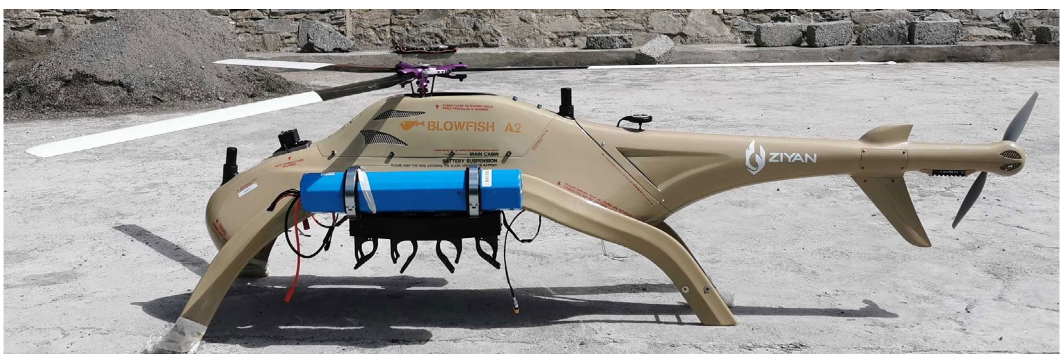


Figure 5. Chinese company Zhuhai Ziyan's Blowfish A2. Source: Ziyan (2021).

B. UAV THREAT OVERVIEW

1. UAV Characteristics

a. Classifications

With the continuation of Moore's Law, the processing power readily available has grown continually while also reducing in size and weight. This has allowed UAVs to vary wildly in size. While the Department of Defense (DOD) currently uses generic categories to classify UAVs, as shown in Table 1. Markarian proposes a more discrete set of classifications that use weight and flight range shown in Table 2.

Table 1. DOD categorical classification of UAVs. Adapted from U.S. Army (2010, 12).

UAV Category	Max Gross Takeoff Weight (lbs.)	Normal Operating Altitude (Ft)	Airspeed (Knots)
Group 1	<20	<1200 AGL*	<100
Group 2	21-55	<3500 AGL*	<250
Group 3	<1320	<18,000 MSL**	<250
Group 4	>1320	<18,000 MSL**	Any
Group 5	>1320	>18,000 MSL**	Any

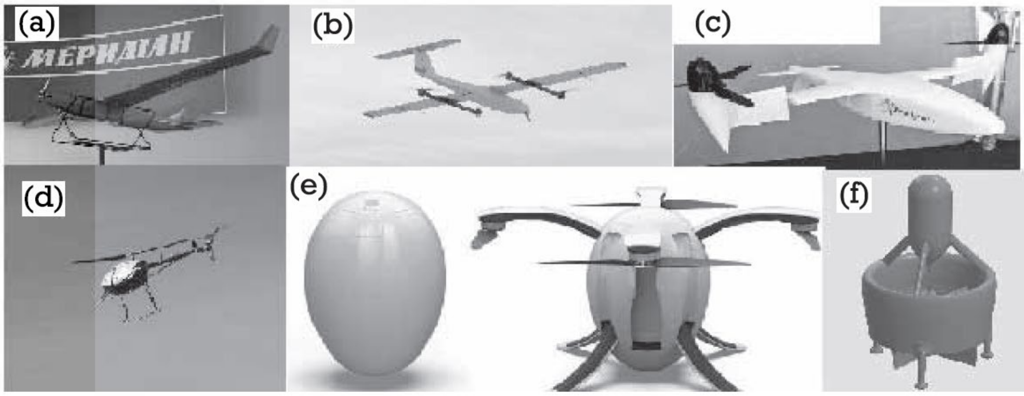
*AGL = above ground level. **MSL = mean seal level. Note: UAV category is determined by its highest categorial characteristic.

Table 2. Markarian UAV categories by weight and range. Adapted from Markarian (2020, 61).

No	Designation	Weight Range (kg)	Flight Range (km)
1	Micro-UAVs and mini-UAVs close range	$W \leq 5$	$25 \leq R \leq 40$
2	Lightweight UAVs small range	$5 < W \leq 50$	$10 \leq R \leq 70$
3	Lightweight UAVs medium range	$50 < W \leq 100$	$70 \leq R \leq 250$
4	Average UAVs	$100 < W \leq 300$	$150 \leq R \leq 1{,}000$
5	Medium to heavy UAVs	$300 < W \leq 500$	$70 \leq R \leq 300$
6	Heavy- to medium-range UAVs	$500 \leq W$	$70 \leq R \leq 300$
7	Heavy UAVs, large endurance	$1500 \leq W$	$R \leq 1{,}500$
8	Unmanned combat aircraft	$500 < W$	$R \leq 1{,}500$

Additional categories for very small UAVs may not have the range or payload requirements to cause a significant threat to military ships. They could, however, create issues such as jamming sensitive equipment or injuring personnel, especially if launched at close range or utilizing wind currents to extend their range.

Method of lift is another way to classify UAVs. The typical UAVs can use conventional horizontal take-off and landing (HTOL), vertical take-off and landing (VTOL), and helicopter designs. The quintessential quadrotor is quick to come to mind when thinking about drone swarms. Other more advanced designs are the ducted fan and tilt-wing. Figure 6 shows some examples of the various types of UAVs.



Note: (a) HTOL, (b) VTOL, (c) Tiltrotor, (d) helicopter, (e) specialized quadrotor, (f) ducted fan

Figure 6. UAV design examples. Source: Markarian (2020, 60).

b. Remote Control

There are various methods to control UAVs. Civilian systems use radio communications as the primary method. However, the radio frequency bands are heavily regulated at the production level by various committees and organizations depending on the country. Table 3 shows and describes the typical frequencies of civilian UAVs and their uses. Military systems use similar bands and others but add more robust encryption to prevent adversarial interception of information. Large military UAV systems will also utilize satellite communications and communicate with many control sites simultaneously (Janes 2021a).

Table 3. Typical civilian UAV bands. Adapted from Markarian (2020, 81).

Band	Usage
2.4 – 2.485 GHz	general UAV control
0.9, 1.2, 2.4, 5.8 GHz	payload control and video transmission
433 MHz, 868 MHz	telemetry

c. *Components of UAV Systems*

Five primary functions describe a typical UAV system: power systems, communications and surveillance, navigation, flight control, and payload modules (Markarian 2020, 69). Figure 7 shows the layout and contents of those modules, except for the payload.

The power system provides the energy to run the other system modules. The system uses an energy storage device such as a battery. This battery could be of many types, but civilian systems would most likely use lithium-polymer (LiPo) due to the high energy density to weight ratio (Markarian 2020, 70). This module would be responsible for providing power to the rest of the system and allowing recharge and reuse if desired.

The communications and surveillance module handles the transmission and receipt of all signals for the UAV. There is a range of types of information that can be transmitted across the various frequencies shown in Table 3. Some systems require a first-person view image to be sent to a pilot and to receive flight commands (DJI 2021). Other systems may be more advanced and only send information about the system's desired state, such as landing location, height, speed, and direction of travel. Still, more advanced systems may only receive instructions about the mission of the UAV or swarm. All these systems rely on radio transmissions as the primary form of communication. UAVs operating in a swarm may form a Flying Ad-Hoc Network utilizing close-range low power communications solely to share information within the swarm (Campion, Ranganathan, and Faruque 2018, 6). The surveillance portion controls the EO/IR cameras and relays that information to the ground control stations (GCS) via the communication module.

The navigation module includes all the onboard systems used to sense the orientation, position, and velocity of the UAV. In the case of autonomous systems, this module compares all these parameters to desired and sends commands to the flight control module for corrections (Markarian 2020, 69).

The flight control module contains the various mechanical and electrical systems that move the control surfaces or energize the motors. In the case of a fixed-wing system, servos will move the ailerons, elevators, or rudder to create a pressure imbalance and the resultant force reorients the UAV. The system also controls throttle and thus the rate of ascent or descent. For quadrotors, the module will control the power flow to each motor to finely control the system's orientation. In the case of rotorcraft, this module carefully controls power to the main and tail rotor. There are additional servos that move a "swash plate" that maintains the stability and orientation of the helicopter.

The final module not shown in Figure 7 is the payload. This module reports the status of the mission payload on the UAV. This module also controls the arming of explosives and the release of kinetic payloads. For jamming payloads, this module controls the frequencies and amplitudes of emitted energy.

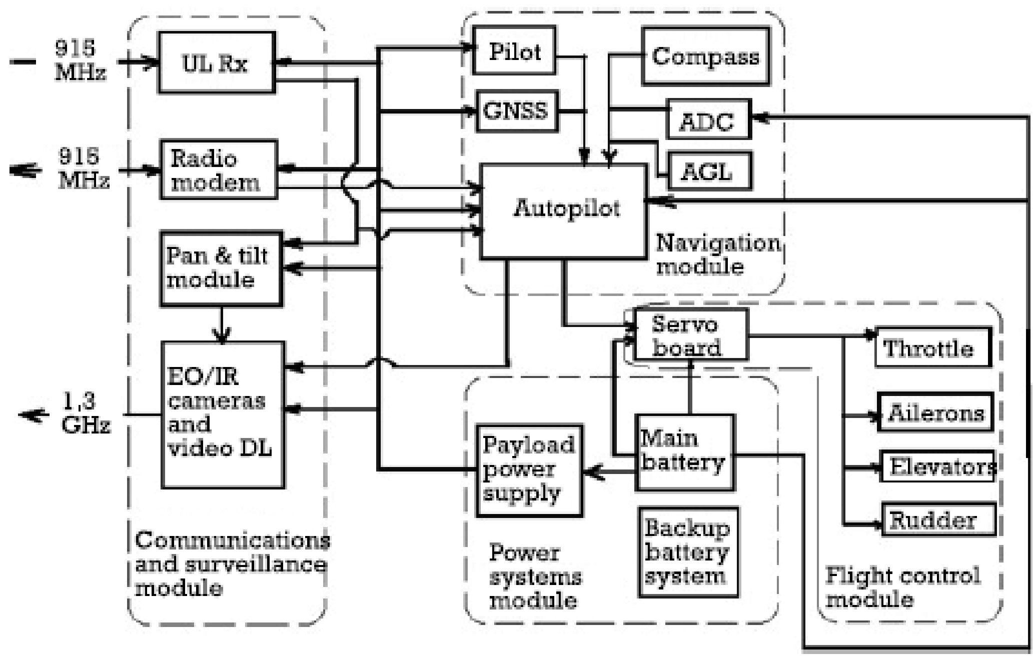
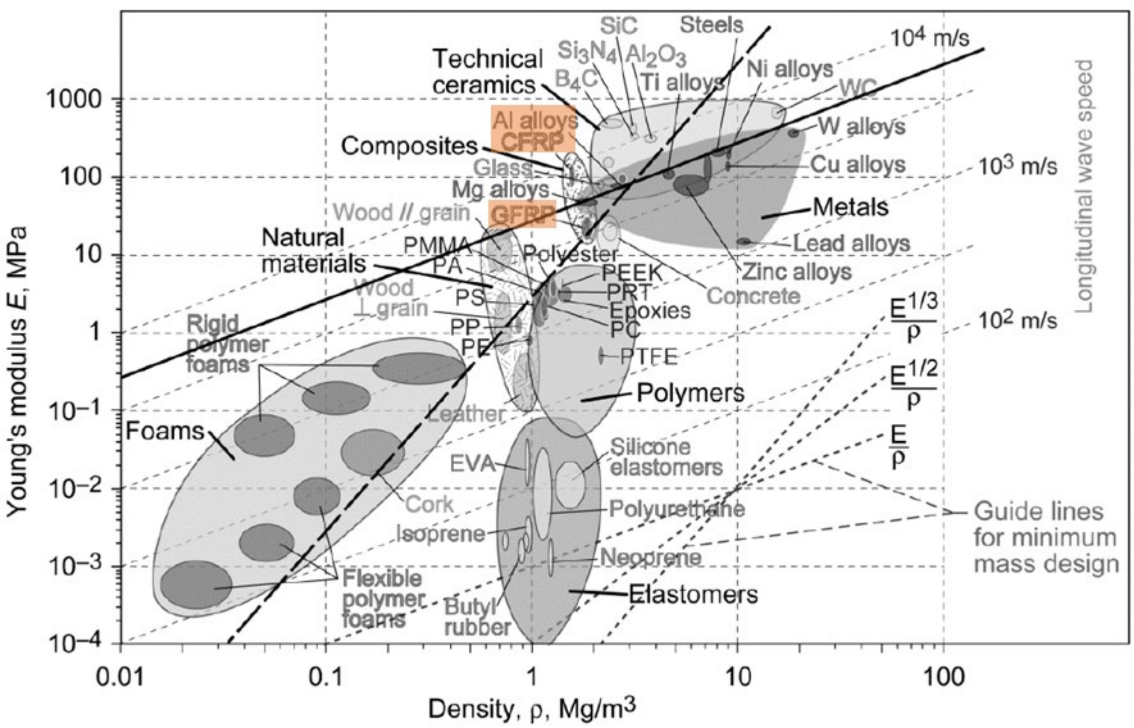


Figure 7. UAV system modules. Source: Markarian (2020, 69).

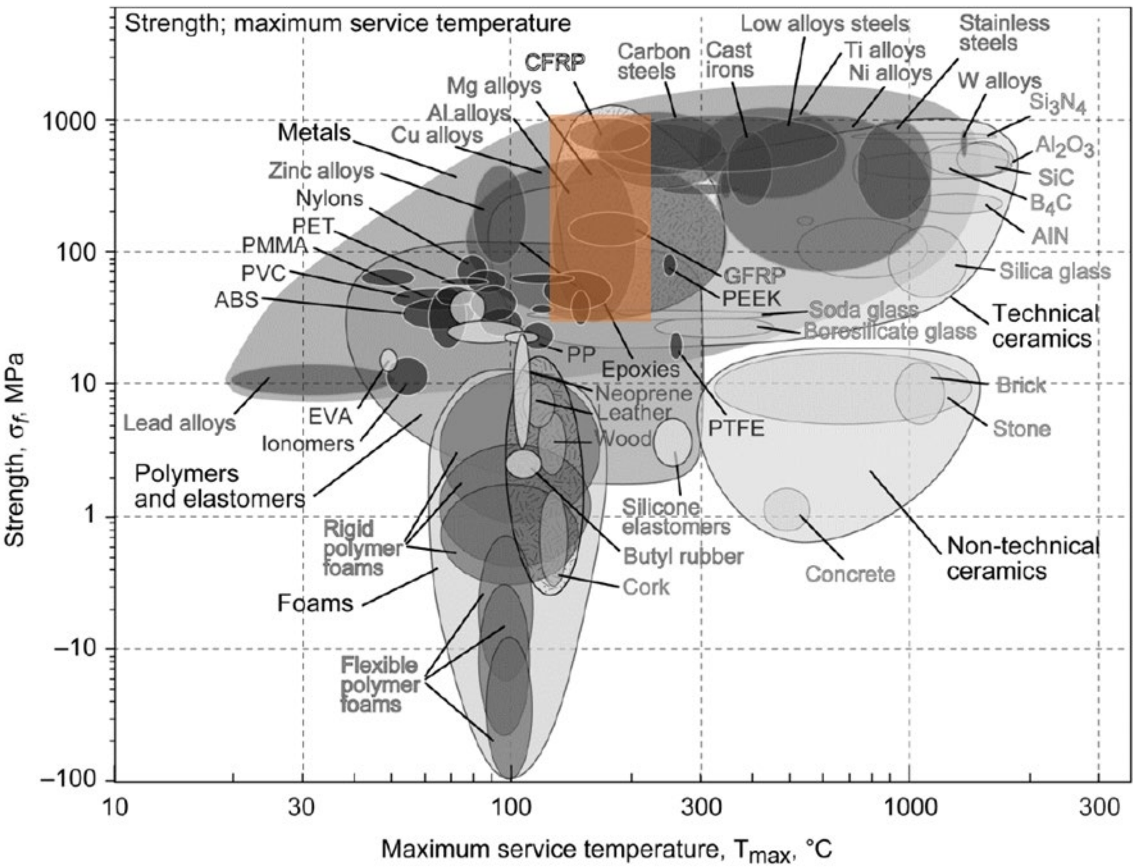
d. Material Composition

The elementary internal compositions of UAV systems include the copper wirings for electric motors, PCB materials, glass or plastic optics, and an energy source as previously described. The shell of the UAV is typical of any aerial system. The chosen material usually has a high Young's modulus to density ratio (E/ρ) for structure (Arnold, Cebon, and Ashby 2012, 17). Additionally, since the materials used must be formed into a surface, they must also have a high ratio of the cubic root of Young's modulus to density ratio ($E^{1/3}/\rho$) as this gives a measure of a plate's tendency to bend (Arnold, Cebon, and Ashby 2012, 17). Figure 8 shows various materials that could be used in aviation applications. Historically, the industry has used aluminum as the primary material, with glass- and carbon-fiber-reinforced-polymers also used (Hoeche et al. 2021). Magnesium-based composites are being evaluated for their production and strength benefits (Hoeche et al. 2021). These materials have relatively low maximum serviceable temperatures, as shown in Figure 9, allowing an LWS to be quite effective against them (Arnold, Cebon, and Ashby 2012).



Note: The solid line indicates a E/ρ of aluminum. The dashed line indicates a $E^{1/3}/\rho$ also of aluminum. The orange boxes indicate typical materials used in UAVs.

Figure 8. Young's modulus versus density of various materials. Adapted from Arnold, Cebon, and Ashby (2012).



Note: The orange area corresponds to typical shell materials of UAVs.

Figure 9. Material strength and max service temperatures of various materials. Adapted from Arnold, Cebon, and Ashby (2012).

2. UAV Applications

UAV systems have a wide range of potential applications. Some of the primary mission types are surveillance, countermeasure, sensor disablement, and payload delivery. Each mission has its unique challenges and requires specialized equipment.

a. Surveillance

Surveillance is the primary use of UAV systems today. Many commercial-off-the-shelf (COTS) systems come equipped with gimballed and high-resolution camera systems. These images or videos can be stored locally on the UAV or beamed back to a GCS. Groups have used these low-cost systems to fly over installation barriers and gather information on sensitive areas such as nuclear power plants (Agence France-Presse 2014). However, a technical analysis conducted in 2019 with the United States Nuclear Regulatory Commission and Sandia National Laboratory has concluded that "U.S. nuclear power plants do not have any risk-significant vulnerabilities that could be exploited by adversaries using commercially available drones to result in radiological sabotage, theft or diversion of special nuclear material (essentially the reactor fuel)" (U.S. Nuclear Regulatory Commission 2020). This UAV mission is quite vulnerable to an LWS. The vehicle's sensors used to gather information are quite vulnerable to electromagnetic radiation allowing an LWS to quickly cause long-term or permanent sensor damage leading to a soft mission kill.

b. Countermeasure or Decoy

Countermeasure systems may create large radar cross-sections to draw enemy weapons systems away from an actual target. Current decoy systems can be hauled behind or left to float as the primary ship moves away from the target. Other systems use rockets to create large radar cross-sections that move in different directions from the main ship, like the Mk. 234 Nulka (Janes 2021b). Drones may serve as a much more cost-effective method to create a decoy radar signature and can even be retrieved for reuse.

In the case of swarm warfare, a small number of specialized UAVs can serve as decoys for the rest of the group. These designated sacrificial units would be positioned at the forefront of an attacking wave to draw and absorb counter-UAV attempts.

c. Sensor Neutralization

Jamming of sensors is another potential use of cheap UAV systems. Small units may get in very close to their target and use minimal power to overwhelm the targeted electronic sensor. These systems could be very effective by exploiting the inverse square law of E.M. propagation. If the UAV system is correctly positioned, very little energy would be required to overwhelm the sensitive equipment used to receive and measure returning E.M. energy.

d. Payload Delivery

The final UAV use is the delivery of payloads. In the case of standard package delivery, UAVs have been used to deliver various materials. Some commercial entities, like Amazon, are exploring regular drone use to deliver customer packages (Lee 2019). Other illegal groups use UAVs to deliver illicit materials into restricted areas like prisons (*BBC* 2016). Terrorist organizations have been suspected of using COTS drones to drop munitions on targets. More sophisticated military UAV systems can use kinetic or explosive payloads to cause damage to a target. Large UAV systems can utilize intelligent munitions such as the hellfire missile to deliver the firepower or fly over a target and drop traditional kinetic bombs. The next iteration of warhead delivery may utilize "kamikaze" UAVs to directly attack vital weak points on a target. This is the primary scenario envisioned in this thesis. Chapter IV explores potential methods that an attacking group of UAVs may overwhelm a defending ship with the goal of payload delivery and potential methods to deal with a heterogeneous attack.

3. UAV Swarms

a. Swarm Warfare

The use of swarms completely changes the battlefield. Arquilla and Ronfeldt (2000) argue that swarming is the most advanced step in warfare evolution. They argue that four primary paradigms have shaped how forces conduct combat: melee, massing, maneuver, and swarming (Arquilla and Ronfeldt 2000, 7). The melee paradigm can be described as individuals sometimes formed into rough lines that can easily be broken and dissolved (Arquilla and Ronfeldt 2000, 10). An example of this would be the traditional dogfights between aircraft in World War 1. As wars were fought, leaders acknowledged that their forces would better resist routes by fighting together in groups. This technique called "massing" led to the creation and control of military "fronts" where individuals would fight as one entity (Arquilla and Ronfeldt 2000, 13). The most famous example of this would be the Greek phalanx (Arquilla and Ronfeldt 2000, 14). With the rise of these formations, it became apparent to early commanders that they could gain considerable advantage by focusing an attack at a specific portion of an enemy formation and an even more significant advantage if attacking from an unexpected direction (Arquilla and Ronfeldt 2000, 17). This concept is the core of maneuver warfare, where a commander can use various portions of his army to apply force with precision (Arquilla and Ronfeldt 2000, 17). The effectiveness and agility of Roman maniples would best describe the advantage of maneuver warfare (Arquilla and Ronfeldt 2000, 17). The next step in warfare is the advent of swarms. Swarming is characterized by the rapid and overwhelming application of force to an adversary from all directions (Arquilla and Ronfeldt 2000, 23). This has been historically very difficult to execute primarily due to the large amount of information sharing required among the swarm. A significant portion, ideally all, of the swarm must have a holistic understanding of the battlefield to conduct swarm warfare properly. Each unit must perform the best actions for the group with little to no regard for their wellbeing. Autonomous or semi-autonomous systems are the best option to achieve this level of detailed control.

b. Swarm UAVs

The UAV is a great platform to achieve this type of warfare. The systems are quickly and cheaply acquired in great numbers. Most commercial systems are controlled remotely but have onboard systems that will assume control in the case of communication failure. These systems can be modified or upgraded to support the control of groups of UAVs to form swarms. The number of units required to form a swarm is unclear. However, a group from the U.S. Military Academy defines it as "a group of three or more robots that perform tasks cooperatively while receiving limited or no control from human operators" (Arnold et al. 2019, 75). GCSs control most of today's swarms where information is sent, processed, and commands are returned to the swarm (Campion, Ranganathan, and Faruque 2018, 6). The next step in swarm systems is to perform the processing locally. This can be done either with a central processing UAV that holds specific processing equipment or shared processing that the group performs.

C. MARITIME UAV SWARM THREAT

The swarm threat to naval ships operating in deep water is likely to be fixed-wing, long-endurance, fast-moving UAVs. This type of UAV can quickly close the distance to the target. The Russian Molniya (Figure 3) is a prime example of this type of threat. The attack formation could wildly vary, but the most effective might be a collapse formation where the UAV swarm holds just at the edge of the expected sensor range.

There is the possibility that shorter-range UAVs could be launched relatively close-in by a submerged threat. A launch of UAVs by a submerged threat would require a relatively close submarine or medium unmanned underwater vehicle (UUV) system. A UUV could solely serve as the launch platform or might carry its own warhead for use after launching the UAVs.

In littoral waters, the types of UAVs that can reach naval ships increase significantly. More threats can quickly traverse the shorter distances while a ship is in transit in a canal or strait. This shift in geography allows hostile forces to use cheaper and less capable UAVs to engage a defending force. Systems initially developed for civilian use would be especially cost-efficient in this scenario. In the case of swarms, civilian systems would require significant modifications to be effective.

D. SUMMARY

This chapter served to present findings on the current state of UAVs and UAV swarms. The world stage has many players that recognize these areas as worthy of significant resources. The characteristics of UAV systems can vary with different classifications, methods of control, internal components, and physical compositions. There are many potential UAV missions; this chapter discussed surveillance, countermeasures, decoys, sensor neutralization, and payload delivery. The use of many relatively cheap systems to form a swarm produces a cost-effective threat. To combat these threats, the LWS may be one of the most effective solutions. The next chapter explores various aspects of LWS and its applicability to naval warships.

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III. SHIPBOARD LASER WEAPON SYSTEM FOR COUNTER-UAV

This chapter presents the thesis findings on the capabilities and limitations of laser weapon systems for countering UAVs and UAV swarms. The primary findings are that LWSs are a cost-efficient solution to the growing UAV swarm threat. LWSs are low-cost per shot, produce an immediate effect, and can adapt to rapidly changing environments. Commanders must be mindful of the physical phenomena that can affect LWSs and how they emerge in the maritime environment. Careful energy storage planning and automated decision aids (ADA) will make LWSs very effective in a combat environment.

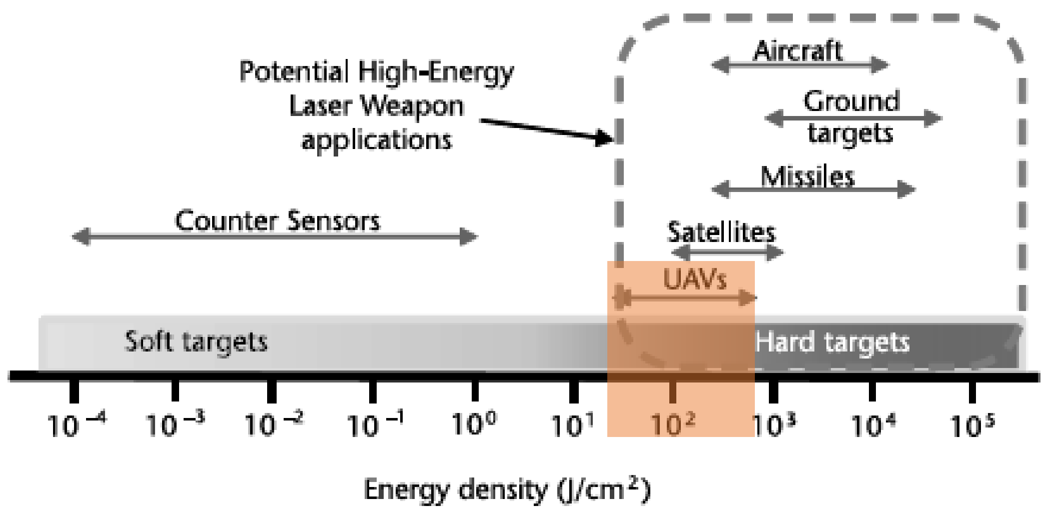
This chapter is organized into four sections. The first section contains an overview of LWS capabilities related to countering UAVs. The second section provides an overview of LWS limitations. The third section discusses the potential use of shipboard LWS to counter maritime UAV swarms. The final section summarizes the contents of the entire chapter.

A. LWS CAPABILITIES

Militaries worldwide are researching the use of LWS as a solution to the growing UAV and UAV swarm threat. Some of the significant benefits to using this system are the low-cost per shot relative to kinetic systems, the short time-to-effect, and the ability to apply energy to particular areas or systems. High-accuracy systems allow the user to choose between soft sensor kills or hard system kills.

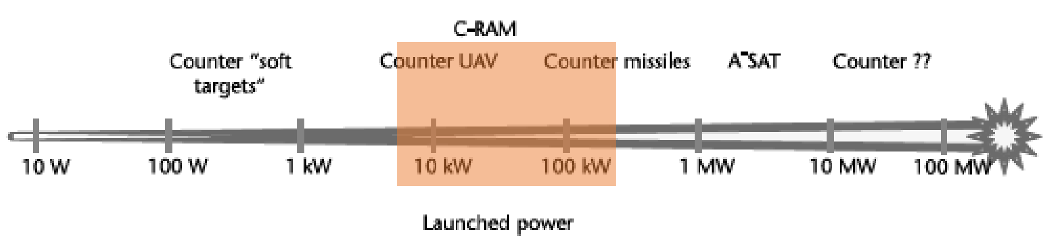
1. Low-Cost per Shot

One of the most attractive benefits of using directed energy is long-term endurance. The U. S. Navy has continued to develop kinetic systems tailored to counter the UAV threat, but the specialized equipment, ammunition, and storage requirements make this method less feasible. The use-case flexibility and expected cost per shot of less than $1 make laser weapon system solutions much more appealing (Smalley 2014). Using this exceptionally low economic cost against commercial drones is much more favorable than when a U.S. ally used a patriot missile costing around $3M (Perkins 2017). Figure 10 shows the amount of incident energy required to engage various target types with the UAV section highlighted. Figure 11 shows the amount of energy required to be transmitted for these types of engagement.



Note: The orange area corresponds to the energy density required for hard counter UAV kills.

Figure 10. LWS energy density vs. potential systems. Adapted from Titterton (2015, 241).



Note: The orange area corresponds to the energy range of interest for LWS.

Figure 11. LWS launched power required for various counter applications. Adapted from Titterton (2015, 241).

2. Lightspeed Effect

The time-to-effect is a crucial factor in engagements. Kinetic systems must wait for their projectiles or missiles to travel the target before performing battle damage assessment. For an LWS, the system delivers power to the target effectively in an instant. Kinematic vector analysis or motion prediction is not required, enabling the targeting and tracking system to be significantly more straightforward (correcting for the environment is more difficult). The short time-to-effect promotes more efficient use of weapon resources. As soon as there is an indication that the effect on the target is sufficient, the weapons system can move on to the next.

3. Beam Propagation Correction

Today's systems employ various methods for beam correction and focus. This includes the use of predictive or reactive systems. Figure 12 shows an example system that uses measured atmospheric aberrations to alter the outgoing beam. These corrections create much more accurate and focused energy delivery and allow the beam to burn through the target material faster.

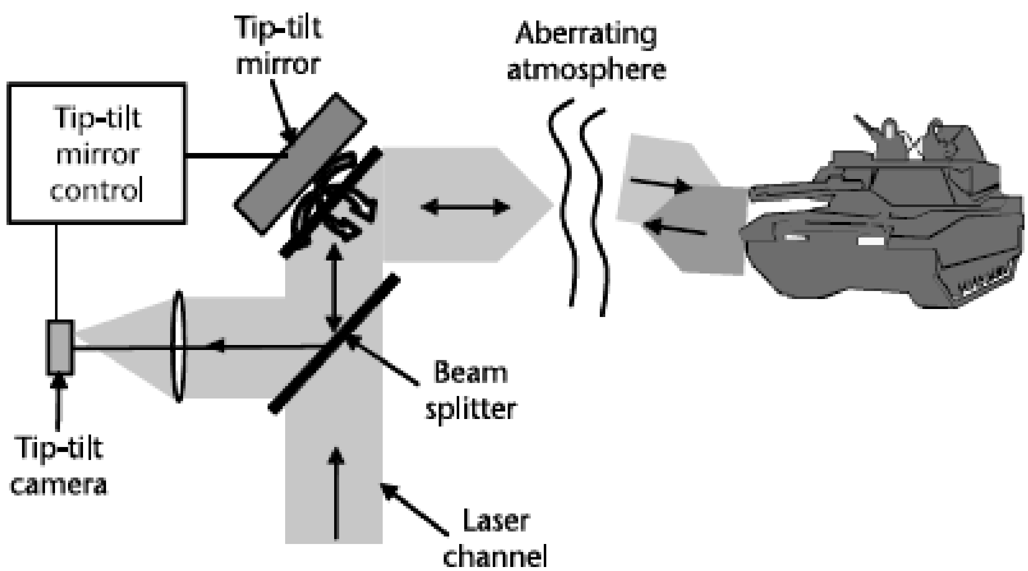


Figure 12. Example first-order beam control system. Source: Titterton (2015, 253).

Tightly delivering energy allows for eliminating critical portions of a UAV. Intelligently targeting the energy storage location, control surfaces, or processing center are examples of how to quickly and efficiently eliminate an aerial system.

An LWS can target system sensors if the target system is out of effective hard kill range, or a hard kill is not desired. For sensor soft kills, the components are designed to be sensitive, so the amount of incident energy required is significantly less. Less required power leads to an increase in effective range for the soft kill of systems.

B. LWS LIMITATIONS

All weapon systems have limitations and directed-energy weapons are no different. Atmospheric attenuation, turbulence, and thermal blooming all affect the way energy reaches the target. The weapon system must be in direct line of sight with its target. Its effectiveness can vary against different materials, and it relies on the ability to store energy on the platform.

1. Atmospheric Attenuation

Atmospheric attenuation consists of resonant absorption, Rayleigh scattering, and Mie scattering. Atmospheric absorption of electromagnetic waves occurs with airborne di-atomic and tri-atomic molecules (Titterton 2015, 167). Rayleigh scattering occurs with significantly smaller molecules than the wavelength of the transmitted energy (Titterton 2015, 167). In a typical atmosphere, the apparent gases cause Rayleigh scattering. Mie scattering requires particles closer in diameter to the transmitted energy's wavelength (Titterton 2015, 169). In a typical atmosphere, Mie particles consisting of dust or condensed water droplets would produce a visible haze or fog (Titterton 2015, 169). All types of aerosols will negatively impact transmission due to Mie scattering. A comparison of extinction coefficients is shown in Figure 13. Depending on the composition of the atmosphere, its absorptivity will vary significantly with changes in wavelength. Figure 14 shows how specific molecules affect the transmission in a typical atmosphere and at what wavelengths these interactions occur. CO_2, O_3, H_2O are strong contributors to absorption.

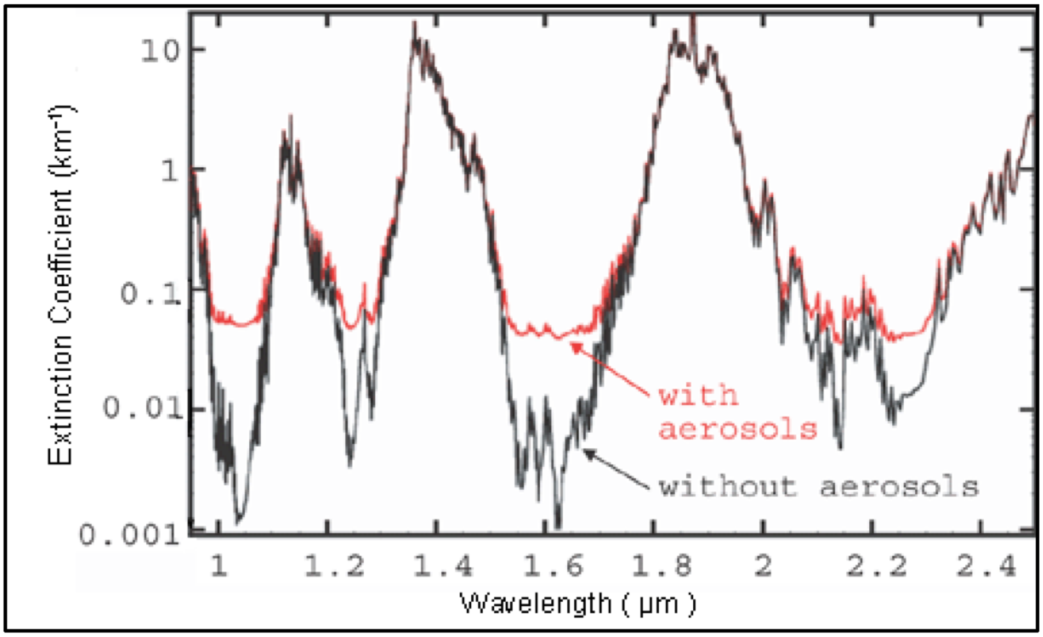
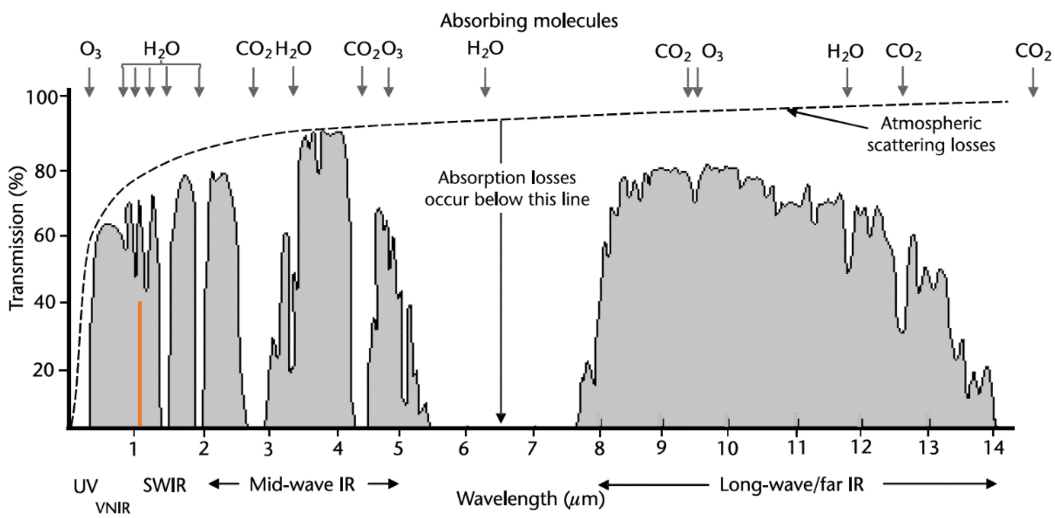


Figure 13. Comparison of extinction coefficients with and without aerosols. Source: Michnewich (2018, 12).



The orange line indicates the wavelength of the SWARM commander LWS at 1.0642 µm.

Figure 14. Typical atmospheric transmission in Northwest Europe. Adapted from Titterton (2015, 168).

2. Effect of Turbulence

Atmospheric turbulence plays a significant role in impacting the delivery of energy to a target. The tiny variations in the laser medium's refractive index produce the scintillation (shimmering) effect on a surface. Lasers produce coherent beams that will "wander" or "spread" due to these slight variations (Titterton 2015, 176). Turbulence results from significant temperature gradients in a fluid. Differences in localized temperatures create differential densities, which drive movement in a gravitational field. The day-night cycle is a significant driver of turbulence in real-world environments (Titterton 2015, 179). Figure 15 shows the change of refractive-index structure parameter (C_n^2) across a typical day. The turbulent peak period is during high noon. The ground absorbs the most sunlight and converts that to heat, creating a large temperature gradient with the cooler atmosphere above. The refractive-index structure parameter is a way to describe the level of atmospheric refractive turbulence and has units of $m^{-2/3}$ (Titterton 2015, 589). Complex systems like the one shown in Figure 12 can compensate for this turbulence. Advanced optic techniques are capable of impressive corrections and produce very small incident diameters, shown in Figure 16.

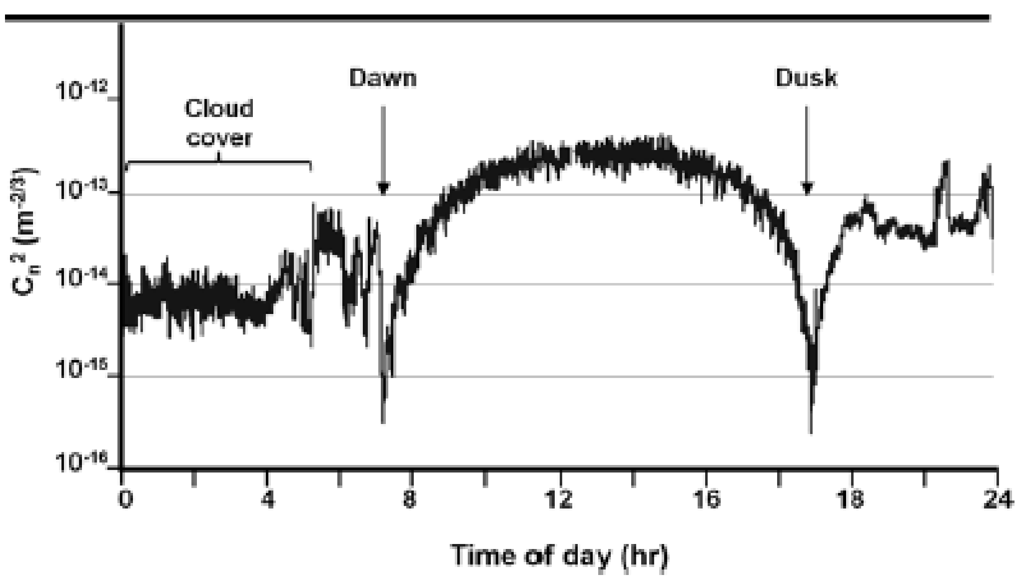


Figure 15. Diurnal effects on turbulence. Source: Titterton (2015, 179).

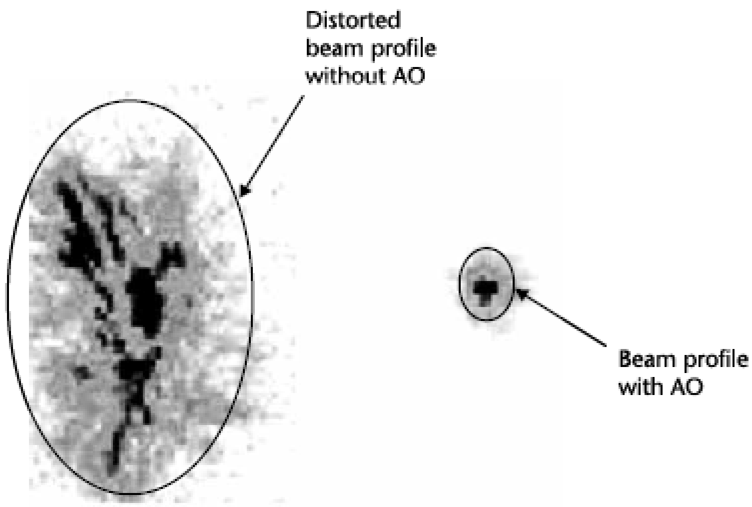


Figure 16. Effects of turbulence and methods to compensate. Source: Titterton (2015, 181).

3. Thermal Blooming

Thermal blooming occurs when molecules in a fluidic laser medium absorb some of the transmitted energy. The energy is converted to heat which causes expansion and a decrease in fluid density. This relative difference in fluid density causes refraction to occur, creating imperfections in the laser propagation. The generated heat is more concentrated in the center, which causes the laser to spread and reduces the overall intensity at the target. Figure 17 shows the effect of a laser beam before and after being affected by thermal blooming.

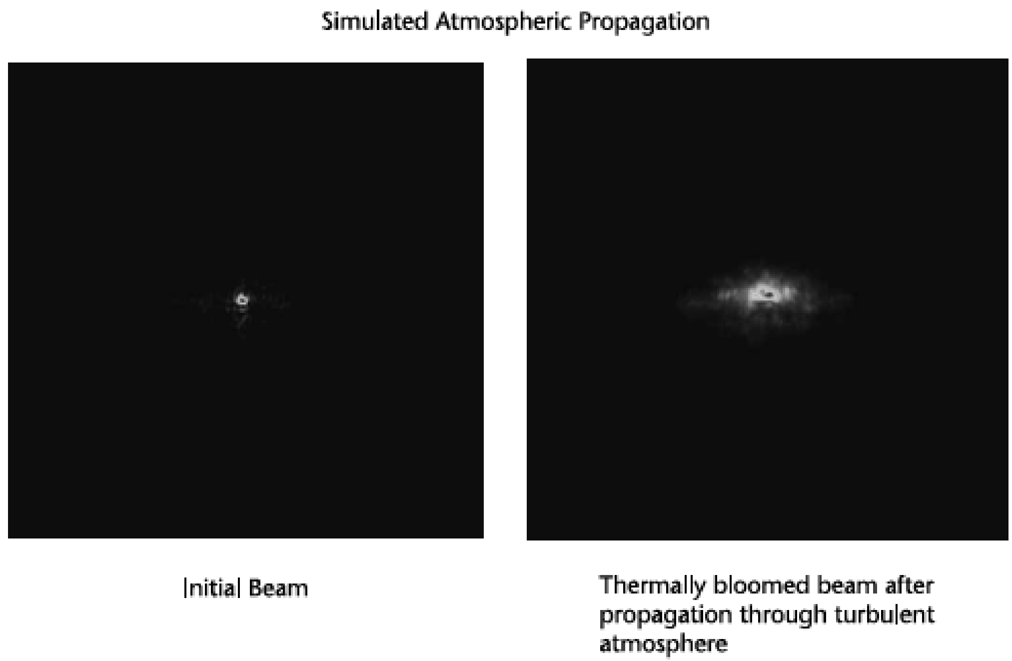


Figure 17. Example of thermal blooming. Source: Titterton (2015, 185).

4. Fine Tracking and Dwell Time

Another critical concern for the LWS is the requirement for fine tracking. In the case of UAV defense, the target in question is exceptionally small and fast. The weapon system's effectiveness largely depends on its ability to precisely direct a narrow beam onto this small object across a long distance. The system must also maintain the beam's position on the target long enough to ablate the shell material and damage the components inside. The amount of time required to penetrate the shell depends on the thickness and composition of the material, as discussed in Section II.B.1.d. If a hard system kill is not desired, the system can achieve various component soft kills that require a shorter dwell time. This feat requires precise robotic control systems and highly accurate EO/IR sensors to collect the required information.

5. Line of Sight

The LWS requires a direct line of sight to the target for engagement. This requirement creates a dependence on the installation location of LWS on a ship. Every unit of height at which the system can be mounted increases the range by one-half the power.

C. LWS FOR MARITIME C-UAV OPERATIONS

Overall, LWS could be a very effective response to the growing UAV and swarm threat. Exceptionally large magazines and low-cost per shot ratios promote their use against targets like UAVs which may also be very low-cost per unit. The Navy has recognized these benefits and is already employing laser weapon systems on ships (Smalley 2014). Figure 18 shows the AN/SEQ-4 Laser Weapon Systems (LaWS) aboard the USS Ponce. This new environment introduces some unique challenges to operating an LWS.

Figure 18. Shipboard LWS. Source: B. Johnson (2021b).

1. Power

Michnewich provided an estimate on the amount of energy required to destroy a UAV with a two-millimeter-thick aluminum skin as approximately 44.4 kJ (2018, 42). His simulation indicated that each UAV engaged at six kilometers required approximately 4 M.J. of stored energy (Michnewich 2018, 62). Extrapolating this estimate out to a UAV swarm of 200, the amount of energy required would be around 800 MJ. The amount of available power on a ship is limited by the power distribution system, generators, and backup batteries that normally support ship operations. To support this significant new load, the Navy must use energy- and space-efficient batteries. Michnewich points to leadacid or lithium-iron batteries as being potential solutions to hold the required energy between engagements. 800 MJ would require eight 24-cell batteries taking up 7.6 m^3 of space and weighing 16240 kg (Michnewich 2018, 71). Finding this amount of continuous space on a ship is quite difficult and will require significant planning and rework to retrofit existing ships with a capable system.

2. Maritime Unique Effects

An LWS operating on a ship has a group of considerations that must be assessed. The placement of the LWS must be carefully considered. Exhaust ports or weather decks can create localized temperature gradients that would severely degrade the performance of the LWS due to differences in fluid densities. Ideally, the LWS would be placed in a high spot to maximize the range to the horizon and to minimize the impact of the ship's superstructure or antenna systems. Every portion of the ship occluding the LWS' arc of influence is a reduction in capability. Finally, if the ship is in a group, the tactical officer and weapon system must consider the positions of blue forces. Figure 19 shows how the geometric configuration of the fleet affects the LWS' arc of influence.

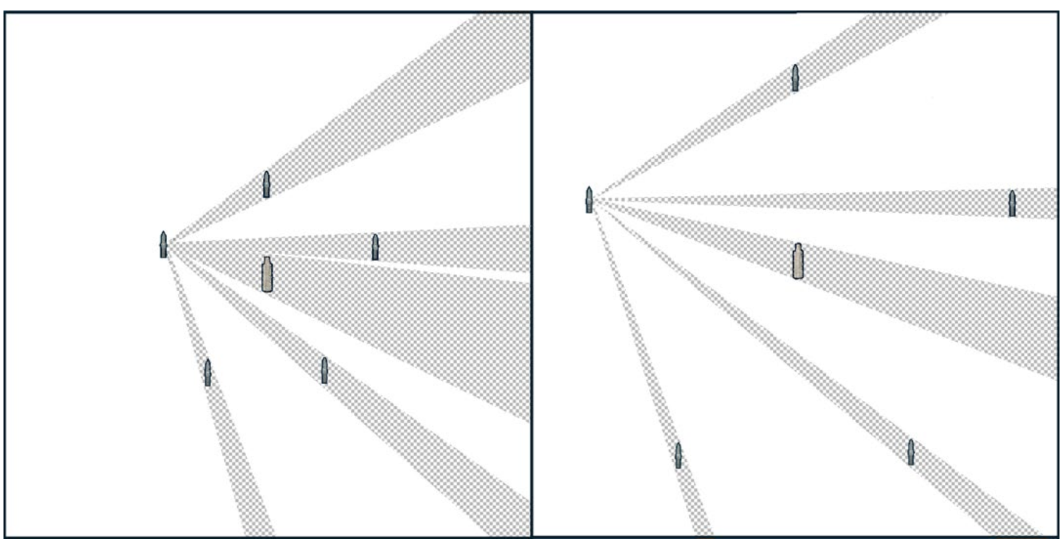


Figure 19. Impact of the formation of a blue fleet on an LWS' arc of influence. Source: B. Johnson (2021b).

3. Complex Decision Environment

The tactical officers aboard a ship have many areas that require their attention, even in day-to-day operations. In the event of an attack, the environment and decisions required become orders of magnitude more complex (Blickley et al. 2021). Figure 20 shows an example of how many elements may be considered during an LWS engagement. The Navy will need more than an enduring and efficient system to compete in swarm warfare. The speed of engagement for humans can be a severe bottleneck, especially in the face of a swarm attack and potential information overload. Figure 21 shows the dynamic model of situated cognition, representing how information flows from the true environment to decision-makers. One of the critical points in this flow of information is step 3, where data is held at the local command and control system. If developed carefully, automated systems that use this data to help tactical officers identify, prioritize, and engage targets will be critical to surviving in the swarm environment.

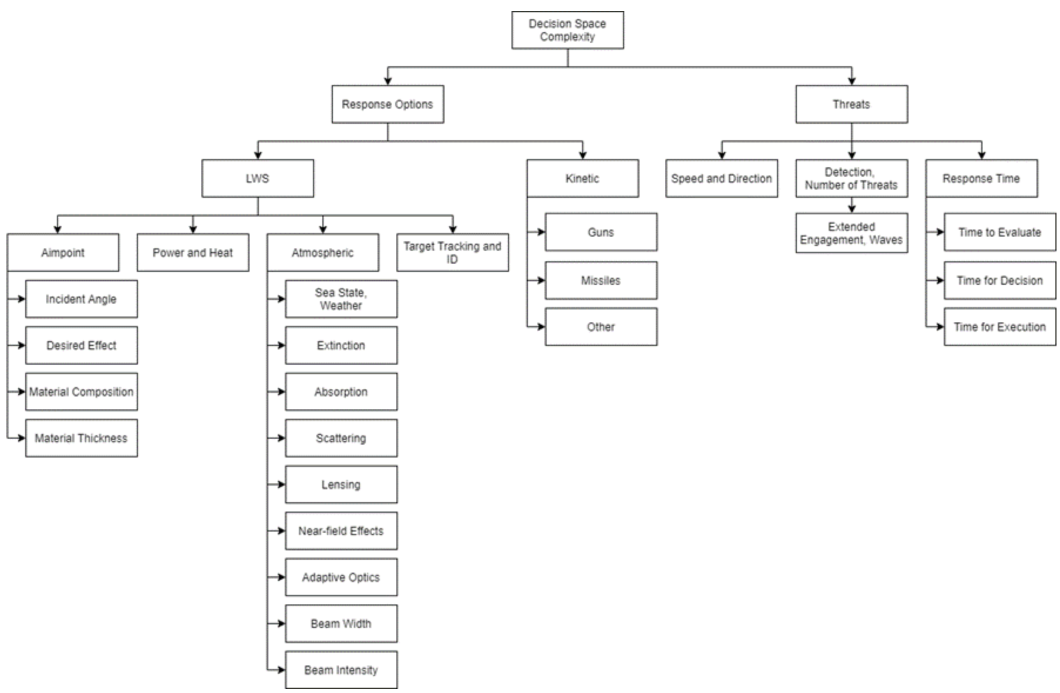


Figure 20. The various complexity factors evaluated for an LWS engagement. Source: Blickley et al. (2021).

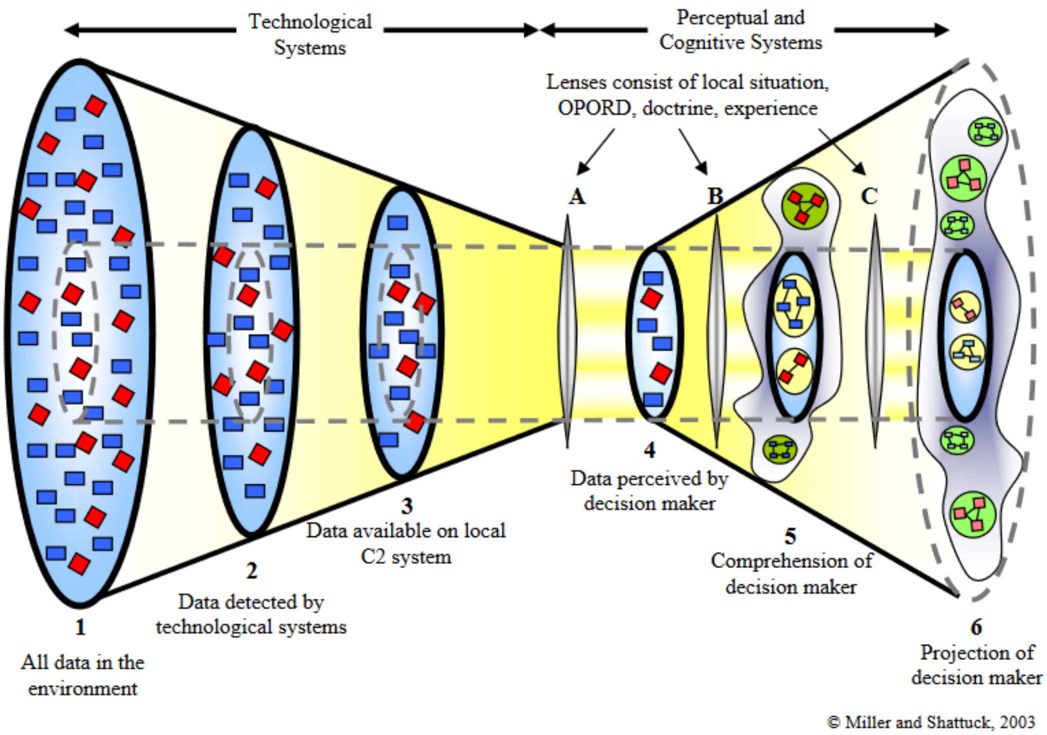


Figure 21. The Dynamic Model of Situated Cognition. Source: Miller and Shattuck (2006).

D. SUMMARY

This chapter presented the findings on the capabilities and limitations of laser weapon systems for countering UAVs and UAV swarms. LWSs enjoy low-cost per shot, which is especially good to counter to low-cost commercial UAVs. LWSs produce an immediate effect on line-of-sight targets; this effect also allows it to eliminate groups of targets quickly. Atmospheric, turbulent, and thermal effects can be corrected by sophisticated beam propagation techniques. Precise control systems for the platform are required to minimize dwell time for each target. The maritime environment presents unique challenges such as power distribution and ship-created turbulence. Finally, the tactical officer's decision environment is exceptionally complicated and only grows more complex with the introduction of a swarm. The use of ADAs will aid in filtering the vast amount of information into crucial bits that the team can more quickly and efficiently process. The next chapter explores various threat scenarios and engagement strategies in which LWSs may be used.

IV. THREAT SCENARIOS AND ENGAGEMENT STRATEGIES

This chapter presents various possible threat scenarios for UAV swarms and possible engagement strategies to counter them. The primary findings are that UAV swarms are highly flexible and will attack in various formations using homogeneous or heterogeneous groups. The optimal LWS engagement strategy will be situational based on the amount of information the ship's sensors can gather.

This chapter is organized into three sections. The first section presents possible threat scenarios involving UAV swarms. The second section presents possible LWS engagement strategies to counter various threat scenarios. The final section summarizes the contents of the entire chapter.

A. THREAT SCENARIOS INVOLVING MARITIME UAV SWARMS

1. Homogeneous versus Heterogeneous

a. Homogeneous

The first and most basic swarm group would be the homogeneous swarm. This attack involves the use of many identical UAVs to overwhelm a target. These types of UAV systems will have basic sensor and communication capabilities. The primary benefit of this type of group is the simplicity and cost. Inexpensive systems such as Kamikaze or traditional bombers would make up the brunt of a force like this. Figure 22 shows a simplified example of a homogeneous attacking wave.

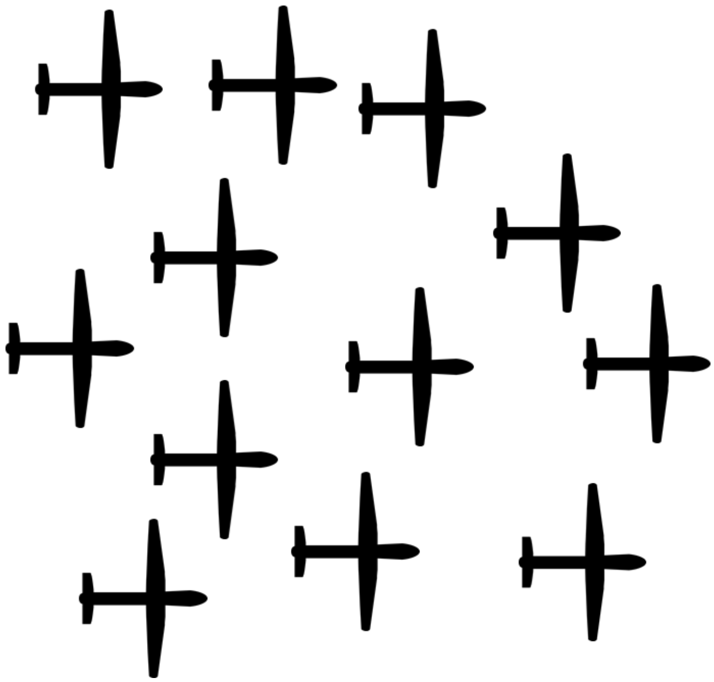


Figure 22. Group of identical UAVs in a homogenous swarm.

b. Heterogeneous

An alternative to this type of attack would be to utilize a heterogeneous swarm. Figure 23 shows various UAV systems in a swarm configuration. This group would consist of many types of UAVs with varying capabilities. The proper composition of these different units can produce an effect more significant than the sum of its parts. The following paragraphs provide some examples of various heterogeneous groups.

The swarm may offload the sensing of the target to a few highly capable systems that lack warheads but instead hold EO/IR sensor suites designed to find and identify the desired target. Only a few dedicated "sensing" UAVs would be required to produce a reliable target picture guiding those carrying the heavy explosive payloads.

There is no need for every single unit in the swarm to report back to the GCS individually. A small number of UAVs could be outfitted with the required antenna and radio transmission systems to report the status of the swarm across longer distances than would be achieved with a smaller system.

UAVs are generally lightly armored, and an LWS only needs to produce short dwell times to eliminate a target UAV. A unique unit to combat this would be a UAV with increased armor potentially made of more robust materials than the rest of the swarm that could be used as a "tank" to protect the other units.

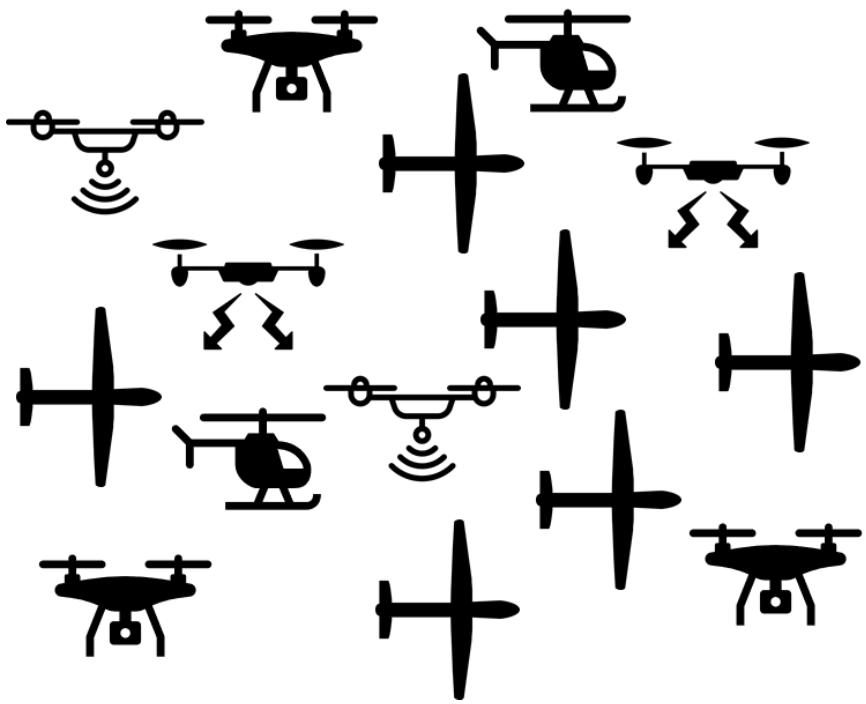


Figure 23. A group of various UAVs in a heterogeneous swarm.

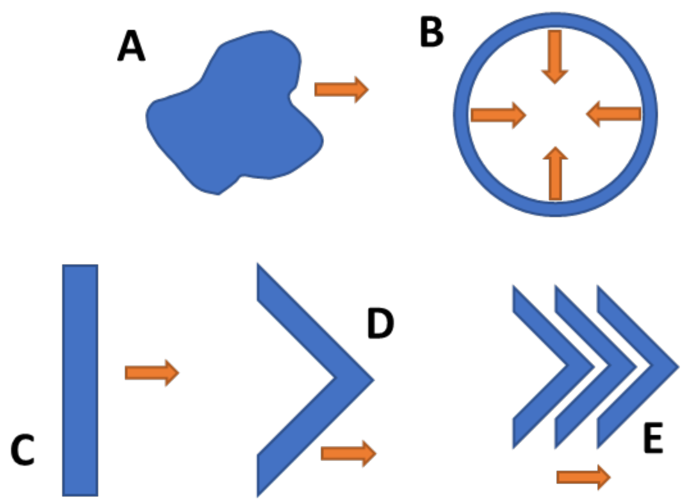
Units with jamming suites could deny valuable information about the attacking swarm. Overwhelming radars would serve to obfuscate the range or number of swarm units and significantly reduce the ability to track individuals or determine their type.

Controlling a swarm system can be complex and computationally intensive. Some groups solve this by passing all instructions through the GCS; however, this method can significantly delay new information and how quickly the swarm responds. The next generation of swarming will utilize machine learning or other forms of artificial intelligence. These methods require rapid ingestion, analysis, and synthesis of orders that would be significantly delayed by remote links. The response to this will be computation

UAVs carrying highly capable processing systems within the swarm. These systems would receive the instructions from the communication units and EO/IR information from the sensing units to analyze for and execute the best decisions for the swarm.

2. Attack Formations

The geometric configuration of swarm attacks significantly affects both homogeneous and heterogeneous groups. Figure 24 shows such examples of various attacking formations. The first and most basic attack involves no overarching shape of the attack. The benefit of this configuration is that it requires no sophisticated control of the individual units. The rest of the formations require the particular placement of each unit to create the tactical shape. The collapse formation is likely to be the most effective at overwhelming a target but requires the most coordination.



Note: (A) amorphous, (B) circle or "collapse," (C) line, (D) wedge, (E) wedge waves

Figure 24. Example of attack formations for UAV swarms.

3. Possible Heterogeneous Attack Scenarios

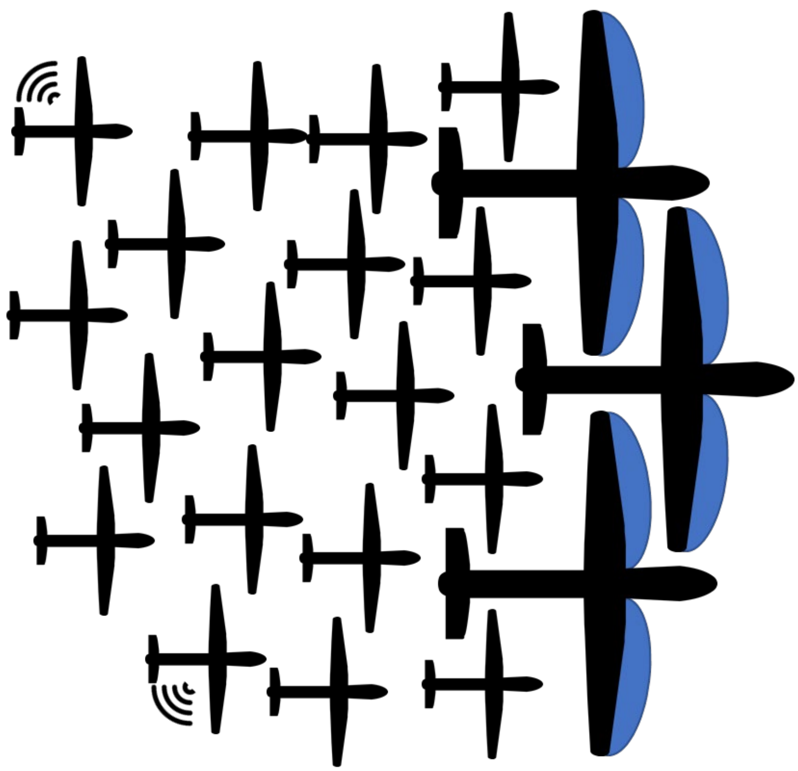
This section discusses various ways to use different UAVs in a swarm and develops potential homogeneous and heterogeneous swarm scenarios. There are many roles that unmanned systems may play; Table 4 lists various potential types of UAV systems and their uses. A heterogeneous swarm allows more possibilities than simply leveraging the best formation. The availability of different units allows the commander to tailor-fit each attack for a given situation.

Table 4. Example types of UAVs and potential uses.

Type	**Use**
Fighters	air-to-air combat and against other enemy UAV or aerial vehicles
Traditional Bomber	holds kinetic payloads that follow standard kinematic motion to a target
Kamikaze	holds a warhead onboard and will maneuver itself to close range before setting off a shaped or standard explosive
Jammers	electronic warfare UAVs that dampen the effect of enemy sensor systems
Communication	UAVs with a communication suite designed explicitly for long-range information exchange; acts as the commlink between the swarm and the GCS
EO/IR	UAVs with a sensor suite specifically designed to better identify and track potential targets
Computation	UAVs with computational suites that are specifically designed to utilize the other sensors of the swarm in tandem with high computation for more advanced control schemes or missions
Tanks/Decoys	UAVs designed with more or different materials shielding the sensitive systems producing a longer required dwell time

a. Armored Decoy

In this scenario, the swarm is protected by a group of armored decoys, as shown in Figure 25. These decoys can absorb significantly more damage than the other units due to different structural materials or plating. This configuration aims to take advantage of a simple LWS engagement strategy that prioritizes the closest targets. The payload carrying units will continue to close the distance to the target while the LWS system struggles to bring down the highly armored decoy units in the front.



Note: the blue portions of the large UAVs indicate increased armor.

Figure 25. Armored decoy threat scenario.

b. Rapid Threat Multiplication

The following scenario of attack involves the use of a mother ship shown in Figure 26. It starts with a group of more capable and expensive UAVs holding at the edge of a target's sensor or weapon range. This system would release a group of smaller kamikaze bombers flying near the sea surface. These small bombers would attempt to exploit any wavetop clutter that would usually be filtered out of a ship's detection systems and may go unnoticed if a majority of the system focus is on the mothership. When the smaller UAVs are eventually detected, this should cause a major shift in the contact picture due to the rapid increase in total incoming targets. Ideally, any confusion will buy more time for the smaller kamikaze bombers to close distance to the ship. Additionally, after a successful attack, the motherships can return to base to refit more kamikaze bombers.

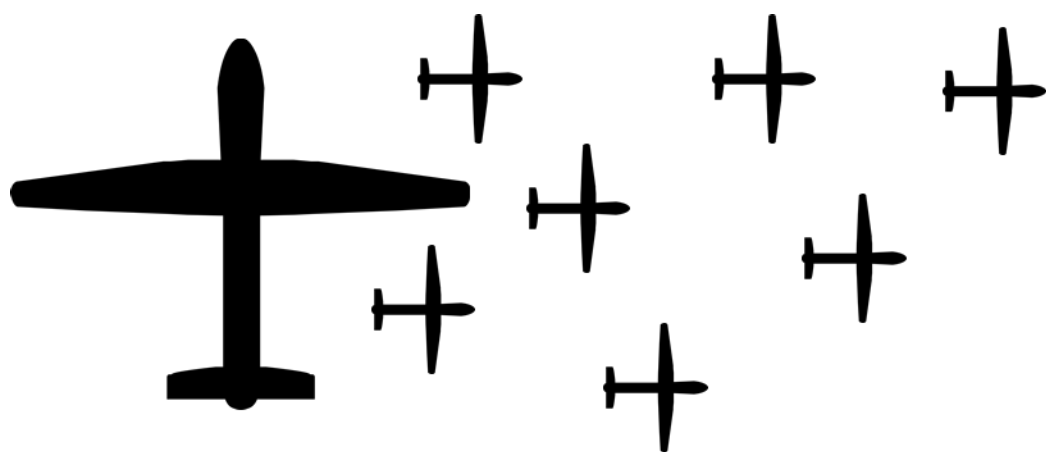


Figure 26. Mother-ship UAV producing additional smaller UAVs.

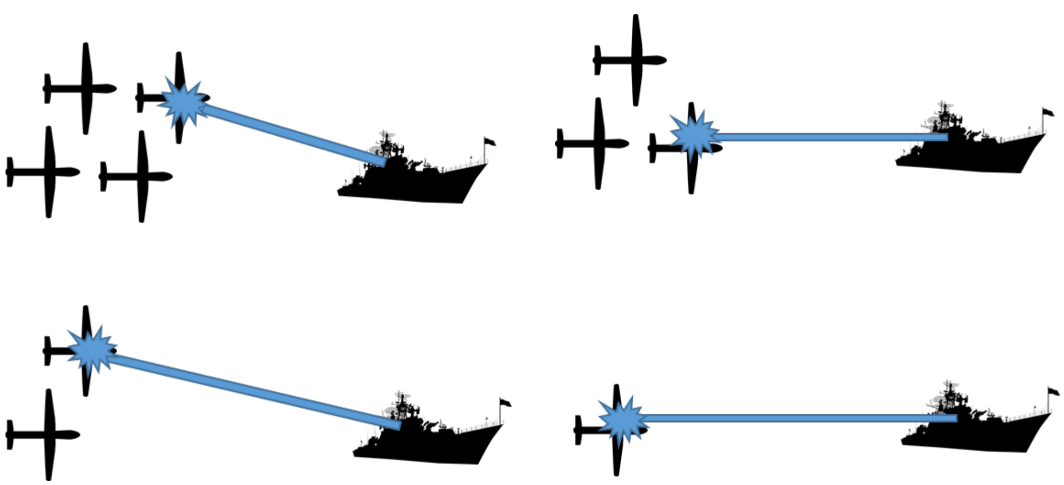
This heterogeneous group may be quite efficient because it allows the fielding of more advanced (and expensive) capabilities, like long-range communications to the strike force, without risking the loss of the system at the front of the attack. The mothership can safely stay back while bringing swarm warfare to the enemy.

B. LWS ENGAGEMENT STRATEGIES

The speed and number of targets in a swarm engagement require that the LWS use a Threat Evaluation and Weapon Assignment (TEWA) algorithm (Carr, forthcoming). The Navy is exploring the use of ADAs to greatly enhance the ability of our ships to defend against a swarm attack like this (B. Johnson 2021a). These systems will follow programmed TEWA algorithms to prioritize which targets to engage and which weapons to do so. The ability to choose the best algorithm for a swarm depends on the amount and quality of information the ship's sensor can obtain. This section proposes some engagement strategies to consider.

1. Prioritize Proximity

The first and most basic engagement strategy is the range-based approach, as shown in Figure 27. This engagement strategy measures the distances between the LWS and each UAV and then prioritizes the closest one. The primary benefit of this strategy is that it usually produces the greatest incidence on a target due to the beam traveling the shortest distance of all available targets. The shorter distance limits the amount of spread, turbulence, and thermal blooming that the beam will undergo. The downside to this strategy is that it can be exploited. Specific swarm attack formations and organization can trick this engagement strategy into firing at armored decoys instead of actual threats or oscillating between target groups in the same range.



Note: Figure is chronological, starting at the top from left to right.

Figure 27. Range-based engagement strategy.

2. Shortest Engagement

The simple targeting strategy that prioritizes closest targets could force significant slew times. If encountering a swarm that has significant angular displacement, oscillatory targeting will occur. When the LWS destroys the closest target, the next closest target is in another group requiring a significant change in weapon aimpoint and thus a long slew time. A targeting strategy that considers the current aim point of the LWS would significantly increase the ship's survival in most scenarios. The proposed algorithm calculates the expected engagement time for every known target and chooses the lowest time. The target selection system can estimate the slew time required to start firing given a target's angular position, range, radial velocity, transversal velocity, and knowledge of the weapon system's aim point and turn rate. The expected dwell time for a target can be estimated using the target's range along with laser propagation models or data sets like in Figure 37. Adding these two values together delivers a rough estimate of the total time required to complete the engagement. If this estimation is performed for all targets, the system can select the shortest estimated engagement time. Doing this for each change in target or even periodically while firing should result in the shortest overall scenario time, maximize the number of bombers killed, and increase the ship's survival. Figure 28 shows the "shortest engagement" strategy where Group 1 is engaged and destroyed before moving to Group 2.

$$Total\ Time = Slew\ Time + Estimated\ Dwell\ Time$$

$$Ideal\ Target = MIN(Total\ Time)$$

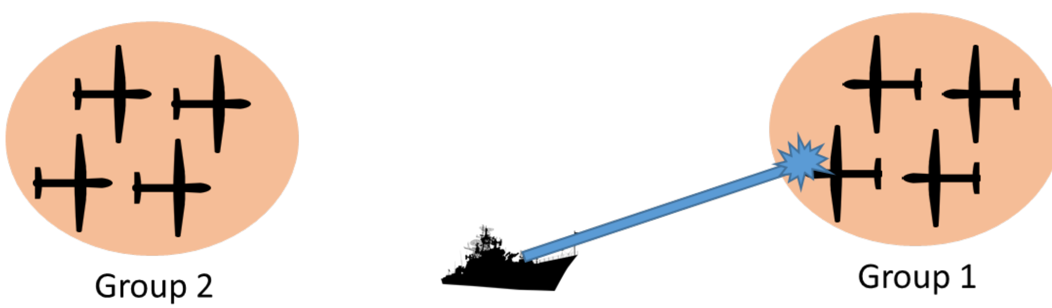
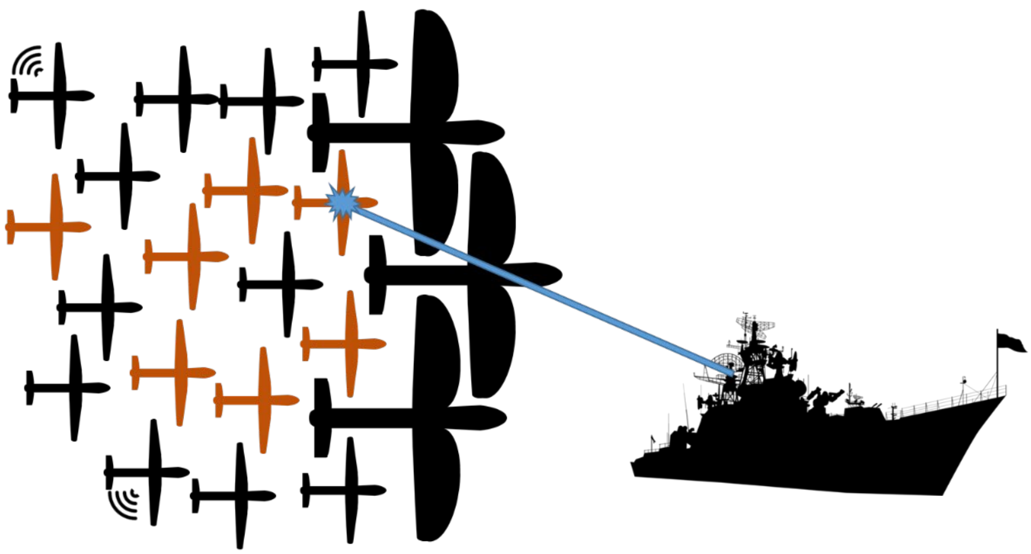


Figure 28. Shortest engagement strategy.

3. Take Out the Shooter

This engagement strategy requires more information than the simple range-based one. When faced with a heterogeneous swarm, this strategy prioritizes eliminating the greatest threat to the ship, the warheads. The greatest benefit of this strategy is that all emitted power is used to kill the genuine threat to the ship. Given the correct information, this strategy will readily defeat the armored decoy scenario shown in Figure 29. The downside to this engagement strategy is the degree of information that is required. The LWS targeting system must identify which UAVs are carrying the correct payloads. Any metrics that might be used to identify genuine threats, such as radar cross-section or imagery, can become unreliable with an enemy modification.

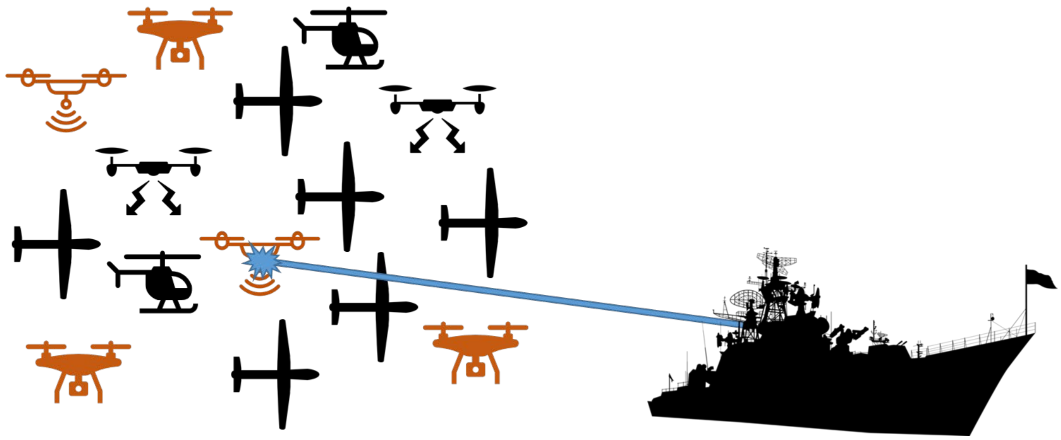


Note: the orange color indicates “shooters” in the hostile swarm.

Figure 29. Take out the shooter engagement strategy.

4. Focus on Information Nodes

This engagement strategy is similar to the last but may be easier to execute. This engagement strategy takes advantage of the lower expected number of UAVs in a heterogeneous swarm with the task of gathering, passing, and processing information. The primary targets would include the EO/IR, communications, and processing units in the swarm. This engagement strategy seeks to damage the enemy swarm’s information flow and disrupt communication by eliminating information nodes. Figure 30 shows an example of this attack. The primary benefit of this strategy is that the total number of targets is only a small subsection of the whole swarm. The information nodes in a heterogeneous swarm would be designed to be as few as possible, maximizing the warhead units. The major downside to this strategy is that the true threat to the ship is not dealt with. There exists a chance that backup systems, such as individual sensors and controllers, could take over and continue the attack.

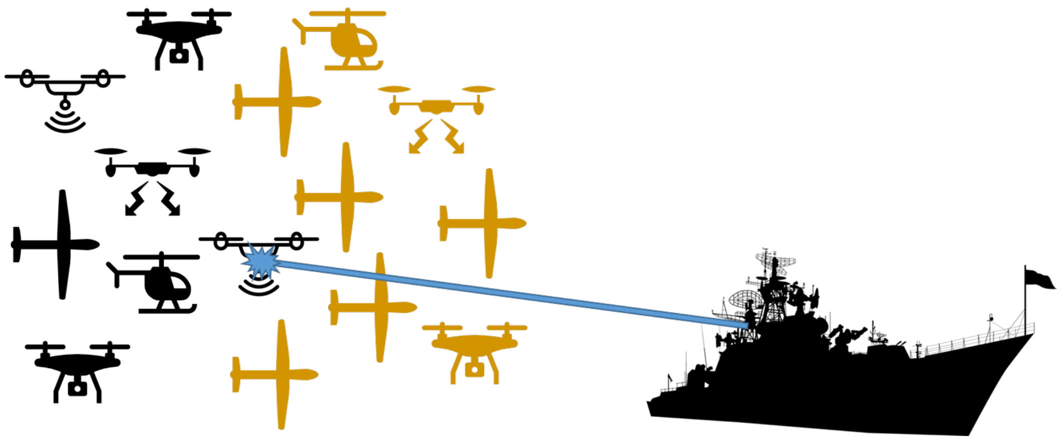


Note: the orange color indicates information nodes in the hostile swarm.

Figure 30. Take out the shooter engagement strategy.

5. Maximize Soft Kill

This engagement strategy leverages the LWS's unique ability to vary energy delivery for soft kills. The system dwells on each target long enough to damage the sensors and then moves to the next target resulting in a much shorter engagement time. The primary benefit of this strategy is that the amount of energy required to cause a soft kill is significantly less for each target. The smaller energy requirements translate to much shorter dwell times, allowing the system to affect a more significant portion of the swarm in the same time it would take to produce hard kills. The downside to this strategy is that the dwell time required is an estimate, may not cause an immediate effect on the target, and the damaged sensors have a possibility of recovery. Figure 31 shows an example of this strategy.



Note: yellow indicates a soft “sensor” kill.

Figure 31. Soft kill engagement strategy sweep.

C. SUMMARY

This chapter presents various possible threat scenarios for UAV swarms and possible engagement strategies to counter them. UAV swarms may consist of either homogeneous or heterogeneous groups. A homogeneous group is simple to acquire and configure and is a cost-efficient method of fielding a swarm. A heterogeneous group can afford more capability to a swarm while increasing the complexity. The attack formation of a swarm is another tactical choice the operators must think about. For a heterogeneous group, there are many roles that a UAV can perform in a swarm; from fighters and bombers to EO/IR scouts and communication units, the composition of these types of swarms can vary greatly. The methods and strategies that an LWS uses will be highly dependent on the information the system has. The simplest to employ is the proximity-based method, where range is the only input. The “shortest engagement” algorithm provides a model that considers LWS slew time as well. If the incoming threat is a heterogeneous swarm, the LWS can employ more sophisticated strategies that prioritize various functions of the swarm. The next chapter will model some of the scenarios and engagement methods described and analyze the results.

V. MODELING AND SIMULATION ANALYSIS

This chapter presents the results of modeling a small number of threat scenarios and engagement strategies. The primary findings are that swarm formations maximizing the angular displacement between units will generally perform better than closely clumped groups. In the case of heterogeneous swarms, thoughtful unit configuration and LWS engagement strategy significantly affect the attack's success.

This chapter is organized into four sections. The first section contains an overview of the Swarm Commander Tactics (SCT) software. The second section describes the scenarios and engagement methods that were chosen for modeling. The third section presents an analysis of the results from the SCT simulation. The final section summarizes the contents of the entire chapter.

This thesis used simulation and modeling to gather information on the performance of some of the theorized threat scenarios from Chapter IV. The simulations analyzed the change in ship survivability via altering the variables of swarm size, geometric configuration, and composition. The SCT program can simulate kinetic weapons in tandem with directed-energy weapons, however, this thesis is an analysis of directed-energy weapons only.

A. MOVES SWARM COMMANDER TACTICS OVERVIEW

The SCT program from the NPS MOVES Institute was developed to explore and simulate swarm warfare environments. This program started as a way for students to visualize and control groups of UAVs (E. Johnson 2021a). The project then shifted gears to help students understand swarms, develop combat strategies, and put them to the test against a scenario or other students (E. Johnson 2021a). The program has continued to progress and can now simulate various sea, land, air, and space vehicles (Johnson 2021c). The simulation can utilize both directed energy and kinetic weapon systems (Johnson 2021d).

The SCT software allows the user to configure various aspects of how the scenario will play out. The scenario editor shown in Figure 32 allows the user to add units to the map, configure their location, speed, formation, and orientation. This screen was used to establish the enemy swarm numbers, distance from the target, and geometric configurations for analysis.

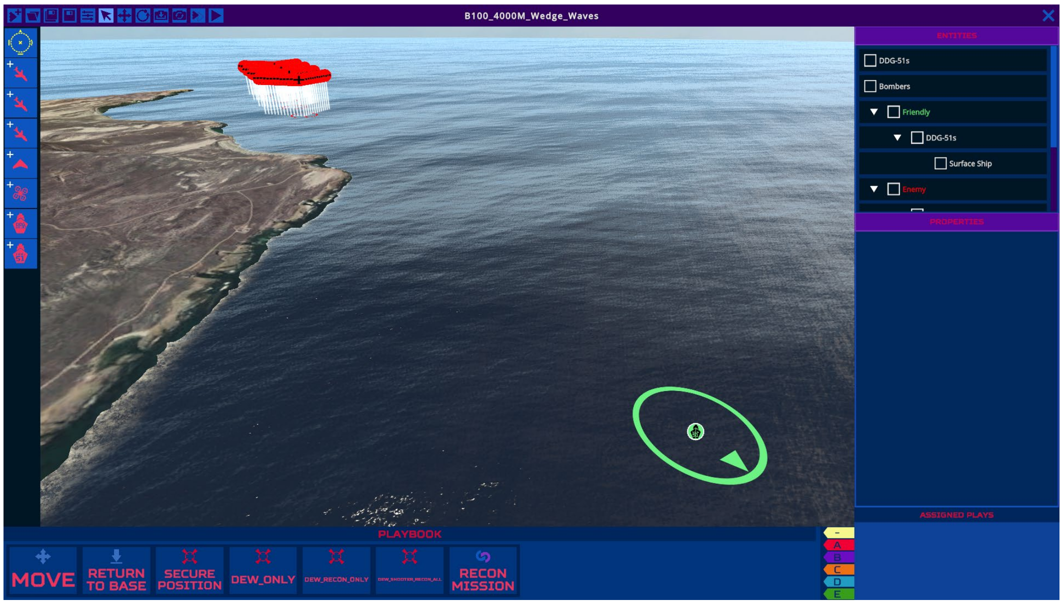


Figure 32. SCT scenario editor screen. Source: MOVES (2021).

The SCT play editor allows the user to develop specialized tactics. The program uses a visual programming approach with arrows to display the flow of logic for a designed "play." Figure 33 shows a simple play for the surface vessel that moves the ship to a specific location while also sensing fighter, bomber, or recon vehicles. The arrow leaving the "Enemies Detected" box and going to the "attack" box indicates that once one of the targets is detected, the play will pass that target to the weapon system.

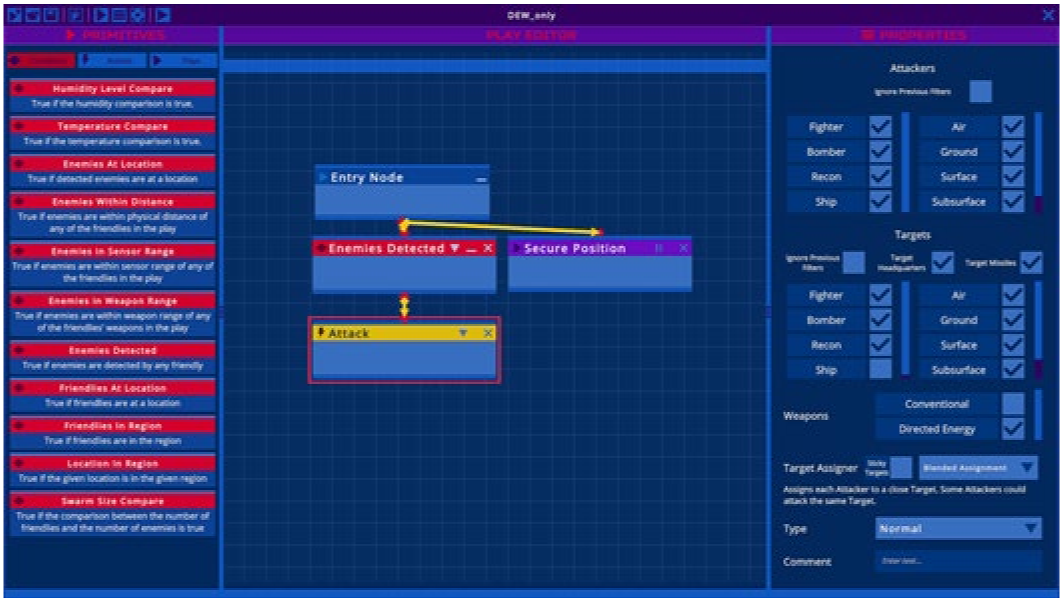


Figure 33. SCT play editor screen for directed energy only. Source: MOVES (2021).

1. Atmospheric Effects

The program can simulate the atmospheric effects utilizing software created by the NPS Physics Department (E. Johnson 2021b). This software utilizes the Atmospheric NPS Code for High Energy Laser Optical Propagation (ANCHOR) atmospheric scaling code to provide rapid estimations of laser performance (E. Johnson 2021b). It does this by using scaling formulas instead of full diffraction codes, allowing the performance calculations to be many orders of magnitudes faster (E. Johnson 2021b). The simulation uses a 9-hour atmospheric data set collected on San Nicholas Island (Carr, forthcoming).

2. Swarm Commander Models

The SCT software can model a range of land, sea, air, and space units. This thesis only analyzed engagement between a swarm of air vehicles and a single surface ship. The models used were bombers (Figure 34), fighters (Figure 35), and a surface ship (Figure 36). The program models each unit with independent hit points. When they reach zero, the unit is considered destroyed.

The fictional bomber unit is a typical bomber shown in Figure 34. It moves towards a target and releases a ballistic bomb causing damage. This thesis used the bomber as the primary swarm threat to the ship. The fighter unit shown in Figure 35 was introduced to fight other aerial vehicles. This thesis used the fighter unit as a decoy to create the "armored decoy" scenario. Finally, the surface ship shown in Figure 36 is the defending platform in all scenarios. This unit has two types of weapon systems onboard; however, this thesis disabled the kinetic system to analyze scenarios using only the LWS. Table 5 holds all relevant data for each of the three units used in this thesis.

Table 5. Summarized unit capabilities. Adapted from Johnson (2021c).

Unit	Weapon	Sensor	Speed (m/s)
Bomber	Ballistic Bomb • Damage: 1 "unit" • Blast Radius: 100 m • Cool Down: 5 sec	Range: 750 m Detectability: 10 m	80
Fighter	Mk1 Laser (NOT USED)	Range: 600 m Detectability: 10 m	100
Ship (DDG-51)	LWS (Characteristics in Table 6) Mk1 Kinetic Weapon (NOT USED)	Range: 5000 m Detectability: 10 m	73

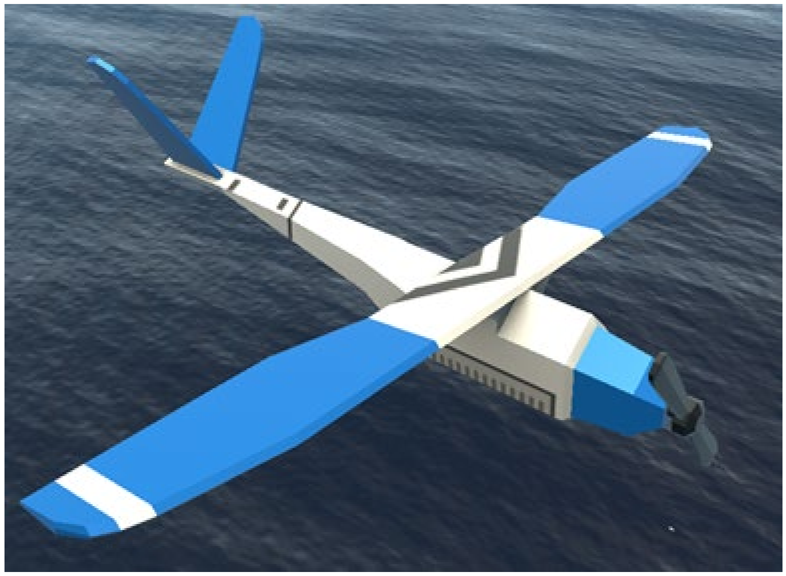


Figure 34. Bomber unit, the threat to the ship. Source: Johnson (2021c).

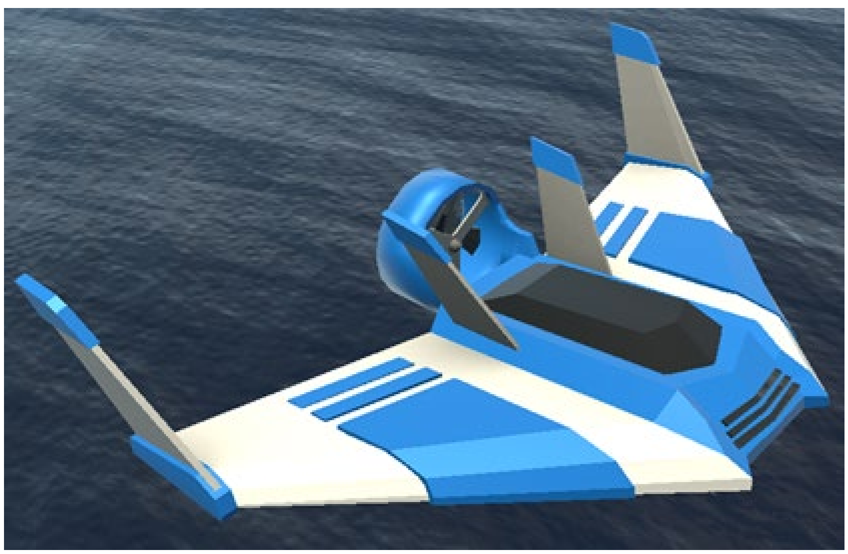


Figure 35. Fighter unit used to simulate "armored decoy." Source: Johnson (2021c).

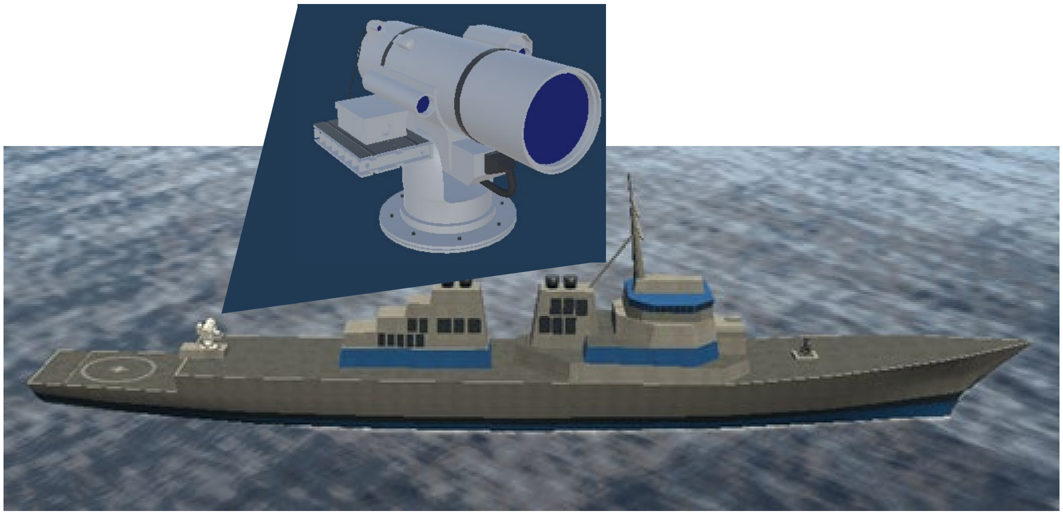
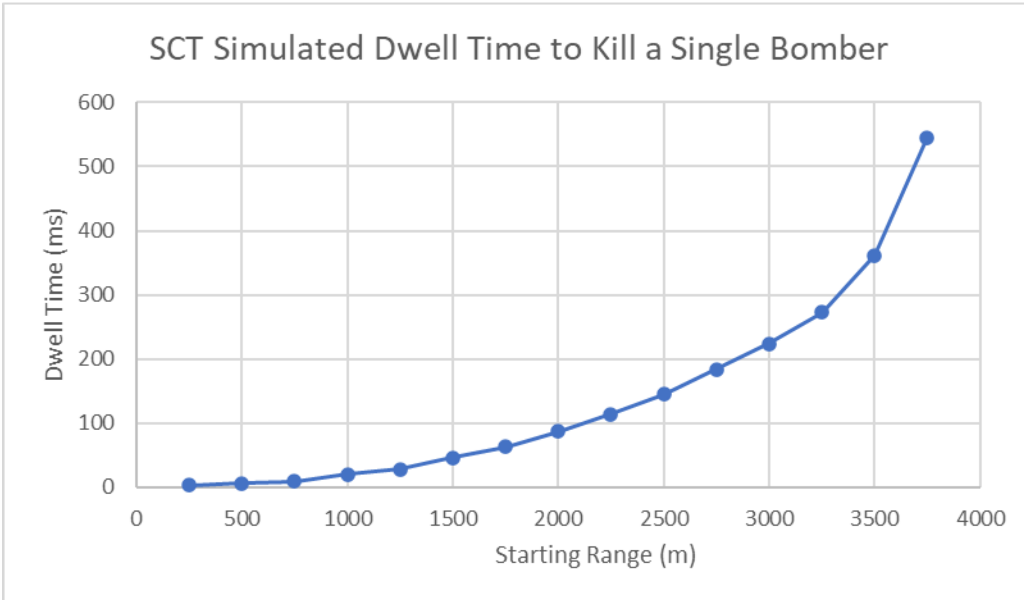


Figure 36. Surface vessel with LWS mounted aft. Adapted from Johnson (2021c; 2021d).

In this thesis, the LWS mounted on the ship (Figure 36) is the vessel's only defense against the incoming bombers. The weapon system engages targets by prioritizing proximity first (Johnson 2021e). User-created scenario "plays" can alter the targeting logic to prioritize specific units over others. Table 6 holds the key characteristics of the LWS that defends the ship. As the range to a target increases, the dwell time needed to destroy the target also increases. Figure 37 shows simulated SCT dwell time data for different ranges and the exponential relationship between dwell time and range. All simulated scenarios in this thesis start engagements with the lead UAV at four kilometers.

Table 6. LWS characteristics. Adapted from Johnson (2021c).

Characteristic	Value
Power	100 kW
Wavelength	1.0642e-06 m
Beam director diameter	0.3 m
Energy capacity	300 "units"
Energy usage	1 "unit" per second
Yaw Rate	90 degree/second
Pitch Rate	45 degree/second
Yaw Limit	N/A
Elevation limit	-10/+89 degrees



Note: Outlying data that occurs past 3500 m has been removed for clarity.

Figure 37. LWS time to kill a single bomber at varying ranges. Source: MOVES (2021).

3. Simulation Limitations

No simulation is perfect at emulating real-world conditions, and the SCT software is no exception to this. This program is a great tool to simulate the atmospheric performance of directed-energy weapons; however, the user cannot yet alter the simulation's atmospheric conditions, UAV target points, or materials of the drones. Altering the types of structural or plating material for each unit can significantly alter the effectiveness of the LWS.

As of the current developer build, each platform has its own sensor detection range and detectability, but the program provides no way to alter these values. Future iterations may introduce jamming mechanics, significantly changing the properties of the sensors. This would introduce new potential attack patterns.

This program simulates a perfect engagement. The defending vessel knows the exact position of all units; therefore, the time between a target being in the sensor range and the LWS firing is synthetic. At the beginning of a real-world engagement, the ship would move through the sense, track, identify, and engage cycle. Figure 38 shows the typical order in which an engagement would take place. The beginning portion of this sequence is entirely skipped. The simulated time between LWS engagements depends on the turret yaw and pitch rate and requires no time to track an incoming target finely. The weapon system benefits from perfect battle damage assessment as well. As soon as an incoming UAV is destroyed, the LWS immediately moves to the next target. In a real-world situation, there is some time between when the directed energy "kills" the target and when the sensors detect a significant change in the target's trajectory (falling); this time is shown as "kill assessment" in Figure 38.

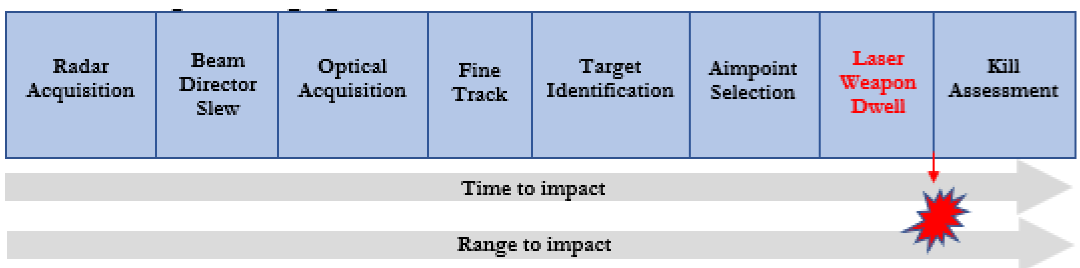


Figure 38. The typical weapon engagement order. Adapted from B. Johnson (2021b, 9).

The final simulation limitation is somewhat minimal. There is no collision detection between units, which allows multiple units to occupy the same space. In a real-world situation, there is the opportunity to cause collateral kills in a dense swarm when "downed" UAVs collide with adjacent units. The current state of the simulation does not account for this. Again, this is a very minimal note as the work required to implement a feature like this may outweigh the potential benefit.

B. MODELING AND SIMULATION DESCRIPTION

Using the SCT software, this thesis modeled and analyzed engagements in two different areas:

1. The effects of scenario success as a function of attacking UAV formation.
2. The significance of targeting strategy vs. heterogeneous swarms.

The first section sheds light on the impact of attack formations on the success rate of a swarm attack. The second section poses a heterogeneous scenario and investigates how a change to the targeting strategy alters the survival rate of the ship.

1. Swarm Formations

This thesis analyzed engagements with the following formations: dot, line, wedge, and waved wedges. Table 7 is a list of all scenarios used for this section. The images in Figure 39, Figure 40, and Figure 41 correspond to the geometric formations used by swarm sizes of 50, 100, and 200, respectfully. Each scenario placed the attacking swarm 4000 meters away from the defending ship. The dot formation (A in Figure 39, Figure 40, and Figure 41) is not physically possible. However, it eliminates the need for the LWS to change yaw or pitch between targets and serves as a best-case scenario (albeit unrealistic) for the defending ship. The line formation (B in Figure 39, Figure 40, and Figure 41) produces a simple geometry for the attacking swarm. The wedge (C in Figure 39, Figure 40, and Figure 41) is a traditional attack formation used to break defense lines. The waved wedge formation (D in Figure 39, Figure 40, and Figure 41) is an alteration of the wedge that condenses the group to four waves. The line, wedge, and waved wedge formations all used a spacing of 25 meters between bombers. The dot formation used no distance (atop on another).

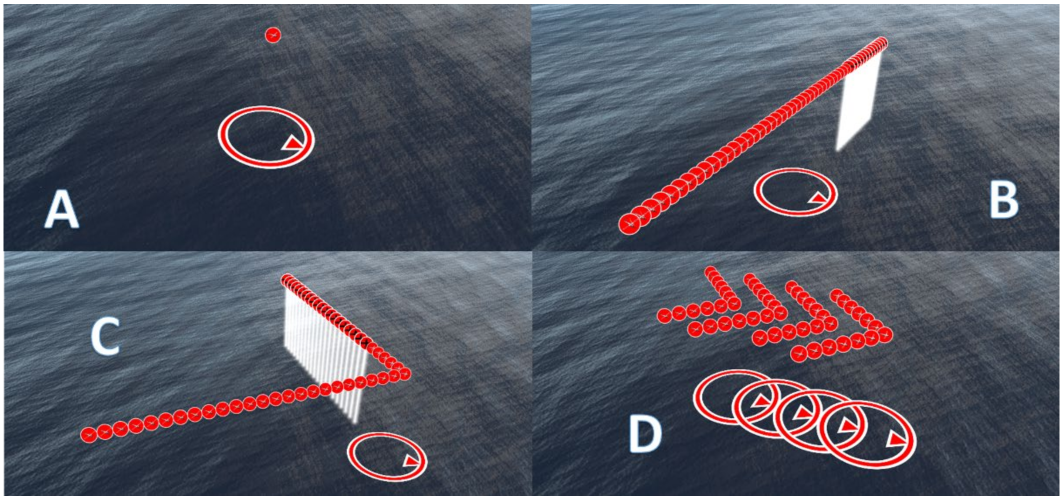
All bombers were given the command to "secure position" at the defending ship's location. The "secure position" command directs the drone to a given location while sensing for targets and engaging once a target is detected. The ship was given the command to "defend" using the LWS only. This command simply directs the ship to attack all units within its range. The initial velocities for the swarming bombers were 75 meters per second, and the ship stayed 0 meters per second the entire simulation. Table 8 is a summary of all relevant initial conditions.

Table 7. Swarm formation scenarios.

Scenario #	Bombers	Formation
1	50	Dot
2		Line
3		Wedge
4		Waved Wedge
5	100	Dot
6		Line
7		Wedge
8		Waved Wedge
9	200	Dot
10		Line
11		Wedge
12		Waved Wedge

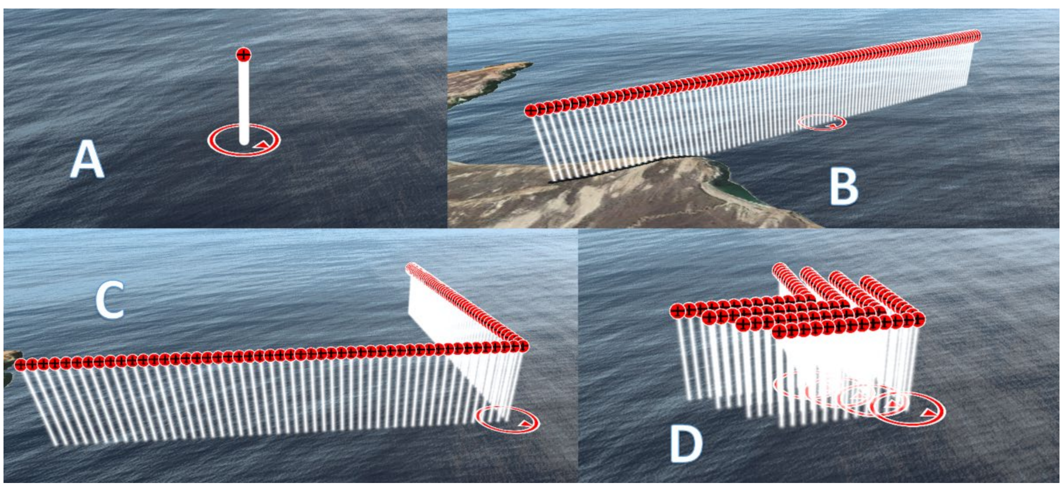
Table 8. Properties for each unit in the swarm formation scenarios. Source: MOVES (2021).

Formation	Circle	Dot	Line	Wedge	Waved Wedge
Ship Initial Speed (m/s)	0				
Bomber Initial Speed (m/s)	75				
Bomber Spacing (m)	Variable	0	25		



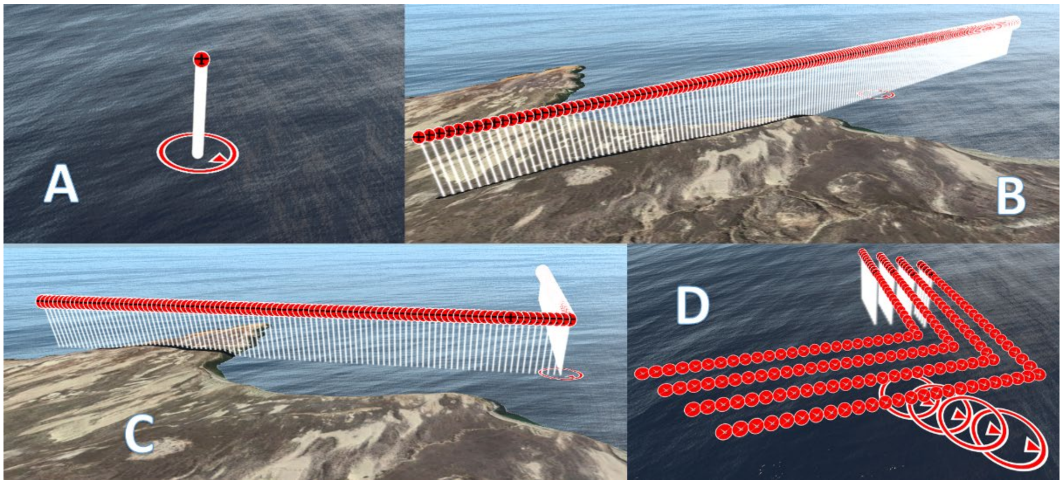
Note: (A) Dot, (B) Line, (C) Wedge, (D) Waved Wedge

Figure 39. Formations used for the runs of 50 bombers. Source: MOVES (2021).



Note: (A) Dot, (B) Line, (C) Wedge, (D) Waved Wedge

Figure 40. Formations used for the 100 bomber runs. Source: MOVES (2021).



Note: (A) Dot, (B) Line, (C) Wedge, (D) Waved Wedge

Figure 41. Formations used for the 200 bomber runs. Source: MOVES (2021).

2. Armored Decoy Scenario and Engagement Strategy

This thesis used the armored decoy scenario to analyze the effectiveness of heterogeneous swarms and targeting strategies to counter them. These configurations are alterations of the waved wedge group of 50, 100, and 200 bombers. Table 9 lists the scenarios and describes the formation used, number of bombers, number of decoys, and targeting strategy used for each one. The leading edges of the waved wedges have been swapped out for decoys (fighters) with three times the health. To simulate the increase in health, each “decoy” is emulated by three identical fighters in the exact location. For example, the first scenario in Figure 42 (A) has replaced the leading edge of 13 bombers with 13 “decoys” consisting of 39 fighters. While imperfect, since the directives for the fighters are all identical, and there is no collision in this simulation, these groups of three fighters effectively act as one unit. The effective total number of units for each scenario remains unchanged. Instead, the mission and capabilities of the swarm change: a quarter of the attacking force is replaced with robust decoy drones that cannot harm the ship.

The default targeting strategy for the scenarios has been to fire at the closest target up to this point. The SCT software allows the user to create custom plays. The ship utilized a “take out the shooter” engagement strategy described in Section IV.B.2 to combat this new heterogeneous composition by ignoring the armored decoys and prioritizing the elimination bombers first. Scenarios 14, 16, and 18 use this engagement strategy against the swarm.

For the initial conditions, the only new information concerns the decoys. They have a higher starting speed. The decoys are more closely spaced to exploit the proximity-based targeting of the ship. Table 10 is a summary of all the relevant scenario conditions.

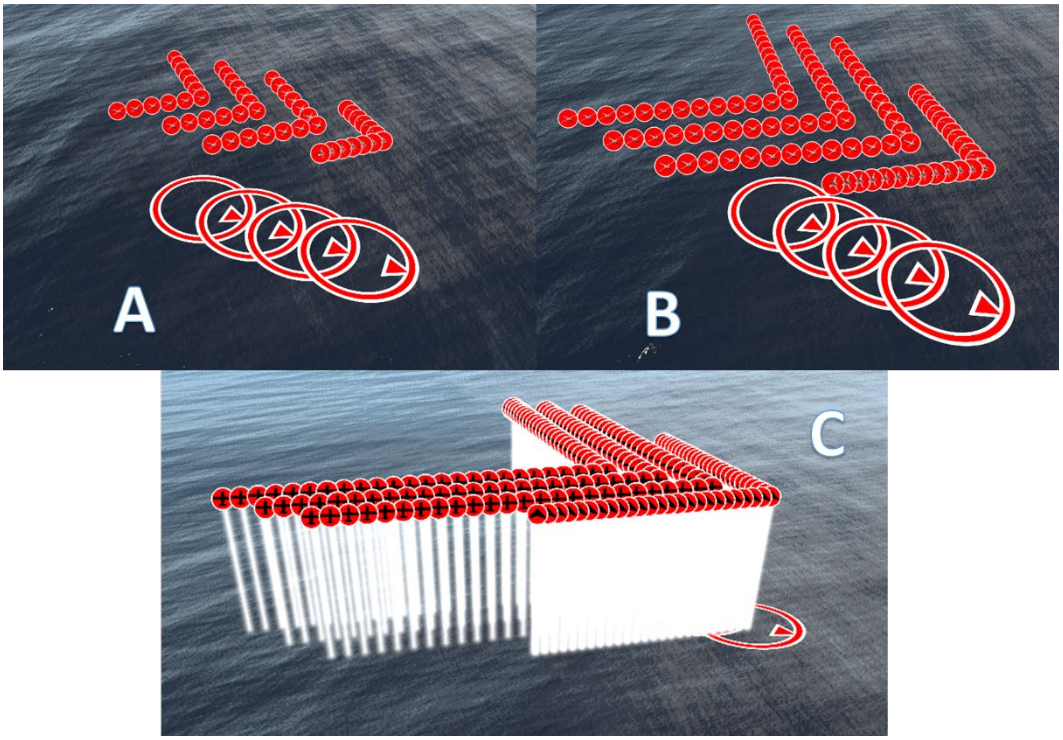
Table 9. Armored decoy and engagement strategy scenarios.

Scenario	4*	13	14	8*	15	16	12*	17	18
Formation Used	Waved Wedge								
Bombers	50	37		100	75		200	150	
Decoys	0	13		0	25		0	50	
Targeting Logic	Proximity		Shooter Only	Proximity		Shooter Only	Proximity		Shooter Only

*Scenarios 4, 8, and 12 are repeated from the earlier section.

Table 10. Properties for each unit in the armored decoy scenarios. Source: MOVES (2021).

Formation	Waved Wedge
Ship Initial Speed (m/s)	0
Bomber Initial Speed (m/s)	75
Bomber Spacing (m)	25
Decoy Initial Sped (m/s)	90
Decoy Spacing (m)	15



Note: (A) 37 Bombers, 13 Decoys, (B) 75 Bombers, 25 Decoys, (C) 150 Bombers, 50 Decoys. Decoys are staged with a smaller spacing to exploit proximity-based targeting.

Figure 42. Armored decoy configurations. Source: MOVES (2021).

C. ANALYSIS RESULTS

1. The Formations of Swarm

Table 11 shows the extrapolated summary values for all scenarios, and Table 12 shows the average values for each group. Figure 43, Figure 44, Figure 45, and Figure 46 all show time-range diagrams for the 100 bomber formation scenarios.

Table 11. Results from altering the formation of the same swarm size.

Scenario #	Bombers	Formation	RNG Min (m)	End Time (s)	Average Slew Time (ms)	Average Dwell Time (ms)	Ship Killed	Total Bombers	Bombers Left	Percentage Bombers Defeated
1	50	Dot	2295.5	22.6	161.9	290.8	0	50	0	100%
2		Line	1829.7	28.8	389.3	187.1	0	50	0	100%
3		Wedge	2247.4	31.4	401.4	226.1	0	50	0	100%
4		Waved Wedge	2392.0	27.4	315.8	233.2	0	50	0	100%
5	100	Dot	1849.3	28.0	84.7	195.7	0	100	0	100%
6		Line	23.7	53.9	457.4	116.6	1	100	9	91.0%
7		Wedge	1184.2	54.2	399.0	142.6	0	100	0	100%
8		Waved Wedge	1658.1	40.5	260.1	144.6	0	100	0	100%
9	200	Dot	1200.9	37.4	59.3	127.8	0	200	0	100%
10		Line	25.9	54.0	546.3	137.4	1	200	121	39.5%
11		Wedge	175.3	70.2	508.2	127.7	1	200	90	55.0%
12		Waved Wedge	30.4	59.2	345.5	113.9	1	200	75	62.5%

Table 12. Averages results grouped by the number of bombers and formations used.

Average Results	RNG Min (m)	End Time (s)	Average Slew Time (ms)	Average Dwell Time (ms)	Ship Killed	Bombers Left	Percentage Bombers Defeated
Bomber Numbers*							
50 Bombers	2156.4	29.2	368.8	215.4	0%	0.0	100.0%
100 Bombers	955.3	49.5	372.2	134.6	33%	3.0	97.0%
200 Bombers	77.2	61.1	466.6	126.3	100%	95.3	52.3%
Formations							
Dot	1781.9	29.4	101.9	204.7	0%	0.0	100.0%
Line	626.4	45.6	464.3	147.0	67%	43.3	76.8%
Wedge	1202.3	51.9	436.2	165.4	33%	30.0	85.0%
Waved Wedge	1360.2	42.4	307.1	163.9	33%	25.0	87.5%

*Averaged results do not include data from the dot formation since it is an impossible ideal.

a. Swarm Size

The data shown in Table 12 gives some cursory results around the chances of success regarding swarm size. The calculated averages for the number of bombers do not include data from the dot formation as this is an impossible ideal for comparison only. As the number of bombers increases, the ship's chance of being killed will also increase. The data supports this assumption as the ship survives all scenarios with 50 bombers, survives two of three with 100 bombers, and survives none with 200 bombers. The average percentage of bombers defeated for each scenario decreases from 100% at 50 bombers, to 97% at 100 bombers, and finally to 52.3% at 200 bombers. The average minimum range decreases from 2156 meters with 50 bombers, to 955 meters with 100 bombers, and 77 meters (atop the ship) in all the 200 sized swarms. The average dwell times decrease as the size of the swarm increases; this is likely due to the reduction of range throughout the scenario run and decreased range reduces the required dwell time, as shown in Figure 37. The average slew time increases with swarm size likely because as the swarm closes the distance with the defending ship, the angular displacement (with relation to the ship) between each unit increases. There is more discussion about angular displacement in the following section. Overall, it is evident that as swarm size increases, the probability of a defending force succeeding decreases.

b. Angular Displacement (Formations)

The formation of the incoming swarm played a significant role in determining ship survival. The performance of the impossible dot formation indicates the best-case scenario. As previously noted, this formation is intended to eliminate the time required to aim the LWS. However, from Table 11, a short slew time still exists, albeit a lower order of magnitude in the 100 and 200 bomber scenarios. The data indicates that slew time is a primary factor in determining the survival of the ship. For the 200-bomber scenarios, the line, wedge, and waved wedge formations had significant changes in bombers defeated. In the 100-bomber scenario, the line formation was the only one to score a ship kill. Figure 39 shows that the line formation created the most significant angular displacement in relation to the ship, followed by the wedge and then waved wedge formations. When using a purely proximity-based engagement, this displacement causes oscillatory targeting between alternating closest targets.

c. *Time-Range Diagrams*

Figure 43, Figure 44, Figure 45, and Figure 46 are all graphics to illustrate engagement timelines. They display data from four runs, 100 bombers each, using four different starting formations shown in Figure 40. The x-axis indicates the range between the attacking units (entities) and the ship. The y-axis displays the simulation run time. The end of each line either indicates when the target was destroyed or when the simulation ended.

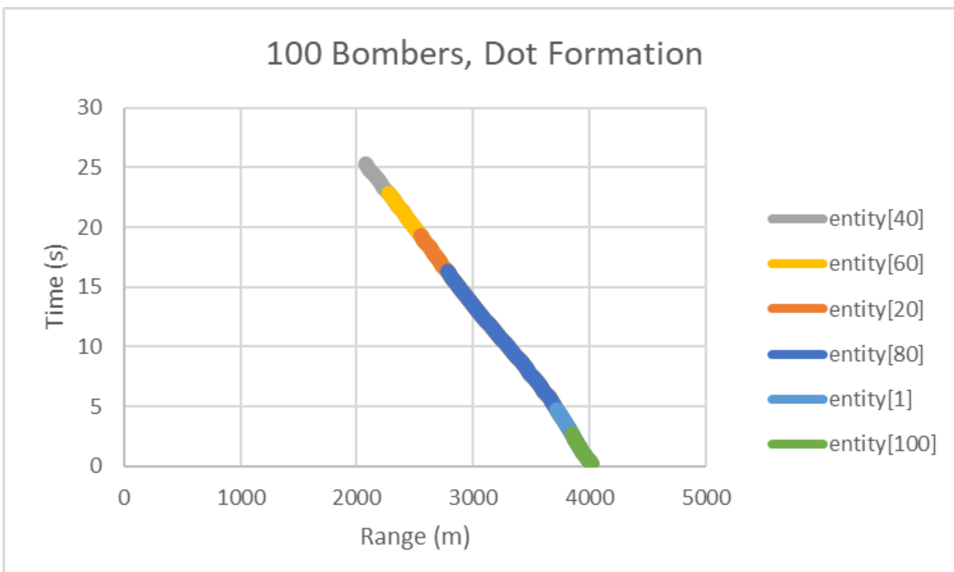
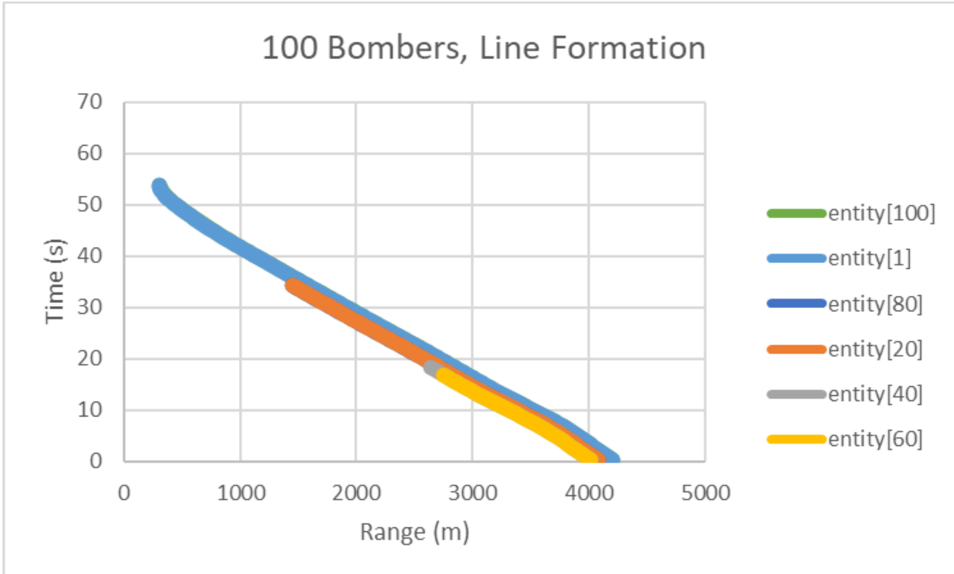


Figure 43. Time range diagram, subset of 100 bombers in a condensed dot formation. The ship survives.



Note: Time and ranges for entity [100] are almost identical to entity [1].

Figure 44. Time range diagram, subset of 100 bombers in a line formation. The ship is killed.

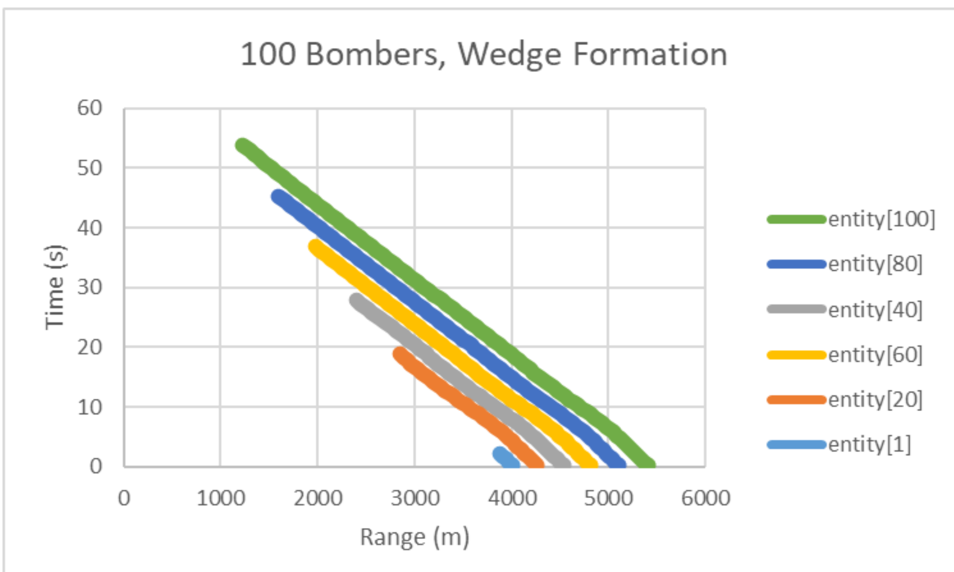


Figure 45. Time range diagram, subset of 100 bombers in a wedge formation. The ship survives.

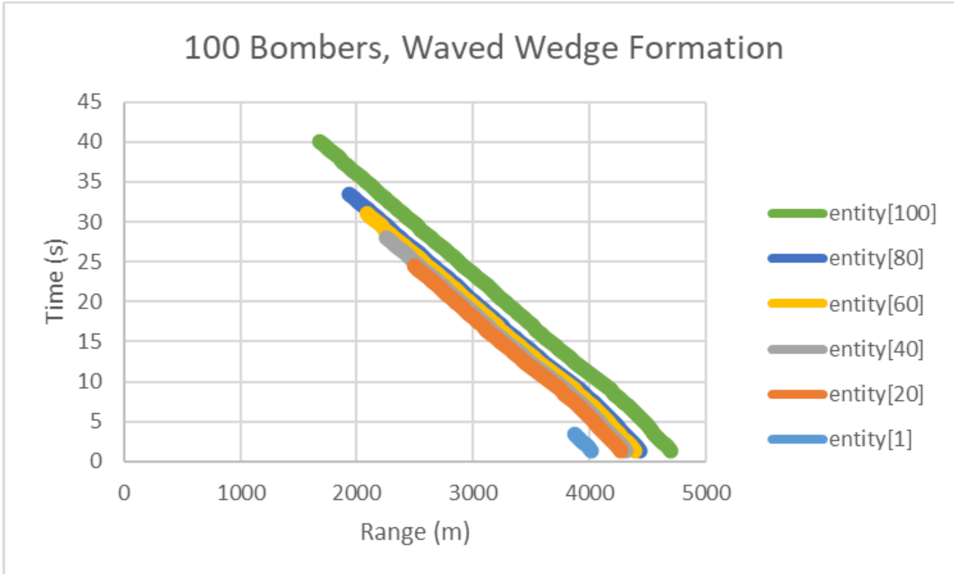


Figure 46. Time range diagram, subset of 100 bombers in a waved wedge formation. The ship survives.

2. Armored Decoy Scenario versus Changing Targeting Strategy

Table 13 shows the extrapolated summary values for the armored decoy scenarios. Table 14 gives the percent change of each parameter as the scenario is altered. All six of the 50- and 100-unit scenarios result in the ship's survival, while all three of the 200-unit scenarios result in a destroyed ship. Figure 47 shows a screenshot captured at the beginning of the 200-bomber simulation.

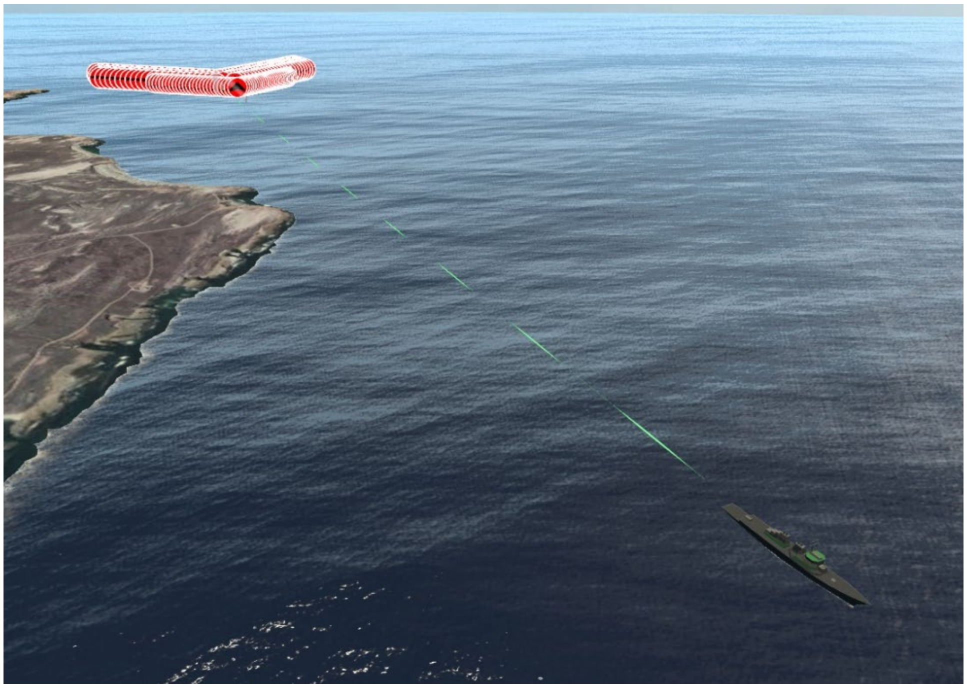


Figure 47. The beginning of the armored decoy scenario with 150 bombers and 50 armored decoys. Source: MOVES (2021).

Table 13. Results from the addition of armored decoys and the change in targeting strategy.

*Scenarios 4, 8, and 12 are repeated from the earlier section.

Scenario	4*	13	14	8*	15	16	12*	17	18
Formation Used	Waved Wedge								
Bombers	50	37		100	75		200	150	
Decoys	0	13		0	25		0	50	
Targeting Logic	Proximity		Shooter Only	Proximity		Shooter Only	Proximity		Shooter Only
RNG Min (m)	2392.0	2257.5	2581.6	1658.1	1293.8	1815.9	30.4	31.1	59.0
End Time (s)	27.4	29.3	25.3	40.5	43.9	37.6	59.2	57.3	64.3
Average Slew Time (ms)	315.8	235.3	412.4	260.1	244.1	317.6	345.5	684.4	359.9
Average Dwell Time (ms)	233.2	350.5	272.1	144.6	195.0	183.5	113.9	351.2	131.5
Ship Killed	0	0	0	0	0	0	1	1	1
Total Bombers	50	37	37	100	75	75	200	150	150
Total Decoys	0	13	13	0	25	25	0	50	50
Bombers Left	0	0	0	0	0	0	75	146	22
Decoys Lefts	0	0	13	0	0	25	0	0	50
Percentage Bombers Defeated	100%	100%	100%	100%	100%	100%	62.5%	2.7%	85.3%

Table 14. Summarized effects from changing scenario. Source: MOVES (2021).

	Change from Baseline when Decoys Added	Change from Decoys when Engagement Logic Shifted
Cases Where Ship is Survives		
50 Total Units (Bombers and Decoys)		
RNG Min	6% Closer	14% Further
End Time	7% Longer	14% Shorter
Average Slew Time	25% Shorter	75% Longer
Average Dwell Time	50% Longer	22% Shorter
Percentage Bombers Defeated	NO CHANGE	
100 Total Units (Bombers and Decoys)		
RNG Min	22% Closer	40% Further
End Time	9% Longer	14% Shorter
Average Slew Time	6% Shorter	30% Longer
Average Dwell Time	35% Longer	6% Shorter
Percentage Bombers Defeated	NO CHANGE	
Cases Where Ship is Killed		
200 Total Units (Bombers and Decoys)		
RNG Min	SHIP IS KILLED	
End Time	3% Shorter	12% Longer
Average Slew Time	98% Longer	47% Shorter
Average Dwell Time	208% Longer	63% Shorter
Percentage Bombers Defeated	4% of Original	3200% More

a. Addition of Armored Decoys (Proximity Engagement Strategy)

The addition of armored decoys to the scenario had a significant result. For all three scenarios, the average dwell time increased as expected with the addition of armored units able to absorb more damage. The slew time was shorter for scenarios where the ship survived but longer for scenarios where the ship was destroyed. In the cases of ship survival, the minimum range was 6% and 22% closer than without decoys for the 50- and 100-bomber scenarios, respectively. In the 200-bomber case, the addition of decoys severely reduced the number of bombers destroyed by 96% of the original value. Overall, the effect of adding armored decoys to the waved wedge scenario was minimal for situations where they would survive but had an immense effect on protecting the bombers when used in larger numbers. Figure 48 shows a screenshot captured in the 200-bomber simulation using the proximity-based targeting strategy.

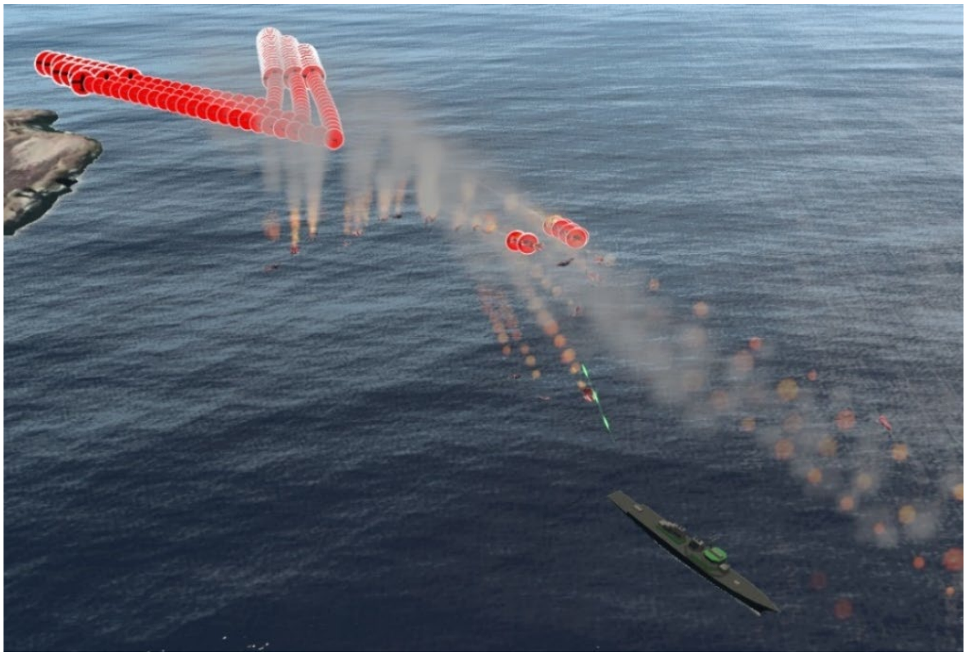


Figure 48. Proximity targeting strategy leads to a failed defense against the decoy attack. Source: MOVES (2021).

b. Shift to "Take-Out the Shooter" Engagement Strategy

The far-right column of Table 14 shows the percentage change in all scenarios when the engagement strategy is shifted to ignore the armored decoys. Simply targeting the shooters first pushed out the minimum bomber range back out for both the 50- and 100-unit scenarios, at 14% and 40%, respectively. For the 200-bomber scenario, the most significant change is the 32 times increase in number of bombers defeated over the proximity strategy. Overall, the shift in targeting strategy was an effective method to counter this heterogeneous swarm. Figure 49 shows a screenshot captured in the 200-bomber simulation using the "take-out the shooter" targeting strategy.

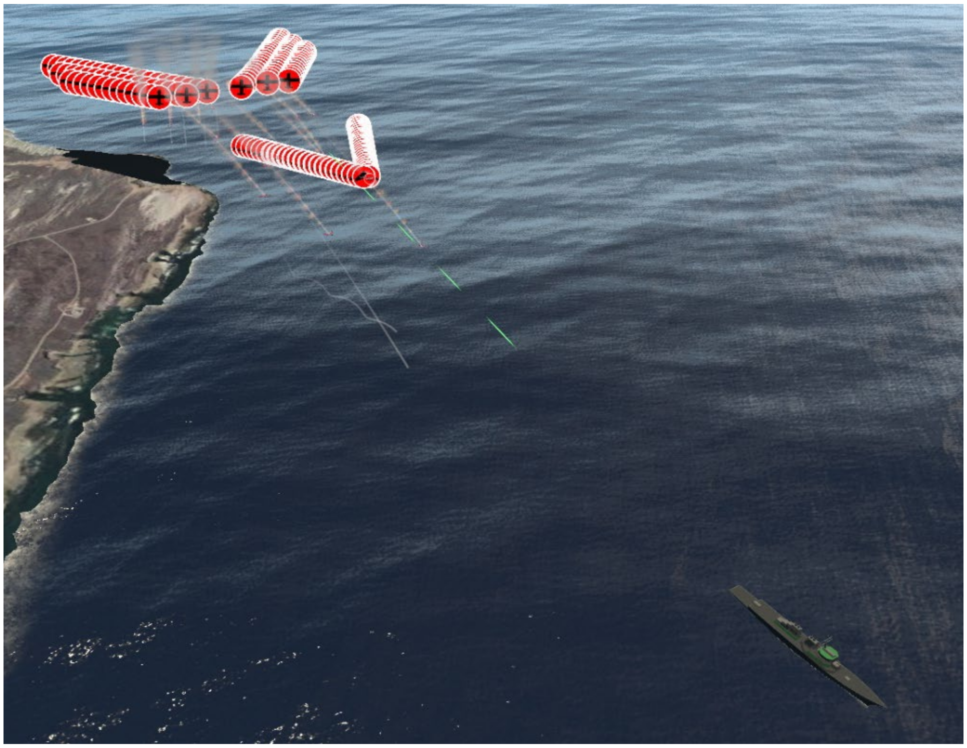


Figure 49. LWS system with “take out the shooter” engagement strategy ignoring the armored decoys. Source: MOVES (2021).

D. SUMMARY

This chapter presents the results of modeling a small number of threat scenarios and engagement strategies. The SCT software provided by MOVES is a handy tool in testing various swarm scenarios and response methodologies. It can accurately simulate laser performance in various atmospheric conditions utilizing the ANCHOR atmospheric scaling code. The program does have some limitations, of which researchers must remain cognizant. Various swarm formations were tested, including the line, wedge, and waved wedge formations. A heterogeneous swarm formation was developed employing decoy drones to shield bomber units. To contend with this configuration, the “take-out the shooter” strategy was tested, and the results were analyzed. The primary findings were that swarm formations maximizing the angular displacement between units were more successful than closely clumped groups. These results were likely due to the increased LWS slew times required between each target. The armored decoy scenario increased overall swarm performance. In the case of ship survival, the bombers were able to live longer and get closer to the ship before being destroyed. In the case of ship destruction, a much greater number of bombers survived the encounter. Shifting the engagement strategy caused an enormous impact on the results. In the case of ship survival, the engagement was much shorter, and the bombers were destroyed much further away. In the case of ship destruction, the engagement lasted longer, and a much larger portion of the bomber group was destroyed. This information reinforces the benefits of utilizing heterogeneous UAV groups and developing LWS engagement strategies to counter them.

VI. CONCLUSION

A. SUMMARY OF RESEARCH FINDINGS

This thesis studied current UAV threats and the efficacy of LWS to counter them. Threat scenarios and engagement strategies were developed, simulated, and analyzed. The results reinforce that the size of the swarm and formations used significantly affect the success rate of the attacking swarm. The complexity of the situation further increases when facing heterogeneous swarms. The results show that the success rate shifts severely in favor of the attacking swarm when using a simple heterogeneous decoy attack. When altering the LWS engagement strategy to counter this, there is a substantial reversal of success rate, which nearly changes the outcome in favor of the defending ship. This information amplifies the need to explore swarm attack and defense tactics that will organically develop with heterogeneous swarms and LWS use.

B. FUTURE WORK

There are various areas in which this work can be continued. The current build of the SCT software is limited in what parameters the user can change. However, new software features are continuously being added. An upcoming update will allow users to add variations of vehicles, each with unique specifications like sensor ranges or velocity (E. Johnson, email message to author, November 15, 2021). A researcher with access to these parameters can gather data that may help determine the degree to which individual vehicle parameters affect the success rate.

In its current state, the SCT software does not allow the user to alter any effects from weather or atmosphere. With access to the environment variables, a researcher could create data that would indicate to what degree an LWS and the ship's defense are affected by the environment.

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