Swarm Weapons: Demonstrating a Swarm Intelligent Algorithm for Parallel Attack

A Monograph

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14. ABSTRACT
Rapid advances in drone technology have shifted swarm robotics from the realm of science fiction to reality. The question is, what is technologically feasible over the next decade and how could commanders use that technology on the battlefield? By integrating existing drone technology, it becomes possible to develop a swarm weapon with hundreds of drones that integrate their actions using emergent behavior. By exploiting the swarm's ability to rapidly concentrate through maneuver, it becomes possible to mass effect at hundreds of points simultaneously. The advantage this provides is the ability to conduct what Colonel John Warden defines as a parallel attack, but at an unprecedented scale. To argue this point, this paper will first analyze what is technologically feasible over the next decade by reviewing existing research and literature. Next, this research effort will develop a concept for the employment of swarm weapons using a parallel attack concept. This paper will then demonstrate the swarm intelligent algorithm designed for this research effort in a computer-simulation. What this paper will show is that within the next decade it is feasible to develop a swarm weapon that can conduct parallel warfare. By adding swarm intelligence to otherwise identical weapons, swarm algorithms make these weapons more efficient and lethal. The results of this research effort could lay the foundation for multiple new concepts of employment for swarm weapons including a swarm breach, swarm area defense, swarm parallel attack, and swarm wide area reconnaissance in a contested environment.

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Abstract

Swarm Weapons: Demonstrating a Swarm Intelligent Algorithm for Parallel Attack, by Maj Sean M. Williams, USAF, 44 pages.

Rapid advances in drone technology have shifted swarm robotics from the realm of science fiction to reality. Today, academic and military institutions are researching how to develop existing drone technology into a swarm. The question is, what is technologically feasible over the next decade and how could commanders use that technology on the battlefield? By integrating existing drone technology, it becomes possible to develop a swarm weapon with hundreds of drones that integrate their actions using emergent behavior. By exploiting the swarm's ability to rapidly concentrate through maneuver, it becomes possible to mass effect at hundreds of points simultaneously.

The advantage this provides is the ability to conduct what Colonel John Warden defines as a parallel attack, but at an unprecedented scale. To argue this point, this paper will first analyze what is technologically feasible over the next decade by reviewing existing research and literature. Next, this research effort will develop a concept for the employment of swarm weapons using a parallel attack concept. This paper will then demonstrate the swarm intelligent algorithm designed for this research effort in a computer-simulation. What this paper will show is that within the next decade it is feasible to develop a swarm weapon that can conduct parallel warfare. By adding swarm intelligence to otherwise identical weapons, swarm algorithms make these weapons more efficient and lethal. The results of this research effort could lay the foundation for multiple new concepts of employment for swarm weapons including a swarm breach, swarm area defense, swarm parallel attack, and swarm wide area reconnaissance in a contested environment.

Contents

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Acronyms

C2	Command and Control
COTS	Commercial Off the Shelf
FSM	Finite State Machine
HARM	High-Speed Anti-Radiation Missile
Hz	Hertz
ISR	Intelligence, Surveillance, and Reconnaissance
Mbps	Megabits per second
RF	Radio Frequency
SDB II	Small Diameter Bomb II
TDMA	Time Division Multi-Access
UCAV	Unmanned Combat Air Vehicle

Introduction

Within the last five years, there has been an explosion in artificial intelligence research and swarm robotics has risen as one of its most promising fields with academic and military institutions demonstrating drone swarms in and out of the lab. In the last year, the United States and China have both demonstrated swarms of more than a hundred drones and at the same time, both China and Russia have proposed they would weaponized their drones for attack. In 2017, China also published their national *Artificial Intelligence Development Plan,* which establishes swarm intelligence as a priority development effort seeking to achieve operational swarm intelligent algorithms by 2020.[1] With each state arguing swarm technology will have a disruptive effect on the battlefield; it becomes important to separate science fiction from reality to truly understand the capabilities this new technology brings. In a time of constrained resources, the questions that military leaders should ask is what capabilities can swarm weapons provide and more importantly is that a capability that does not already exist. To understand this concept, you must look beyond just the quantitative advantage of swarm weapons or their ability to overwhelm an enemy's advanced weapons systems. Swarm weapons provide more than just a quantitative advantage, they represent a system of interconnected weapons that can reactively adapt to the environment and a dynamic enemy.

Drone technology has matured to the point that it is technologically feasible to employ swarm weapons in the next ten years to gain an operational advantage on the battlefield. To show what is technologically feasible within the next ten years, this paper will first review existing

[1] Rogier Creemers et al., trans., *China's Next Generation Artificial Intelligence Development Plan* (New America Cybersecurity Initiative, 2017), 6, accessed January 22, 2018, https://www.newamerica.org/cybersecurity-initiative/blog/chinas-plan-lead-ai-purpose-prospects-and-problems/; Jamie Condliffe, "A 100-Drone Swarm, Dropped from Jets, Plans Its Own Moves," *MIT Technology Review*, January 2017, accessed August 30, 2017, https://www.technologyreview.com/s/603337/a-100-drone-swarm-dropped-from-jets-plans-its-own-moves/; China Electronic Technology Group, *119 Fixed-Wing UAV Cluster Flight Test*, accessed August 30, 2017, https://www.youtube.com/embed/tE6qzRu0p3Q; Jason L. Miere, "Russia Developing Autonomous Swarm of Drones in New Arms Race With U.S. and China," *Newsweek*, May 2017, accessed August 30, 2017, http://www.newsweek.com/drones-swarm-autonomous-russia-robots-609399.

literature to determine what technology researchers have demonstrated outside the lab. Using this methodology, it will show that the hardware necessary for smaller swarm weapons with 100-agents is already possible today and over the next ten years that technology will scale to the point that swarms of up to 1000 drones will become possible. Next, it will use warfare theory to introduce a concept of employment for swarm weapons that go beyond just the quantitative advantage. Finally, it will link the two, by demonstrating a swarm intelligent algorithm that implements this concept of employment using a computer simulation. This simulation will allow us to understand and analyze the impact a swarm weapon could have using the employment concept proposed in this paper. This software will also facilitate an analysis of the strengths and weaknesses of human-swarm teaming. By linking existing hardware to a theory of warfare and a concept of employment, this paper will show that swarm weapons can be an extremely disruptive technology. It helps to start this conversation by developing a common understanding of how swarm weapons can achieve adaptive behavior using a swarm intelligent algorithm.

Swarm intelligent behavior is a naturally occurring phenomenon that for centuries has enhanced the chances of survival for hundreds of different animal species. You can see the concept of swarming in flock of birds, schools of fish, colonies of ants, swarms of bees, and across hundreds of other species.[2] Swarm intelligent algorithms emerged as scientists tried to study, understand, and replicate these behaviors. What computer scientists and biologists learned was that in each case, the animals were communicating in some way, there was no leader, and that each agent within that swarm was following a set of rules. By trying to replicate this behavior, scientists discovered that each swarm was optimizing behavior to maximize the swarm's overall survival.

[2] Louis P. Walters, *Applications of Swarm Intelligence* (New York: Nova Science Publishers, 2011), 167–70.

A common example many use to describe swarming is a flock of starling birds as shown in Figure 1. Although the synchronization of their flight is impressive, what is occurring within that flock is even more impressive. The flock is implementing a complex problem-solving process that is optimizing the flock's behavior to search for food and avoid threats. When one bird detects a threat, the entire flock reacts and avoids that threat. When they detect food or a place to land, the entire flock follows. The flock accomplishes all of this without a leader by using a local and decentralized network of communication where each bird is only communicating with his neighbor.[3] Instead of a leader, the swarm's complex behavior is the result of the established rules each bird follows.[4] Swarming is an adaptation that optimizes the swarm's ability to disperse and search a large area while still allowing the swarm to rapidly concentrate when one agent finds food or a threat. This ability to disperse and concentrate will become critical later with the discussion of the swarm's ability to maneuver through pulsing.

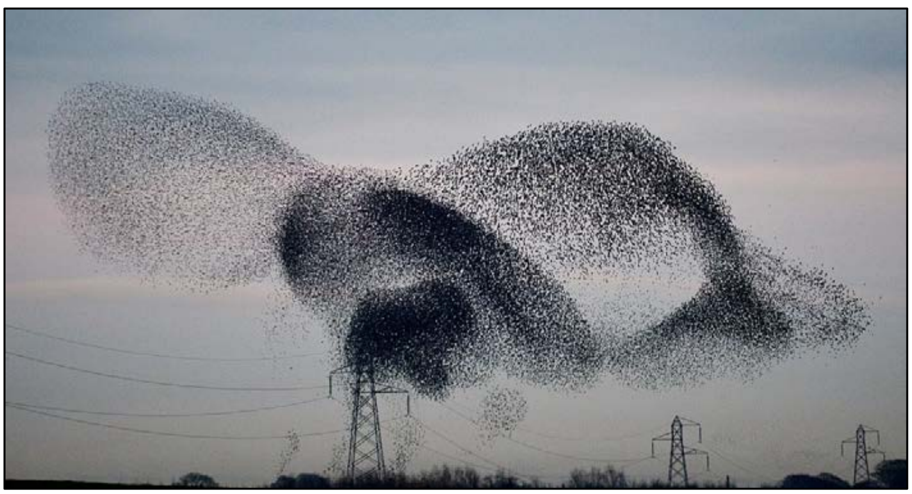

Figure 1. Flock of Starling Birds. Jennifer Smith, "Electric Flock," Daily Mail, November 2013, accessed September 12, 2017, http://www.dailymail.co.uk/news/article-2514252/Incredible-photos-ofhe-moment-TEN-THOUSAND-starlings-fly-formation-Scottish-Borders.html.

[3] Tim Jones, *Artificial Intelligence: A Systems Approach*, Computer Science Series (Sudbury, MA: Jones and Bartlett Publishers, 2009), 236.

[4] Stuart J. Russell, Peter Norvig, and Ernest Davis, *Artificial Intelligence: A Modern Approach*, 3rd ed, Prentice Hall Series in Artificial Intelligence (Upper Saddle River: Prentice Hall, 2010), 439.

Scientists describe this behavior as swarm intelligence, which is when a population of agents use decentralized and self-organizing behaviors in their decision-making to adapt to environmental changes and solve problems.[5] For decades, researchers have drawn their inspiration from these naturally occurring swarms to develop swarm intelligent algorithms like the ant colony, bees hive, or particle swarm optimization algorithms. There are thousands of different variations on swarm intelligent algorithms, which would be beyond the scope of this paper, but what is common across all these algorithms is that each has a swarm of agents that uses a local rule set and decentralized communication network to adapt to environmental changes.[6] Today, swarm engineering has begun to integrate multiple algorithms and modify rule sets to solve new problems. For example, the swarm intelligent algorithm presented later is a modification of the particle swarm optimization. As a result, swarm engineering can develop new more complex swarm behavior. This ability to engineer behavior will also be important later to the discussions on warfare theory and a concept of employment for swarm weapons.

Today, the reduced cost of drone technology has allowed these swarm intelligent algorithms to transition to the real world. Both China and the United States have demonstrated their ability to operate swarms of a hundred drones. For example, in 2016 the United States Strategic Capabilities Office demonstrated a swarm of 103 drones launched from a flight of F-18 aircraft. Now, that same group is in the process of developing a 1000 drone swarm.[7] This paper will focus on the weaponization of swarms. Because the technology is just now emerging, researchers have written very little on swarm weapons. It is also a complex and controversial topic, but an important one because these weapons have the potential to significantly shape the

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[5] Walters, *Applications of Swarm Intelligence*, vii–xii.

[6] Juan Ramon Rabunal, Julian Dorado, and Alejandro Pazos Sierra, eds., *Encyclopedia of Artificial Intelligence* (Hershey, PA: Information Science Reference, 2009), 1537.

[7] The Strategic Capabilities Office, *Perdix Fact Sheet*, (Washington, DC: United States Department of Defense, n.d.)

battlefield to one's advantage or disadvantage. To date, what authors have written about swarm weapons have primarily focused on the swarm's quantitative advantage or the ability to overwhelm advanced weapons systems. Although it is true that swarm weapons could provide this capability, this only scratches the surface of their true potential. The swarm weapon's ability to react in real time to dynamic enemy actions allows the swarm to rapidly change states and behavior. With this, you can engineer the swarm's behavior to align with military theory and the principles of war. By engineering behavior, you can create a swarm weapon with the ability to remain dispersed while searching for targets, and then depending on enemy behavior rapidly concentrate on one, two, three, or hundreds of targets simultaneously (Figure 2). Within the Joint Principles of War, this ability to pulse integrates the principles of maneuver and mass to attack the enemy in depth and breadth.[8] The following will argue this concept is feasible and could have a disruptive effect on the battlefield within the next ten years.

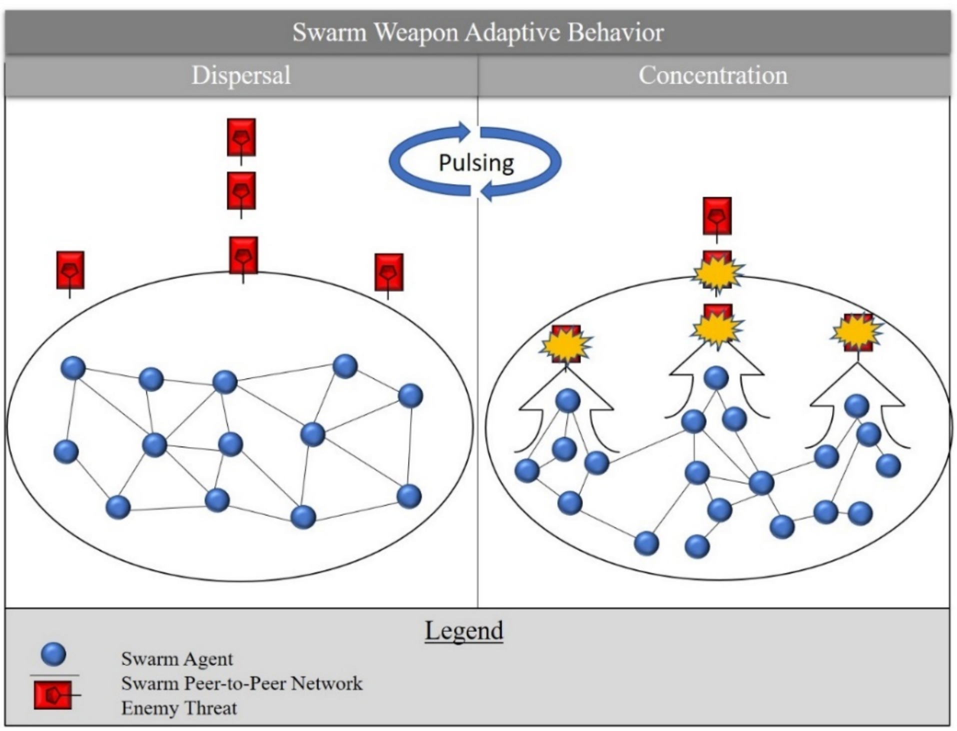

Figure 2. Swarm Weapons Pulsing. Created by author.

[8] US Department of Defense, Joint Staff, Joint Publication (JP) 3-0, *Joint Operations* (Washington DC: Government Printing Office, 2017), A-2.

Methodology

For swarm weapons to provide an operational advantage on the battlefield within the next ten years there must be a link between what is technologically feasible and a concept of employment that provides an operational advantage. To develop this link, the following sections will answer three sub-questions.

First, are swarm weapons technologically feasible in the next ten years? To separate science fiction from reality, Section 1 will first determine whether swarm weapons are technologically feasible and what capabilities they could provide. To answer this question, this paper will look at what is possible today and speculate on what is possible within ten years. The timeline used is ten years because it addresses more near-term capabilities and threats. It also allows a more accurate anticipation of what swarm technology will be available and its impact. For this research effort to consider something technologically feasible within the next ten years, it must be a demonstrated capability. Therefore, this analysis did not consider theoretical technologies. The product of Section 1 will be a table of swarm weapon's capabilities that are feasible today or within ten years.

The second question is how should militaries use the concept of swarm weapons to gain an operational advantage on the battlefield? To answer this question, this analysis will start with military and warfare theory to determine how militaries can use swarm weapons to their advantage. Although there are thousands of uses for swarm weapons, this paper will use military theory as a foundation to develop a swarm weapons concept. Section 2, will answer this question by introducing a concept of employment built on military theory. It will use that military theory to argue that swarm weapons provide a capability that currently does not exist.

The final question is whether existing technology can provide the capability outlined in Section 2 and whether that capability will result in an operational advantage. To answer this question, this research effort will develop a swarm intelligent algorithm that implements this military theory using swarm technology that is feasible within the ten-year timeframe. This section will analyze this swarm intelligent algorithm's ability to provide the desired capabilities using a computer simulation (Figure 3). Each agent within the swarm will implement the swarm intelligent algorithm to attack this enemy system with the objective of finding and destroying as many of the 200 dispersed targets as possible in 120 minutes. To analyze the result, this research effort will use the simulation to compare a mass of 1000-agents without swarming and a mass of 800-agents with swarming. If either of these can find, fix, and destroy over 50% of the designated targets then based on Army doctrine this analysis will consider the enemy system non-operational or combat ineffective.[9] Using this methodology, this paper will compare each to determine if swarm weapons could provide these capabilities within the next ten years.

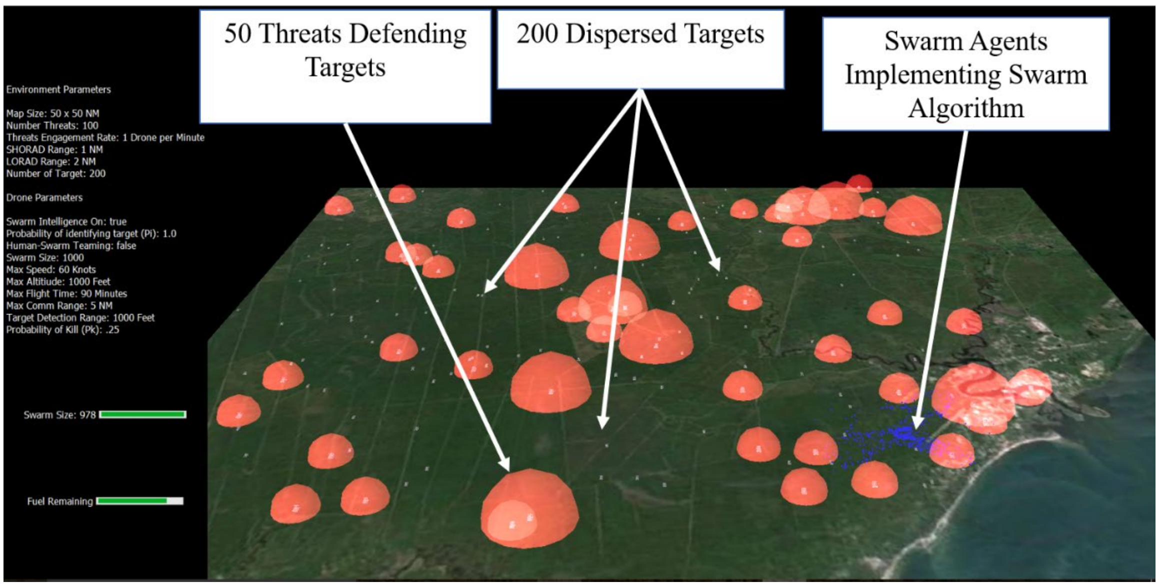

Figure 3. Swarm Weapons Wargame Screenshot. Sean Williams, *Swarm Weapon Wargaming Simulation Software to Model Systemic Attack*, Java, 2017

Section 1: Swarm Weapons are Technological Feasible

To answer the question of whether technology has matured to the point that swarm weapons are feasible within the next ten years this section must critically analyze the state of current research and technology. Technology has already matured to a point that a swarm of 100-

[9] US Department of the Army, Army Doctrine Reference Publication (ADRP) 1-02, *Terms and Military Symbols* (Washington, DC: Government Printing Office, 2016), 4–32.

agents is possible today and over the next decade that technology will continue to mature making swarms of 1000-agents feasible. To argue that point, this section will use a building block approach to show how the individual hardware components necessary for a swarm to function already exist. If the individual components exist, then it is feasible to develop a swarm weapon by integrating those components. This building block approach will show that the most basic component of a swarm, being the swarm agent, already exists and is in use on the battlefield in the form of drone weapons. Incorporated within those drones is all the hardware necessary to develop a swarm agent. To integrate those agents into a swarm, the next step is a decentralized communications network. By integrating these existing technologies, it is feasible to develop swarm weapons within the next ten years.

The first technology to address is the swarm agent or drone itself. To autonomously search the operating environment, the swarm agent must have a targeting system with the ability to determine whether it has found a certain type of target. This ability to autonomously search for targets will become critical to the parallel warfare concept of employment proposed in Section 2. Although this technology is continuing to advance daily, what is more important is that this technology is already in use on drone weapons. Most existing autonomous weapons use radio frequency (RF) to detect targets on the battlefield. The United States has used this technology since 1984 on their AGM-88 High-Speed Anti-Radiation Missile (HARM).[10] Since then, other states like Israel and China have integrated this technology into autonomous drones able to loiter while searching the battlefield for targets. For example, Israel's Harpy Unmanned Combat Air Vehicle (UCAV) is an expendable drone capable of loitering over the target area while searching for and attacking targets.[11] China has also developed a very similar capability with the ASN-301,

[10] United States Air Force, "AGM-88 HARM Fact Sheet Display," accessed October 4, 2017, http://www.af.mil/About-Us/Fact-Sheets/Display/Article/104574/agm-88-harm/.

[11] Air Force Technology, "Harop Loitering Munitions UCAV System," *Air Force Technology*, accessed January 23, 2018, http://www.airforce-technology.com/projects/haroploiteringmuniti/.

which searches the target area for up to eight preset radar types then autonomously strikes when it finds a target.[12] The limitation of this technology is that it requires a target that is transmitting RF energy. To address this limitation many states have begun to develop targeting systems that use electro-optical sensors and robot vision algorithms.

Figure 4. Israel's Harop Missile. Jerusalem Post, "IAI Exhibits Upgraded HAROP Suicide Drone," *Jerusalem Post*, June 2015, accessed on October 6, 2017, http://www.jpost.com/Israel-News/IAI-exhibits-upgraded-HAROP-suicide-drone-for-clients-405266.

Robot vision is a rapidly growing field that researches methods and algorithms for computers to classify objects within an image. Although this technology will continue to advance over the next decade, you can already see demonstrated capabilities and technologies in use. Robot vision algorithms search for patterns within an image to find and classify objects. To determine if a target exists in the image, these algorithms search for certain unique identifiers. For example, if the robot vision algorithm is searching for a tank, it will try to find the tank track, the cannon barrel, and the turret. The algorithm's confidence level will depend on how many of these unique identifiers it finds.[13] Although this technology is still in development, you are already seeing weapons with a demonstrated capability. For example, the Small Diameter Bomb II (SDB

[12] Ami R. Dombe, "China Unveils a Harpy-Type Loitering Munition," *Israel Defense*, January 2017, accessed on 6 October 2017, http://www.israeldefense.co.il/en/node/28716.

[13] Russell, Norvig, and Davis, *Artificial Intelligence*, 928–65.

II) which entered low rate production this year provides a seeker that allows the weapon to classify targets using millimeter wave radar or infrared sensors.[14] Israel has also developed a similar capability with the Harop UCAV shown in Figure 4, which uses an electro-optical (EO) sensor to find non-emitting targets on the battlefield.[15] Finally, earlier this year the US Department of Defense launched Project Maven, which is arguably the most advanced implementation of robot vision algorithms to date and is operational in the fight against the Islamic State. Project Maven uses robot vision algorithms to identify people and vehicles in drone video with an 80% accuracy.[16] Technologically it is feasible that within the next decade swarm agents will be able to autonomously search the target area using robot vision algorithms.

Although drones will be able to use these robot vision algorithms to detect and classify objects on the battlefield, these sensors are still not as advanced as a human at visual classification. Although the 80% accuracy project Maven has achieved is impressive, it is still not as accurate as the human eye and would not be feasible for an autonomous lethal weapon. This is an important note when you consider the complexities of a battlefield where camouflage, obscurants, decoys, and noise all complicate a drone’s ability to classify targets. For example, if the enemy covers their tank using camo netting, the drone’s robot vision algorithm will only see the barrel giving the drone a low confidence level match. In comparison, a human can quickly look at the same image and see that it is a tank. Limitations like this have driven Department of Defense policy to limit the level of autonomy implemented in drone weapons. According to

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[14] U.S. Government Accountability Office, “Defense Acquisitions Assessments of Selected Weapon Programs,” Report to Congressional Committee, March 2017, 153; Sean OMelveny, “Small Diameter Bomb II Completes Live Fire Test Destroying T-72 Tank,” *Military.com*, accessed October 4, 2017, http://www.military.com/daily-news/2015/02/25/small-diameter-bomb-ii-completes-live-fire-test-destroying-t72.html.

[15] Air Force Technology, “Harop Loitering Munitions UCAV System.”

[16] India Ashok, “What Is Project Maven? The Pentagon’s New AI Is Hunting Terrorists in the Wild,” *International Business Times UK*, December 30, 2017, accessed on January 22, 2018, http://www.ibtimes.co.uk/what-project-maven-pentagons-new-ai-hunting-terrorists-wild-1653150.

Department of Defense Directive 3000.09 *Autonomy in Weapons Systems*, lethal weapons must be semi-autonomous, which it defines as "a weapon system that, once activated, is intended to only engage individual targets or specific target groups that have been selected by a human operator."[17] Although this might seem like it limits the capabilities of a drone weapon what this research effort has found is that you can pair the strengths of the human and swarm together making the overall system more capable than its individual components.

As drones enter the realities of a complex battlefield, the enemy will use deception measures. As a result, swarm agents will find targets, but those targets will likely have low confidence level matches due to enemy protection measures. With this reality, the question to ask is: how can you integrate the human to overcome these limitations? By integrating the human-swarm team together you can exploit the strengths of both. The strength of the swarm is that it offers a large search capacity with a lower processing capability. In contrast, the human offers high processing capability with a lower search capacity. By integrating the two together into a human-swarm team, the swarm agents can autonomously search the target area for potential threats while using the human for high-level processing. An additional advantage is that because a human is in the loop, the swarm can consider lower confidence matches as well. Although this will return false targets, it also expands the range of potential targets the human-swarm team can find to include camouflaged targets. The swarm agent presents these targets to the human operator's targeting queue where the capability of the human brain allows higher-level image processing. This teaming concept integrates the capability of the human brain with the capacity of the swarm. Section 3 will expand on this by using the computer simulation to determine if human-swarm teaming increases the swarm's capabilities.

[17] Department of Defense, Defense Directive (DoDD) 3000.09, *Autonomy in Weapon Systems* (Washington, DC: Government Printing Office, 2017), 14.

The final technology to consider is the swarm's communication network. The communication network is critical to the swarm's ability to conduct parallel attacks because it will determine the swarm's range, resilience, scalability, and adaptability. Therefore, it is critical that a swarm weapon use the right command and control (C2) model. Figure 5 offers four different swarm C2 models. Of these, the centralized model is the easiest to develop but also has significant vulnerabilities. For example, in the 2017 Super Bowl, Intel demonstrated a swarm of 300 drones during the half time show. Although this was an impressive sight, the drones used the centralized C2 model, which would not work for a swarm weapon because it significantly limits the swarm's range.[18] With this model, swarm agents must stay in communications range of the base station and are less resilient because a critical node exists in the network. Because of the range and resiliency limitations that exist for the first three models, this paper will focus on the emergent C2 model.

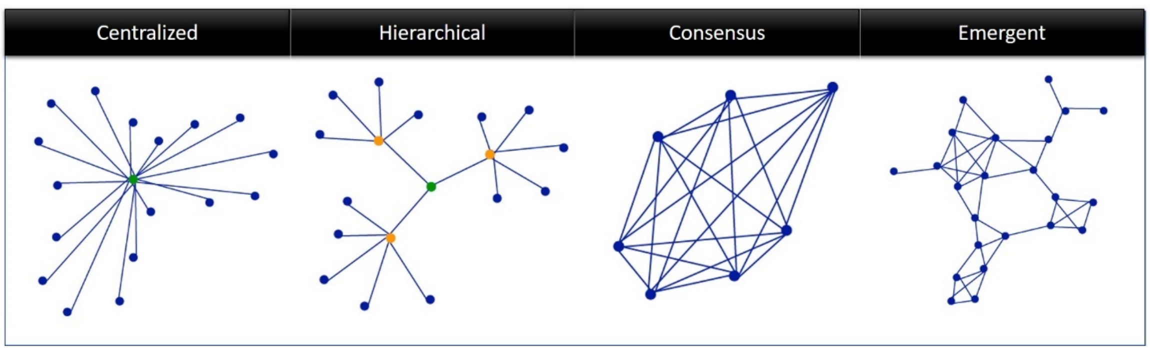

Figure 5. Swarm Command and Control Models. Adapted from Paul Scharre, *Robotics on the Battlefield Part II: The Coming Swarm* (Washington DC: Center for a New American Security, 2014), 39.

The value of the emergent C2 model is that it extends range, decreases bandwidth, and allows the swarm to dynamically scale in size. This C2 architecture is what you see in the starling flock example earlier. Each bird in the flock only communicates with those birds around it. In contrast, it does not know what the birds on the other side of the flock are doing. This means that

[18] Wired, "All About Lady Gaga's Super Bowl Halftime Show Drones," *Wired*, accessed October 6, 2017, https://www.wired.com/2017/02/lady-gaga-halftime-show-drones/.

the geographic coverage area of a swarm weapon using an emergent C2 model is significantly larger than either a consensus or a centralized model. For example, if you have a swarm of 100-agents, the search area of a swarm using an emergent model would be 100 times larger than that of either a consensus or a centralized C2 model.[19] Over the last three years, researchers have started to develop and demonstrate decentralized C2 models like these. For example, in 2015, Dr. Timothy Chung and his Advanced Robotics Systems Engineering Lab team developed a swarm of 50 drones using Wi-Fi connections to coordinate actions within the swarm.[20] Then in 2016, the Office of Strategic Studies demonstrated a similar capability with their swarm of 103 agents, which also used decentralized command and control.[21] These examples show that as of today it is technologically feasible to develop a swarm weapon of 100-agents, but the size of these swarms are currently limited to around 100-agents because they are using commercial off the shelf technology (COTS). In discussions with Dr. Timothy Chung, what he has found through live demonstrations is that current COTS Wi-Fi technology cannot handle network capacities much larger than 100 nodes before issues arise.[22] As a result, using existing technology you could deploy swarm weapons with up to 100-agents but more research is necessary before you can scale to larger swarms.

Although COTS technology cannot support swarms larger than 100 aircraft, swarms of 1000-agents are still technologically feasible within the next decade using non-COTS technology. Researchers can still develop emergent networks using existing hardware technology to

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[19] Agents using either a centralized or a consensus model must remain within communication range of every agent in the swarm. Therefore, this limits swarm coverage to $A = \pi r^2$ where r is the agent's communication range. With an emergent model, they only have to communicate with neighbors. By multiplying the swarm's coverage area by the number of agents in the swarm ($A = x\pi r^2$) where x is the number of agents in the swarm. It is feasible that a mesh network could extend the range of a consensus model, but this research effort did not consider that in these calculations.

[20] Timothy H. Chung et al., "Live-Fly, Large-Scale Field Experimentation for Large Numbers of Fixed-Wing UAVs," *2016 IEEE International Conference on Robotics and Automation*, 2016, 1255-1258.

[21] The Strategic Capabilities Office, *Perdix Fact Sheet*.

[22] Timothy H. Chung, Interview by author, October 2, 2017.

implement network architectures other than Wi-Fi. For example, time division multi-access (TDMA) and mesh networks provide a dynamic networking capability that researchers could use to develop an emergent C2 model as shown in Figure 5. Although not COTS technology, these networking architectures are mature concepts that researchers can integrate into a swarm network. Researchers could use either a mesh or TDMA network architecture to implement an emergent C2 model and TDMA is already in use on the battlefield in the form of Link 16. The military's Link 16 network uses TDMA to coordinate a peer-to-peer architecture that allows airborne aircraft to communicate and pass location, sensor data, and other critical information.[23] Within a swarm weapon, a TDMA network would divide a communication channel into time segments. Each agent within that swarm would use that time block to broadcast data to its neighbors. Although it is dependent on what data the agents pass, a TDMA network would likely limit a swarm weapon's size to around 1000 agents.[24] In summation, one of the biggest hurdles researchers are still addressing for swarm weapons is the communications network. Today, technology has matured to the point that it is feasible to deploy a swarm weapon with 100-agents. Depending on the network used, that swarm weapon may have a limited range. In contrast, over the next decade, it is likely that emergent C2 models will become feasible using existing hardware. This will both increase the swarm's range and size.

As this section has shown, swarm weapons on a smaller scale are already feasible today with some integration of existing technology. At any point, it is possible that you could see swarm weapons of up to 100-agents emerge on the battlefield. Over the next decade, that

[23] Northrop Grumman, *Understanding Voice and Data Link Networks* (San Diego, CA: Northrop Grumman, 2014).

[24] The argument that 1000-agents is feasible on a TDMA network assumes a swarm where each agent broadcasts data at a rate of six Hertz (Hz) with 160 bits of data transferred including drone location, target location, drone vector, and status data. Using the COTS nRF24L01 transceiver chip's transfer rate of one megabits per second (Mbps) as a baseline, this would limit the swarm's size to around 1000 agents without more advanced networking algorithms. This is based on one Mbps divided into 6,250-time frames at 160 bits per frame. One thousand drones can use those timeframes to transmit at a six Hz rate.

technology will continue to mature making it possible for those swarm weapons to scale into the hundreds and even potentially reaching 1000-agents. By looking at the maturity level of existing technology, you can start to anticipate how swarm weapons will emerge on the battlefield over the next decade (Table 1). Drone aircraft are the most mature technology and it is likely that swarm weapons will initially start in the air domain designed to attack land and maritime surface targets. These swarms will likely search using EO sensors to find targets on the battlefield. Initially, these will emerge as small swarms of around 100 drones, but over the next decade, those swarm sizes will increase in size to 1000-agents. This leaves the question of whether this technology will be of any use. Does any of the technology discussed here provide capability militaries do not already have or is it just a new way to accomplish an old task?

Table 1. Feasible Capabilities of Swarm Weapons Over the next Decade.

	Today	Within Ten Years
Vehicle	Aircraft	Aircraft Maritime Maritime sub-surface
Modes of employment	Air to Surface	Air to Surface Maritime Surface-Surface
Autonomy	Navigation: Autonomous Search: Autonomous Targeting: Semi-autonomous Attacking: Semi-Autonomous	
Targeting Sensors	Radio Frequency Limited EO	Radio Frequency EO Imaging Milli-Meter Wave Radar
Targets	- Stationary aircraft - Stationary/Moving vehicles - Stationary/Moving boats - Communications nodes - Unhardened buildings	
C2 Model	Consensus C2 Model	Emergent C2 Model
Network Architecture	Wi-Fi	TDMA or Mesh Network
Swarm Size	100	Up to 1000

Source: Created by author.

Section 2: Integrating Swarm Weapons with Theory of Warfare

The next question is how militaries can use swarm weapons to gain an operational advantage on the battlefield. To do this, you must look beyond just the simple quantitative advantage of swarm weapons. By using military theory as a foundation, new concepts emerge that exploit the swarm's ability to present adaptive behavior using both mass and maneuver. To argue this point, the following section will first introduce the traditional theory of a swarm weapon, which uses a quantitative advantage to overwhelm and breach an enemy's defensive capabilities. Next, it will go beyond that quantitative advantage by introducing the concept of understanding the enemy as a system. This systemic understanding will be critical to developing a concept of employment that exploits the swarm's adaptive behavior. Finally, if properly developed, swarm weapons have the potential to conduct parallel warfare at a rate unmatched by today's technology.

Mass: Overwhelming Quality with Quantity

Before introducing a new concept for swarm weapons, it helps to first look at the traditional quantitative advantage they provide. On the surface, the advantage many see in swarm weapons is quantitative or the ability to overwhelm quality with quantity. It is the production of hundreds of less capable systems that can overwhelm advanced weapons. This form of attack is not exclusive to swarm weapons. Ever since the Napoleonic Wars, armies have tried to mass their forces at a point of enemy weakness.[25] Today, Field Manual 3-90-1, *Offense and Defense* refers to this form of attack as a breaching mission and defines it as the employment of all available means to break through and establish passage through an enemy defense.[26] The advantage a

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[25] Michael A. Bonura, *Under the Shadow of Napoleon: French Influence on the American Way of Warfare*, Warfare and Culture Series (New York: New York University Press, 2012), 16.

[26] US Department of the Army, Field Manual (FM) 3-90-1, *Offense and Defense Volume 1* (Washington, DC: Government Printing Office, 2013), B-3.

swarm provides in a breaching operation is that the swarm can use its targeting sensors, emergent C2 network, and swarm intelligence to adaptively react to enemy actions after launch. As shown in Figure 6, with a swarm breach, the swarm can focus all its agents on a breach point. Although not represented in this picture, at the tactical level, as each agent in that swarm attacks a target, they will likely coordinate multi-axis attacks where agents overwhelm the target by attacking from different directions simultaneously. Once the swarm has breached the enemy lines, the adaptive nature of the swarm combined with the human interface allows the weapons to hold that breach open. For example, if the enemy commits forces to close the breach the swarm can identify those targets, coordinate the attack with the human operator, and hold the breach open by striking those targets. Additionally, the swarm's ability to scale using the emergent C2 model discussed earlier allows the swarm to absorb losses and if necessary integrate reserves. Using the principles of war as a foundation, the advantage of this employment concept is that it masses the swarm's firepower at a single point to facilitate a breakthrough. Although this form of employment is advantageous, what it fails to do is exploit the principle of maneuver at an operational scale. By integrating the swarm's ability to maneuver militaries can use parallel warfare to their advantage.

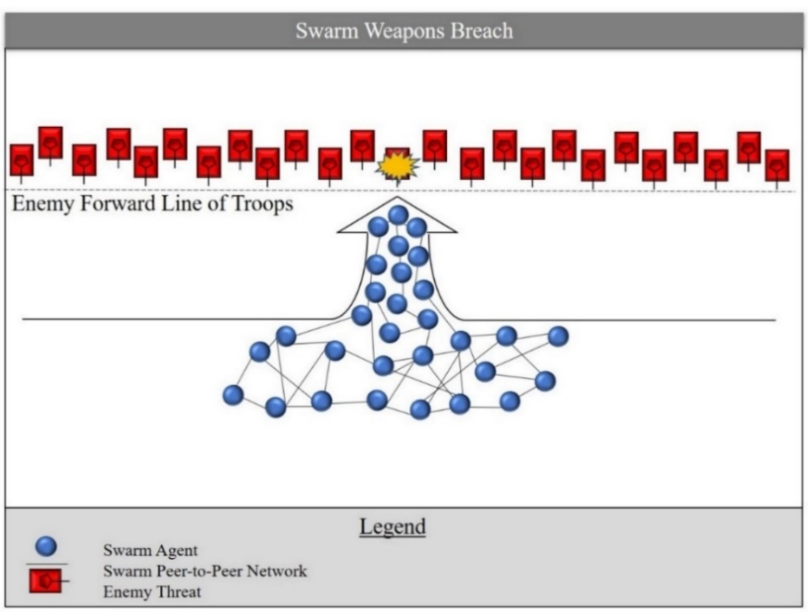

Figure 6. Swarm Weapon Breach. Created by author.

Maneuver: Operational Paralysis Through Parallel Warfare

By integrating the swarm's ability to maneuver and dynamically mass, militaries can gain an operational advantage well beyond anything possible with a simple breaching mission. History has shown that commanders can use maneuver to defeat armies much larger than our own. Napoleon Bonaparte offers a perfect example to illustrate this point. At the Battle of Austerlitz, Napoleon defeated two armies much larger than his own because he combined the principles of maneuver and mass.[27] What was different about Napoleon was twofold. First, he understood warfare and the enemy as a non-linear system of interdependencies. The more linear a system is, the more proportional and arithmetic the outputs are. In contrast, non-linear systems depend on the relationship between elements.[28] Understanding these relationships allows the exploitation of what Shimon Naveh describes as synergetic effects. Synergetic effects are when a set of actions produce an effect greater than the sum of their individual inputs.[29] The second thing that set Napoleon apart was that he developed independently maneuvering combined arms units that allowed him to attack the enemy system simultaneously at multiple points. By exploiting his ability to use maneuver to mass his forces at multiple points of enemy weakness. Napoleon was able to defeat armies larger than his own because he attacked the enemy as a system gaining synergetic effects. Transitioning to a theory of warfare for swarm weapons, going beyond just mass, a swarm can exploit this same principle of maneuver to attack the enemy system, not at one, two, or three points, but hundreds of dispersed weak points simultaneously. Employed as a system to attack a system, militaries can multiply the effects a swarm weapon by exploiting synergetic effects to gain a larger operational advantage.

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[27] Donald D. Horward and Michael V. Leggiere, eds., *Napoleon and the Operational Art of War: Essays in Honor of Donald D. Horward*, History of Warfare, vol. 110 (Leiden: Brill, 2016), 145–47.

[28] Alan Beyerchen, "Clausewitz, Nonlinearity, and the Unpredictability of War," *International Security* vol. 17, no. 3 (Winter 1993): 61–62.

[29] Shimon Naveh, *In Pursuit of Military Excellence: The Evolution of Operational Theory*, The Cummings Center Series 7 (London: Frank Cass, 1997), 13.

Before using swarm weapons to attack the enemy as a system, a methodology for understanding the enemy as a system is necessary. In 1988, Colonel John Warden wrote *Air Theory for the 21st Century* where he proposed what is arguably one of the most valuable models for understanding the enemy as a system. He argued that the way military planners and strategists looked at the enemy focused entirely on a quantitative understanding. In particular, he believed the emphasis on an enemy order of battle ignored and hindered our ability to understand the relationships between those units.[30] To go beyond that surface level quantitative understanding you would have to understand the relationships between those units and more importantly how those relationships allow the overall enemy organization to accomplish its mission. To help planners develop this systemic understanding, John Warden proposed his Five Rings Model as shown in Figure 7. This Five Rings Model takes the same information but depicts it as a network of interdependent entities each with an assigned function within the larger organization.[31] He argues that although there are differences between organizations, you can represent most using this model. Using this model, every unit within the enemy organization assumes a function or role like the organs of a body.

[30] John Warden, “Air Theory for the 21st Century,” *Challenge and Response, Anticipating US Military Security Concerns*, edited by Dr. Karl P. Magyar (Maxwell Air Force Base, AL: Air University Press, 1994), 357.

[31] Sean Williams, "John Warden’s Air Theory and Its Relevancy to Multi-Domain Warfare" (paper presented at School of Advanced Military Studies, Fort Leavenworth, KS, 2017).

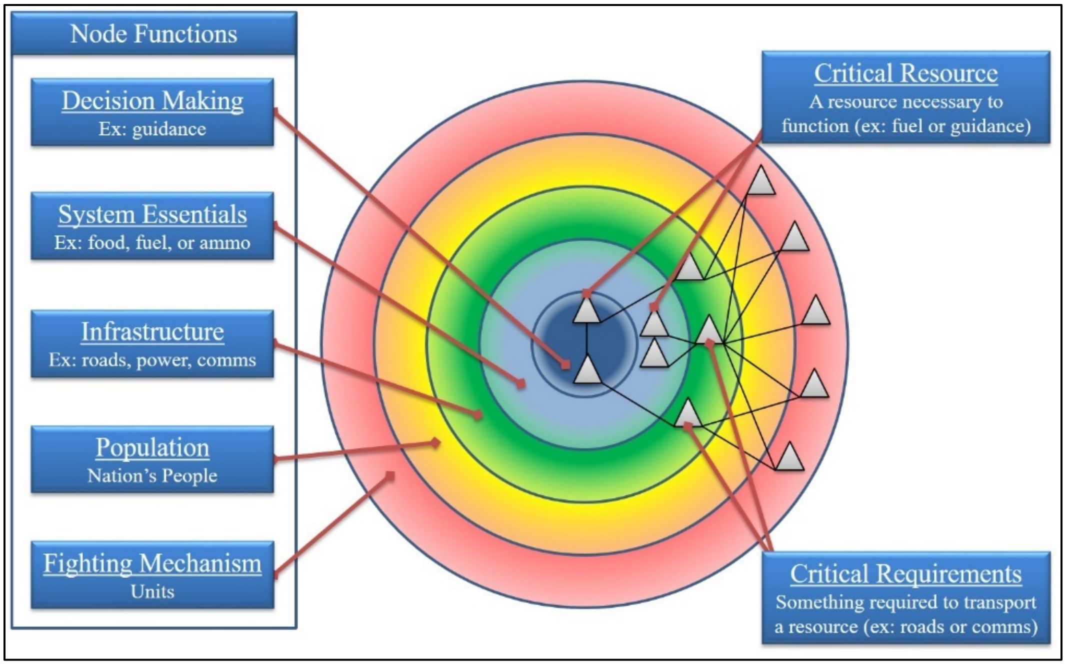

Figure 7. John Warden's Five Ring Model. Adapted from John Warden, "Air Theory for the 21st Century," *Challenge and Response, Anticipating US Military Security Concerns,* Edited by Dr. Karl P. Magyar (Maxwell Air Force Base, AL: Air University Press, 1994), 357.; Paul Theron, "Cyber-Attack Strategies Against a Massively Collaborative System," March 2, 2016, accessed 22 January 2018, https://www.linkedin.com/pulse/identifying-potential-cyber-attack-strategies-against-paul.

Using a logistics unit as an example. Like a human's blood veins, the logistics vehicles represent infrastructure that moves critical resources from the system essentials ring to the defensive mechanism ring. By assigning units to one of these functions, you start to see relationships emerge between nodes. For the enemy organization to function, the infrastructure must move critical resources from the inner ring to the outer rings. As you start to see the enemy organization as a system, vulnerabilities also emerge. By attacking critical nodes in this system, Col Warden argued that you could operationally paralyze the enemy organization. He defined operational paralysis as a temporary state of being combat ineffective due to a lack of an essential resource.[32] Col Warden was not the only one to think of warfare in this way. In 1937, Russian Deep Battle Doctrine emerged which also viewed the enemy as a system. This doctrine argued

[32] Warden, "Air Theory for the 21st Century," 360.

that the maneuver forces should attack the enemy simultaneously in breadth and depth. The result of these simultaneous attacks is that the enemy as a system would be shocked.[33] Whether you call it shock or operational paralysis, there is a common theme. By looking at the enemy as a system, you can use swarm weapons to attack nodes in that system to gain synergetic effects well beyond the swarm's size.

What John Warden went on to propose was that through the rapid application of pressure at multiple choke points in the enemy system you could achieve synergetic effects because it will overload decision-making, communications, defenses, and repair capabilities.[34] He referred to this ability to attack multiple points in the system as parallel warfare. The limitation of this theory has always been the capacity to attack the enemy system. In his book *Bombing to Win,* Robert Pape argues against John Warden's theory of operational paralysis by arguing that it is unlikely the enemy will build a house of cards where destroying one node will stop the whole system.[35] The enemy also knows the risk of single points of failure and as a result, protects those nodes and builds redundancies. Using the logistics as an example, the enemy will disperse supply points and use hundreds of vehicles to move those supplies distributed across a wide area. This makes it very difficult to target these dispersed nodes with a limited number of long-range weapons. Robert Pape is correct, the enemy will seldom knowingly build these vulnerabilities into their system, but swarm weapons have the potential to change how militaries think about systemic targeting. To this point, military forces have had a limited number of strike platforms; therefore, they have had to search for critical nodes where they can apply those limited assets. Swarm weapons change this because they have the capacity to attack in breadth and depth.

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[33] Georgii S. Isserson, *The Evolution of Operational Art*, trans. Bruce W. Menning (Fort Leavenworth, KS: Combat Studies Institute Press, 2013), 63–71.

[34] Warden, "Air Theory for the 21st Century," 365.

[35] Robert Anthony Pape, *Bombing to Win: Air Power and Coercion in War*, Cornell Studies in Security Affairs (Ithaca, NY: Cornell University Press, 1996), 84.

Rather than dedicating mass to a single point, the swarm weapons ability to maneuver allows them to mass effects at hundreds of points simultaneously. This would allow swarm weapons to conduct parallel warfare at an unprecedented rate. This ability to maneuver and capacity for parallel warfare is a result of an increasing ability to communicate, coordinate, and synchronize the actions of smaller and smaller units. You can see this same evolution across military doctrine as well. In their book, *Swarming & the Future of Conflict*, John Arquilla and David Ronfeldt argue that military doctrine has evolved over time because of our increasing ability to synchronize. They propose that the earliest form of warfare was a melee, which involved an uncoordinated attack using individual agents without communication.[36] The next step in the evolution of military doctrine was the introduction of command, which allowed massing, but because of the limitations of battlefield communication, once the commander committed his units he has little ability to adapt.[37] This form of warfare allowed militaries to mass but did not exploit the advantage of maneuver. This is also very similar to how militaries employ many of our standoff weapons today. Once launched there is little opportunity to adapt to the enemy. Arquilla and Ronfeldt argue that around the Napoleonic wars, maneuver warfare emerged which allowed attacks at multiple points. Additionally, the commander could now adapt to a dynamic enemy.[38] Today, this is very similar to the capabilities provided by weapons like the SDB II and Harop UCAV. Since the Napoleonic wars technology has continued to develop allowing maneuver units to synchronize more and more actions. Finally, Arquilla and Ronfeldt propose a final form of warfare called swarm warfare, which they argue is just now becoming technologically feasible as communication technology matures. Swarm warfare uses one's ability to communicate to synchronize the actions of many smaller units. It is the ability to attack

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[36] John Arquilla and David Ronfeldt, *Swarming & The Future of Conflict* (Santa Monica, CA: RAND National Defense Research Institute, n.d.), 10.

[37] Ibid., 13.

[38] Ibid., 17.

everywhere at the same time using the swarm's ability to pulse effects.[39] Swarm warfare uses superior maneuver to mass effects at multiple weak points simultaneously.

Using John Warden's theory, the advantage of using swarm weapons as small attack and maneuver units is that it becomes possible to attack the enemy at hundreds of weak points simultaneously. By exchanging capability for capacity, a new form of systemic targeting emerges. Rather than searching for critical nodes that are vulnerable, now swarm weapons can attack in breadth. Today militaries must search for critical choke points in the enemy system. Using logistics as an example, there are too many vehicles to strike with limited platforms; therefore, militaries must look for choke points like supply yards, train depots, and bridges. The enemy, knowing these are choke points, dedicates his protection assets at these choke points. With swarm weapons, it is possible to attack the dispersed vehicles instead. For example, by deploying swarm agents to search for and destroy logistics trucks. When a swarm agent finds a potential target, it relays that position to a human operator who confirms the target. Once confirmed, the swarm agent contacts neighboring agents to coordinate a multi-axis attack. The swarm agents concentrate on the attack, destroy the asset, and then any unused agents return to their search tasking. This is occurring hundreds of times across the search area.

By using our systemic understanding of the enemy, you can exploit parallel warfare to achieve synergetic effect. Commanders should not use the swarm to just attack any military target in the enemy organization. They can achieve better effects by attacking certain functions in the enemy organization. For example, to operationally paralyze an armored brigade, the swarm weapon should not attack the armor. Armored vehicles are difficult to destroy especially for low-cost swarm drones and can defend themselves. Instead, by avoiding the armor units and infiltrating into the enemy support area, a swarm can attack critical support assets as shown in Figure 8. In this case, by focusing on fuel and ammunition trucks, the swarm can operationally

[39] Arquilla and Ronfeldt, *Swarming & The Future of Conflict*, 21.

paralyze the enemy system by isolating the armor units from their critical resource. Section 3 will analyze this concept in more detail using computer simulation to determine if it is feasible.

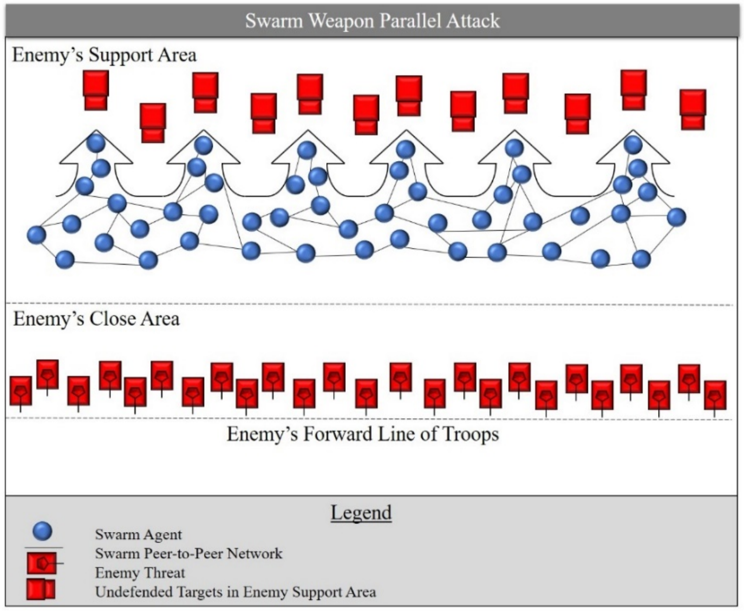

Figure 8. Swarm Parallel Warfare. Created by author

Swarm weapons have the potential to provide an operational advantage on the battlefield because they allow researchers to integrate the principles of mass and maneuver into the weapon. This is possible because swarm weapons have an adaptive capability that emerges from their swarm intelligent algorithm. Today, militaries must use their systemic understanding of the enemy to search out nodes in their organization that are both critical and vulnerable. Often these nodes are extremely difficult to find and the adversaries have also observed this doctrine of attacking critical nodes. As a result, future enemy systems will protect these critical nodes using advanced defensive systems and redundancy. Swarm weapons change the concept of targeting from a focus on high-value point targets to a function's systemic value. Rather than attacking one or two critical nodes, swarms can create a critical node by attacking hundreds of redundant nodes simultaneously. The next section will introduce a swarm intelligent algorithm that provides these capabilities using existing technology and will demonstrate the effects of parallel warfare using a computer simulation and wargame.

Section 3: Analysis of a Swarm Intelligent Algorithm for Warfare

The final step in arguing the impact swarm weapons could have on the battlefield is to show their potential by demonstrating a swarm intelligent algorithm. Although the complexity of warfare makes the development of these algorithms difficult, this section will show that it is feasible to develop an algorithm that can adapt and respond using emergent behavior. To argue this point, this section will introduce the swarm intelligent algorithm developed for this research effort and show how this algorithm facilitates human control and implementation of the swarm breach and parallel attack concepts proposed earlier. To demonstrate the potential of swarm weapons, this paper will outline the result of a computer simulation and wargame showing the efficiencies gained with swarm intelligence. What it will show is that a swarm intelligence algorithm for parallel attack is technologically feasible and that it is more efficient and more lethal than a non-swarming mass. These efficiencies are possible because swarm intelligence uses emergent behavior to exploit the synergetic effects of swarm warfare by attacking multiple points through mass and maneuver.

At this point, it is important to understand and define what emergence is because the swarm's emergent behavior is what makes this concept of swarm warfare possible. To start, it helps to understand the adaptive capabilities of a non-swarming weapon. Without swarming, a non-swarming weapon's adaptive nature is self-centered. Although it can adapt to the environment, it only considers its own sensors and information. The non-swarming weapon does not consider the location of or information from any other weapon around it. In contrast, a swarm weapon is a network of weapons. With a swarm weapon, there is an interdependence between the micro and the macro scale where the actions of one agent at the micro-scale shape the actions of the entire swarm at the macro scale and vice versa. In his book *Making Thinks Work, Solving Complex Problems in a Complex World,* Yaneer Bar-Yam defines this relationship between the macro and the micro-scale as emergence or in this case emergent behavior.[40] This concept of emergence is the true benefit and strength of any swarm intelligent algorithm because it allows the agent's behavior at the micro-scale to shape and adapt the swarm's behavior at the macro. This emergent behavior is what makes the concepts proposed in this paper feasible. Without emergence, concepts like pulsing, cooperative survival, parallel warfare, and adaptive area reconnaissance would not be feasible.

This concept of emergence requires a different understanding of control. In the past, humans have controlled weapons only at the micro-scale, but swarm weapons require humans manipulate both the micro and macro scale. To accomplish this, the human must provide inputs to individual agents at the micro-scale to shape that agent's behavior, which in effect also shapes the swarm's overall behavior at the macro-scale through emergence. Although this might sound complicated, the human is in effect controlling the swarm's behavior at the macro and micro-scale by manipulating the rules that drive its emergent behavior. Army Doctrine Reference Publication 6-0 *Mission Command* offers a useful example to highlight this concept.[41] Within the concept of mission command, a commander enables agile and adaptive subordinate leaders by providing mission type orders.[42] When commanders assign a tasking to their subordinate units they do not micro-manage every detail of their units' action. That type of centralized control would limit their unit's ability to accomplish complex tasks. Instead, they assign taskings, rules of engagement, and supporting relationships between units. Once sent on their tasking, the commander manages those units from the macro scale by manipulating their taskings, rules, and the relationships between units. The human-swarm teaming concept proposed here is very

[40] Yaneer Bar-Yam, *Making Things Work: Solving Complex Problems in a Complex World*, (Cambridge, MA: Knowledge Press, 2004), 27.

[41] David Blair, interview by author, December 29, 2017.

[42] US Department of the Army, Army Doctrine Publication (ADP) 6-0, *Mission Command* (Washington, DC: Government Printing Office, 2012), 1–1.

similar. A human controls the swarm's behavior by assigning mission orders, which in effect manipulate the rule sets the swarm's agents follow.

By manipulating these rules, a human can control the swarm's behavior through emergence. An agent can be in one and only one state at any one point; therefore, each agent only follows one set of rules at any one point. Using the mission command metaphor discussed earlier, this state is very similar to the unit's tasking. It is impossible to develop one set of rules that will address all the taskings necessary for a swarm weapon; therefore, multiple states become necessary and in each state, the swarm's behavior changes based on human input. Figure 9 depicts the finite state machine (FSM) used for the swarm intelligent algorithm proposed in this paper.[43] In this case, each of the six states represents a tasking or set of rules each agent in the swarm must follow. The arrow between states represents how an agent would transition between states. The important aspect to take away from this FSM is not the architecture, but instead how humans would control a swarm. Unlike a conventional weapon where they control the details at the micro-scale, with swarm weapons humans control the weapon by changing the swarm's state or rule set which will in effect shape the swarm's behavior at the macro scale through emergence.

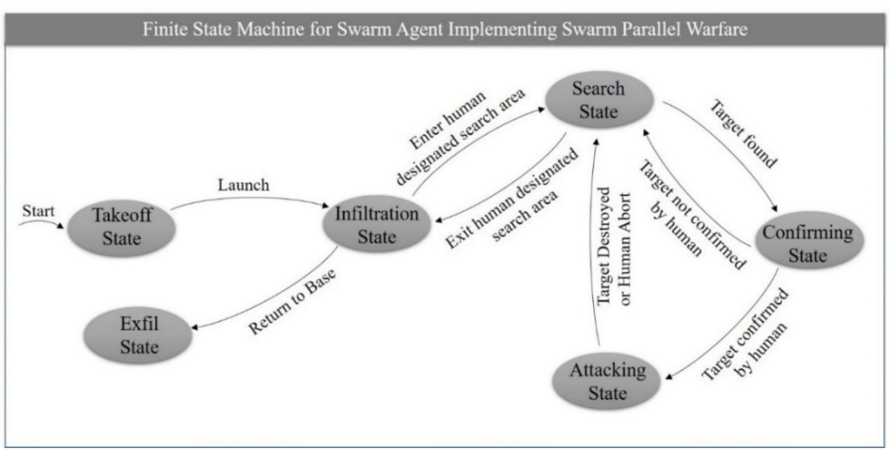

Figure 9. FSM for Swarm Implementing Swarm Parallel Warfare. Sean Williams, *Swarm Weapon Wargaming Simulation Software to Model Systemic Attack*, Java 2017.

[43] Kenneth H. Rosen, *Discrete Mathematics and Its Applications*, 4th ed. (Boston, MA: WCB/McGraw-Hill, 1999), 640.

To demonstrate the feasibility of developing a swarm intelligent algorithm to conduct the parallel warfare concept proposed earlier, this research effort developed an algorithm that offers one potential solution. To show the strength of a swarm weapon, the swarm intelligent algorithm designed for this effort integrates six different emergent behaviors using the FSM shown in Figure 9. The first state to discuss is the infiltration state, which the swarm enters after launch. In the infiltration state, the swarm is responsible for moving from the launch point to the search area. In this state, the swarm uses a particle swarm optimization algorithm modified for cooperative survival. With cooperative survival, when an agent detects a threat it not only avoids it but also broadcast the location to other local agents. At the micro level, this drives other local agents to also avoid the threat. Finally, the change in direction of travel for 20 or so local agents also changes the behavior of the other 800 agents through emergence even though the other agents in the swarm are unaware of why the swarm is changing direction. This behavior is very similar to the starling birds discussed earlier.

Once an agent enters the search area, it assumes an anti-social swarming behavior, which causes the swarm to disperse sensor capability to establish an adaptive area reconnaissance network. This network is adaptive because the anti-social behavior of the swarm autonomously fills in sensor gaps caused when threats destroy agents. Once an agent identifies a potential target, they transition to confirm that target with a human. Once a human approves the target, the swarm agent transitions to an attack state. In the attack state, the swarm uses a pulsing algorithm to coordinate a cooperative attack with other agents in the area. The benefit of the anti-social network is that agents remain in communication range; therefore, when an agent finds a target it calls on other local agents to coordinate an attack. Those agents rapidly consolidate on the target using the pulsing concept proposed earlier. Once the swarm destroys the target, unused agents return to the swarm to search for follow-on targets. For the parallel attack concept proposed here, this pulse attack combined with the wide-area surveillance network represent the true benefit of a swarm weapon.

To analyze this algorithm's ability to adapt and conduct parallel warfare, this research effort used a computer simulation. Within this simulation, the swarm had to contend with 50 randomly paced threats while trying to find and destroy 200 randomly placed targets in 120 minutes. Each drone had a .25 probability of killing the target; therefore, it is likely that each target will require multiple drones to destroy it. Table 2 provides detailed capabilities for each case. The first iteration considered non-swarming weapons with a sensor able to scan for certain targets. This would be representative of a mass attack using the Harop or a similar weapon that does not use swarm capabilities. The second iteration considered weapons with the same exact sensor, range, and attack capabilities, but integrated the swarm intelligent algorithm proposed here. To summarize the result of this effort, what this research effort found was that addition of a swarm intelligent algorithm significantly increased the efficiency and lethality of the weapon as shown in Table 2. The following will cover four takeaways from this research in more detail.

Table 2. Simulation Criteria.

	1000 Agents No Swarming	800 Agents with Swarming
Swarming	No	Yes
Swarm Size	1000	800
Communication Range	None	5 Nautical Miles
Swarm Network	None	Emergent
Probability of Target ID	.95	
Probability of Kill	.25	
Drone Speed	60 Knots	
Max Target Detection Range	500 ft	
Search Area Size	1,590 square miles	
Number Short Range Threats	40	
Range of Short Range Threats	1 NM	
Number Long Range Threats	10	
Range of Long Range Threats	3 NM	
Threat Rate of Fire	1 Shot per minute with 100% probability of killing the drone	
Number of Targets	200	
Number of Iterations Averaged	Results show the statistical average across ten iterations	
Percentage of Targets Destroyed	47%	55%
Combat Effectiveness[44]	Marginally Operational	Non Operational

Source: Sean Williams, *Swarm Weapon Wargaming Simulation Software to Model Systemic Attack*, Java, 2017.

[44] US Army, ADRP 1-02 (2016), 4-32.

Takeaway #1: Swarm Intelligence Can Increase Efficiency and Lethality

This computer simulation showed that the addition of a swarm intelligent algorithm to otherwise identical hardware made the weapons significantly more efficient at finding and destroying targets because of emergent capabilities like pulsing and the adaptive area reconnaissance. Figure 10 offers a comparison of targets found and destroyed over the course of a 120-minute iteration. By launching 1000 agents, the non-swarming weapon was able to find and destroy 47% of the targets in 120-minutes. Although this is a significant number of targets, it did not meet the criteria of 50% destruction laid out earlier.[45] In contrast, with all other capabilities being identical, the introduction of a swarm intelligent algorithm significantly increased the swarm's efficiency, lethality, and capability.

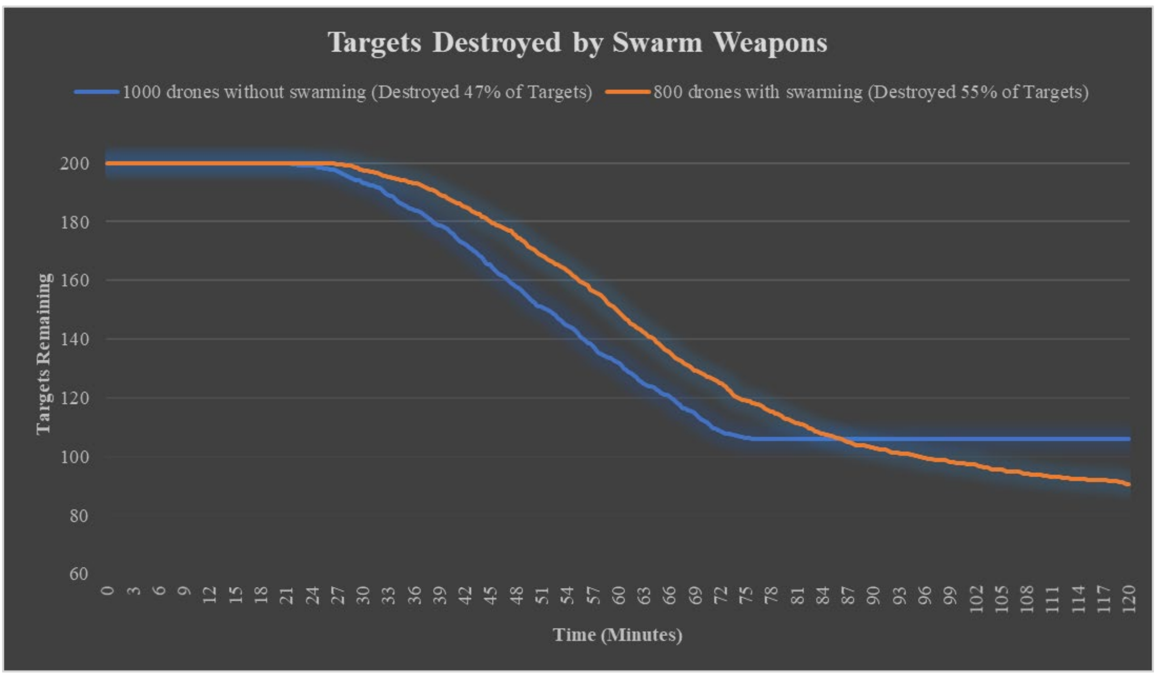

Figure 10. Results of Swarm Intelligent Algorithm and Computer Wargame. Sean Williams, *Swarm Weapon Wargaming Simulation Software to Model Systemic Attack*, Java, 2017.

The swarm intelligent algorithm proposed earlier made it possible for 800 agents to achieve what 1000 non-swarming agents could not. Even though the swarming agents used 200

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[45] Sean Williams, *Swarm Weapon Wargaming Simulation Software to Model Systemic Attack*, Java, 2017.

fewer drones, it was able to find and destroy 8% more targets than the non-swarming weapon. This means even though the swarm was 20% smaller, swarm intelligence allowed it to search a 1,590-square mile area to find and destroy 55% of the enemy's support capability in 120 minutes. From observation, what made the swarm weapon more efficient was the adaptive surveillance network and the ability to pulse. The reason for this was that because the conventional weapons did not communicate, they could not adapt to the loss of drones due to threats, which left gaps in the sensor and strike coverage area. In contrast, swarming and the associated anti-social algorithm ensured other drones filled those gaps. Additionally, as agents found targets, the ability to pulse drew other weapons to reattack the target if necessary. What this simulation showed is that swarm weapons have the potential to be significantly more efficient and adaptive than non-swarming weapons. The implications of this are significant because this efficiency has the potential to reduce the swarm's logistics footprint and cost.

Takeaway #2: Parallel Warfare is Feasible with Swarm Weapons

What this simulation also showed was that it is feasible to operationally paralyze an enemy using a swarm weapon for parallel warfare. As shown in Figure 10, the swarm of 800 agents was able to find and destroy over 50% of the targets in the target area while ignoring threats. Col John Warden's theory proposed that attacking an enemy's ability to move critical resources from the inner circles to the fighting mechanism would temporarily paralyze an enemy.[46] In the past this, required planners find critical choke points. What this simulation showed was that swarm weapons potentially change that. Rather than searching for choke points, swarm weapons make it feasible to attack vulnerable redundancies in parallel. In this case, this simulation was able to avoid threats, while selectively targeting 110 systems of a particular type spread out over a 1,590-square mile area in 120 minutes. Now consider the impact if an enemy

[46] Warden, "Air Theory for the 21st Century," 360.

lost 55% of its logistics vehicles in two hours. *Army Doctrine 1-02 Terms and Military Symbols* defines any losses greater than 50% as not operational.[47] As a result, this would degrade any front-line fighting forces due to a lack of essential resources like fuel and ammunition. What this simulation showed was that a swarm weapon used for parallel attack and selective targeting has the potential to operationally paralyze the enemy because it has the capacity and a selective targeting capability using robot vision algorithms. This concept could change how planners think about John Warden's theory. Rather than a tool to search for critical nodes or choke points, swarm weapons have the potential to attack an entire ring. Through parallel attack and selective targeting, swarms create a weakness or criticality in the system rather than having to find one.

Takeaway #3: Swarm Weapons are More Survivable

Because swarm weapons use cooperative survival in their algorithm they are more survivable than non-swarming weapons. As discussed earlier, the drones in this algorithm used a particle swarm optimization algorithm modified for cooperative survival. In this case, when one agent detected a threat it immediately tried to avoid that threat, but at the same time, it alerted other drones within range that there was a threat. That notification at the micro-scale changed the other local drones' behavior to avoid that threat at the macro scale. Because this small pocket of local drones is flying in one direction, even though other drones do not know why, they follow because of their particle swarm optimization. The result is that, even though the swarm loses one drone, the swarm as a whole survives because of emergence from the micro to the macro back to the micro. This behavior had a significant impact on survivability. Although many often consider swarm agents expendable, another potential benefit of a swarm weapon is that swarm intelligence also makes them more survivable. During later iterations, this research effort also used the simulation to analyze the swarm's survivability. The swarm launched into the same environment using the same FSM, but instead of attacking, they operated as ISR platforms finding target, but

[47] US Army, ADRP 1-02 (2016), 4-32.

not destroying them. During this simulation, the swarm also showed an increased survivability over the non-swarming weapon. As shown in Figure 11, the swarm agents' survivability was 9% higher than the non-swarming losing only 220 aircraft. What this shows is that, swarm intelligence also has the potential to make swarm agents more survivable. This has the potential to change how militaries look at wide area ISR in contested environments.

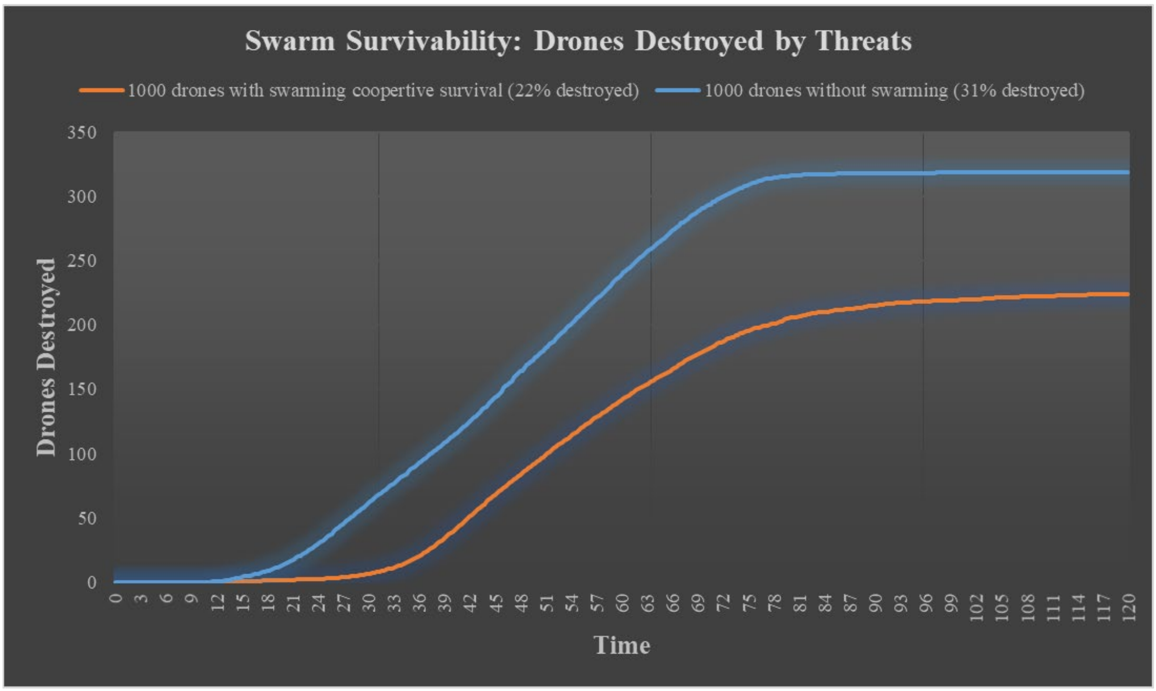

Figure 11. Swarm Intelligent Algorithm's Survival Rate. Sean Williams, *Swarm Weapon Wargaming Simulation Software to Model Systemic Attack*, Java, 2017.

Takeaway #4: Human-Swarm Teaming Improves Overall Performance

Finally, although human-swarm teaming arguably increases centralization and decreases the swarm's capacity, this simulation showed that it is feasible to actually increase the swarm's overall capability by integrating the strengths of both the human and the swarm. The quantity of agents combined with their parallel actions makes it impossible for a human to control the detailed actions of every swarm agent without a concept like the mission command or human-swarm teaming proposed here. The number of agents within a swarm means humans must delegate some level of control to the agents, but the question is how much capability should the human delegate to the swarm agent. Yaneer Bar-Yam argues that within a hierarchical model, the complexity of the human at the top limits the collective behavior of the system.[48] In this case, an overly centralized model would limit the swarm's ability to adapt whereas an overly decentralized system would be impossible to control. What this computer simulation showed was that it is feasible for a human to control a swarm's emergent behavior using the FSM proposed earlier. Rather than detailed control, humans control emergence by changing the swarm's state. To demonstrate this, the swarm intelligent algorithm proposed here used a targeting queue. As swarm agents found targets, they placed those targets in a targeting queue and transitioned to a confirming state until the human could approve the target. This concept allows the human to control the swarm's behavior at the macro scale using the concept of mission command proposed earlier. By establishing rules within each state, it is feasible to manage the swarm's behavior while at the same time meeting Department of Defense requirements for semi-autonomous weapons.[49]

The first advantage this provides is that by balancing the strengths of both, the target screening process actually increases the swarm weapon's targeting capacity because it detects more targets. As discussed earlier, robot vision algorithms work, but their confidence levels decrease with uncooperative targets and environmental noise, which in combat will be prevalent. Robot vision algorithms have not reached a point anywhere close to the capabilities of the human eye. In contrast, a single human would never have the capacity to search a 1,590-square mile area in 120 minutes. But, by combining the two, the swarm can use its search capacity to screen targets proposing potential candidate targets for the human to consider. In this case, the human receives the potential targets screened by the swarm and determines which are targets and which are not. This two-layer screening process has the potential to increase the number of targets engaged because there is a higher probability of detecting non-compliant targets.

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[48] Bar-Yam, *Making Things Work*, 61–66.

[49] Department of Defense, DoDD 3000.09 (2017), 8.

The second advantage of a human-swarm team is the ability to integrate multiple levels of analysis. In his book *Thinking Fast and Slow,* Kahneman breaks the human decision-making process down into two systems. System 1 is intuition based and is responsible for most of your daily actions like driving, eating, moving etc. System 2 is cognitive and analytic which is slower and requires more energy, but capable of much deeper analysis.[50] As an artificial intelligence algorithm, the swarm intelligence proposed here falls into the System 1 intuition based thinking. Swarm agents analyze their environment and decide what to do based on a rule set. As a swarm, this System 1 intuition is very fast and facilitates the emergent behavior discussed earlier. With that said, the swarm's artificial intelligence is not capable of System 2 analysis. That form of analysis requires a human. The question then is, whether a swarm weapon needs System 2.

What this simulation showed is that without a human in the loop it was possible for the enemy to manipulate the swarm's behavior based on how they placed threats and targets. Kahneman highlights that a disadvantage of System 1 is that you can easily trick it because biases make it susceptible. The same is true for swarm algorithms because their rule sets represent their biases. As an example, although the fish have a very advanced swarming algorithm, it is still intuition-based and susceptible. Dolphins have actually learned to manipulate the school's swarming algorithm by circling them. As the dolphins circle, the fish continually run away forcing other fish in the swarm to aligning which in effect drives the swarm into a tighter and tighter ball trapping the fish.[51] If all the swarm algorithm can depend on is System 1, then it will be susceptible to manipulation. The same was true in the simulation where it was possible to set threats and targets up in a way that it lured the swarm into a trap.[52] As a result, integrating the human-swarm team using the mission command concept proposed here actually increases the

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[50] Daniel Kahneman, *Thinking, Fast and Slow*, (New York: Straus and Giroux, 2013), 97–105.

[52] Williams, *Swarm Weapon Wargaming Simulation Software to Model Systemic Attack*.

swarm's targeting capability while at the same time freeing the human to integrate critical analysis into the process.

In summary, this research has shown that swarm weapons are feasible and have the potential to provide an operational advantage on the battlefield within the next decade. By using an FSM to manipulate the rules swarm agents follow, operators can shape the swarm's behavior at both the macro and micro level using this concept of emergence. What that allows is parallel attack at a scale that has been impossible to this point. If properly targeted a swarm weapon could operationally paralyze the enemy by isolating their fighting forces from the critical resources they need to operate.

Conclusion

What this research and analysis have shown is that swarm weapons are feasible within the next decade and that those swarm weapons could have a significant impact on the battlefield providing operational advantages through employment concepts like swarm parallel warfare, cooperative survival, pulsing, and adaptive area reconnaissance. To some extent, swarms are already starting to emerge on a small scale. Today, academic and military institutions are continually launching smaller scale swarms with up to 100-agents. Even a swarm of this scale could have an impact on the battlefield, but the real change and potential will come as the size of these swarms start to increase over the next decade. As swarms measured in the hundreds start to emerge the true potential of swarm weapons becomes possible. By integrating already existing technology with these new and larger swarms, their potential becomes apparent. A swarm weapon is more than just a quantitative advantage; it is the ability for a weapon to adapt to the changing environment through emergence.

Emergence allows the actions of a single agent at the micro-scale to shape the swarm's overall behavior at the macro scale. In effect, a swarm is capable of battlefield wide adaptation. The combination of macro and micro adaptation allows the swarm weapon to advantageously shape the battlefield. Integrating the human and swarm together into a team achieves a new level of capability that is impossible otherwise. The swarm offers a search capacity, but the human offers the advantage of reason, analysis, and critical thinking. By integrating the strengths of both, the human-swarm teaming concept is truly more capable than either is alone. The question now is how you could use these capabilities of pulsing, parallel warfare, area adaptive reconnaissance, and cooperative survival on the battlefield.

Concept of Employment #1: Swarm Breach

The first concept of employment to discuss is the swarm breach because it is feasible even today with 100 weapons using the algorithm proposed in this paper. The most likely use of a swarm breach would be a shaping operation to enable the maneuver of another unit. In the land and maritime domain, it might be the breach of an enemy defensive line then holding that breach point open while the force designated as the main effort exploits the breach. In the air domain, this would be very similar, but likely against surface to air missile systems with a follow-on force exploiting the breach by penetrating the enemy support area to interdict targets. The advantage of a swarm breach over conventional weapons is that the adaptive behavior of the swarm would allow the swarm to hold the breach open, integrate swarm reserves, and respond to enemy re-enforcements as shown in Figure 12.

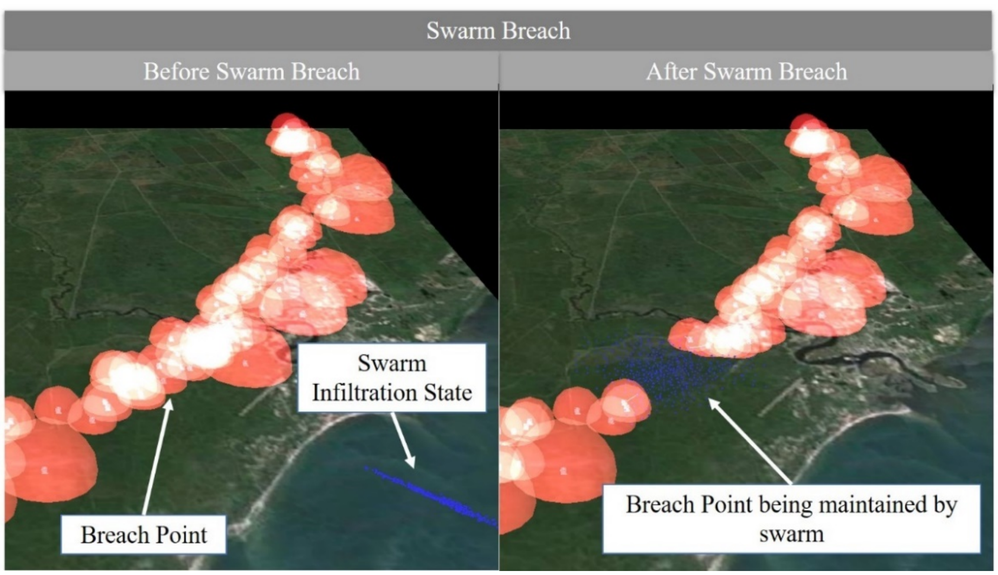

Figure 12. Swarm Breach. Sean Williams, *Swarm Weapon Wargaming Simulation Software to Model Systemic Attack*, Java, 2017.

Concept of Employment #2: Swarm Area Defense

The second concept of employment to consider is the swarm area defense. Field Manual 3-90-1, *Offense and Defense* defines area defense as a defensive task that concentrates on denying enemy access to designated terrain for a specific time.[53] In this case, the swarm's search area would coincide with the unit's defense area. As threats enter the defense area, the swarm would detect threats then relay imagery and position to a human for confirmation then attack. In this case, the swarm can act in a layered defense with the swarm out further providing an outer perimeter defense. The advantage of swarm area defense is that the swarm's adaptive area reconnaissance capability combined with pulsing allows the swarm to adapt and overcome both enemy breaches and frontal attacks.

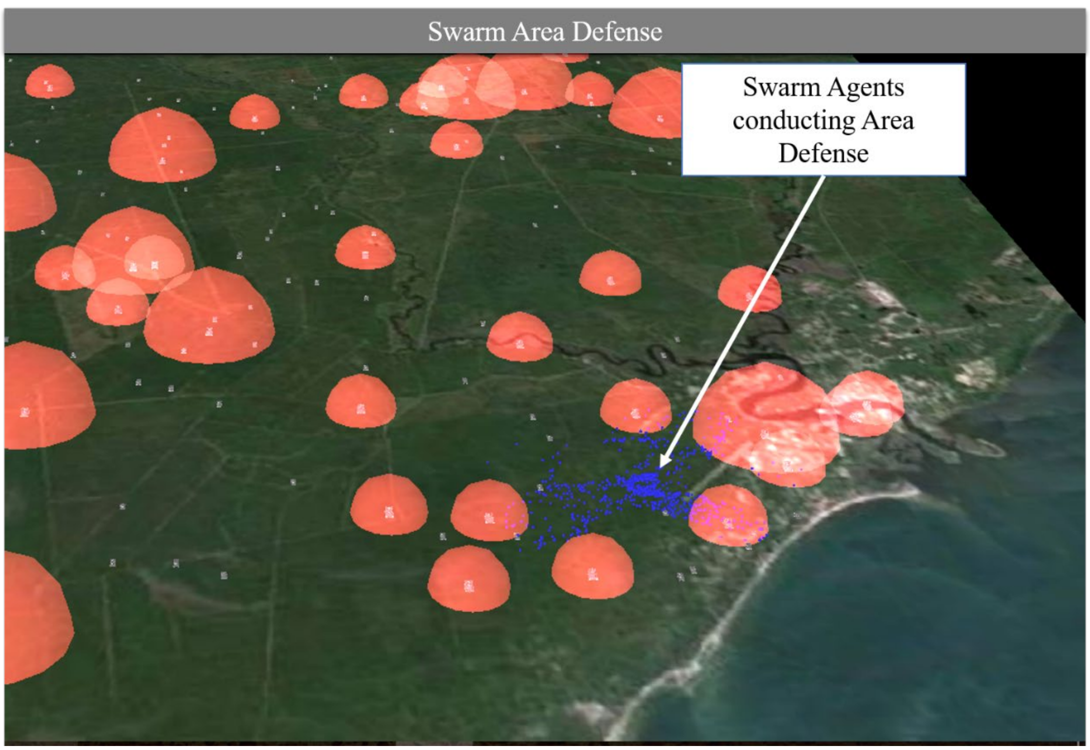

Figure 13. Swarm Area Defense. Sean Williams, *Swarm Weapon Wargaming Simulation Software to Model Systemic Attack*, Java, 2017.

[53] US Army, FM 3-90-1 (2013), 6–2.

Concept of Employment #3: Swarm Wide Area ISR

The third proposed method to employ the swarm weapon would be a wide area surveillance network in a contested environment. The US military has typically dominated the air, land, sea, and space domain, but the proliferation of advanced weapons is challenging that dominance especially in near-peer contested environments. Many of the intelligence platforms used today will not be survivable against a near-peer competitor requiring military leaders rethink how they gather intelligence. Swarm weapons offer a potential solution that can surge into a contested environment to gather intelligence using the same concept proposed for the parallel attack. In this case, rather than attack the target, the drone only captures imagery to either store onboard for exploitation after it returns to base or it could be offboarded using beyond line of sight communication. In effect, the swarm can find both threats and targets in a search area using RF and visual sensors. The adaptive wide area network as shown in Figure 14 allows the network to adapt to losses of drone assets and communication degradation. Cooperative survival increases the swarm's resilience allowing the swarm to search a wide area for targets while surviving in a contested environment. The advantage of this form of employment is that it meets a critical ISR requirement in a contested environment while maintaining survivable systems.

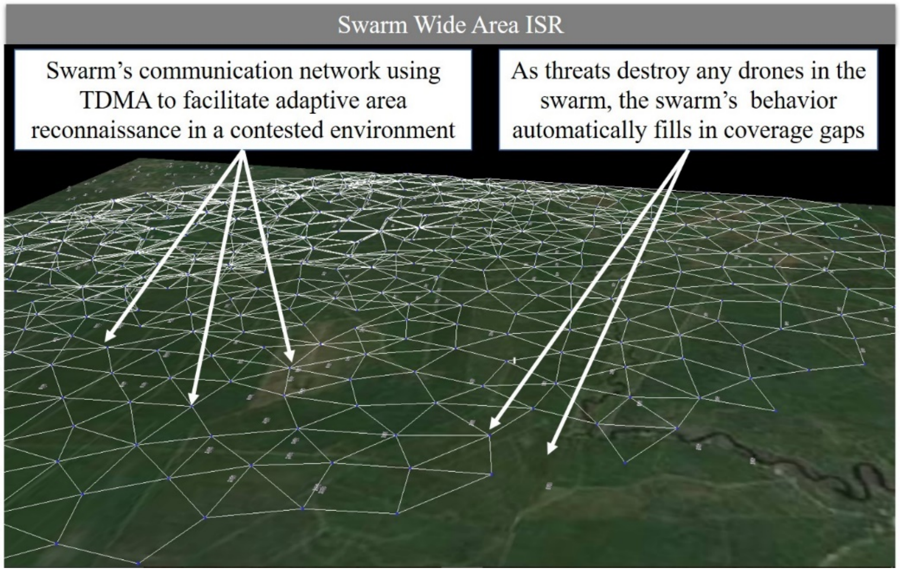

Figure 14. Swarm Wide Area ISR. Sean Williams, *Swarm Weapon Wargaming Simulation Software to Model Systemic Attack*, Java, 2017.

Concept of Employment #4: Swarm Parallel Warfare

The final concept proposed here is parallel warfare, which is arguably the most difficult and contentious but also provides a significant advantage. This paper has shown that this concept is feasible within the next ten years. Additionally, the use of swarm weapons and their adaptive emergent behavior makes the weapon more efficient and lethal. Rather than having to deploy 1000 non-swarming weapons, a swarm can accomplish more with less. Using only 800 drones, the swarm was able to achieve the same effects. This form of selective targeting makes it possible to implement John Warden's theory of operational paralysis by simultaneously attacking the enemy's vulnerable redundancies.

Each of these capabilities offers an operational advantage on the battlefield, but there are still gaps in existing research to address. First, research efforts must find a technological solution to the swarm communications network. This network should emphasize the use of the emergent C2 model because of the advantages in swarm range especially when considering the wide area surveillance and parallel attack concept proposed earlier. The range of the emergent network would be critical to either one of these concepts. Next, researchers need to analyze the human-swarm teaming concept in more detail looking at long-range communications architectures. Because parallel warfare would require these weapons operate beyond the enemy front-line forces, beyond line of sight communications with the swarm would be critical. Finally, an often-overlooked issue with swarm weapons is the logistical requirements of supporting swarm weapons.[54] The results of this research effort showed that although expendable, swarm weapons have the potential to also be survivable. Research efforts should analyze whether it is technologically feasible to reuse swarm weapons and what impact would that have on logistics. As swarm weapons develop, researchers must address each of these issues as early as possible.

[54] Chung et al., "Live-Fly, Large-Scale Field Experimentation for Large Numbers of Fixed-Wing UAVs," 1258.

In conclusion, swarm weapons have begun their transition from science fiction to reality. As states progress along this path over the next decade, the question they must ask is what impact they will have on the battlefield. Although they will not dramatically change our concept of war, they have the potential to significantly shape the battlefield to one's advantage. Through emergence, swarm weapons can adapt at both the macro and micro-scale. The advantage they provide is more than just a quantitative advantage. Swarm weapons can adapt and selectively target in a way that they shape the battlefield. This provides more than just an interdiction capability and it is more than just an air capability. Through swarm breach, wide area surveillance, parallel warfare, and area defense, they have the potential to shape and affect all domains.

Bibliography

Air Force Technology. “Harop Loitering Munitions UCAV System.” *Air Force Technology*. Accessed January 23, 2018. http://www.airforce-technology.com/projects/haroploiteringmuniti/.

Arquilla, John, and David Ronfeldt. *Swarming & The Future of Conflict*. Santa Monica, CA: RAND National Defense Research Institute, n.d.

Ashok, India. “What Is Project Maven? The Pentagon’s New AI Is Hunting Terrorists in the Wild.” *International Business Times UK*, December 30, 2017. Accessed January 22, 2018. http://www.ibtimes.co.uk/what-project-maven-pentagons-new-ai-hunting-terrorists-wild-1653150.

Bar-Yam, Yaneer. *Making Things Work: Solving Complex Problems in a Complex World*. Cambridge, MA: Knowledge Press, 2004.

Beyerchen, Alan. “Clausewitz, Nonlinearity, and the Unpredictability of War.” *International Security* vol 17, no. 3 (Winter 1993): 59–90.

Bonura, Michael A. *Under the Shadow of Napoleon: French Influence on the American Way of Warfare*. Warfare and Culture Series. New York: New York University Press, 2012.

China Electronic Technology Group. *119 Fixed-Wing UAV Cluster Flight Test*. Accessed August 30, 2017. https://www.youtube.com/embed/tE6qzRu0p3Q.

Chung, Timothy H., Michael R. Clement, Michael A. Day, Kevin D. Jones, Duane Davis, and Marianna Jones. “Live-Fly, Large-Scale Field Experimentation for Large Numbers of Fixed-Wing UAVs.” 2016 IEEE International Conference on Robotics and Automation, 2016.

Condliffe, Jamie. “A 100-Drone Swarm, Dropped from Jets, Plans Its Own Moves.” *MIT Technology Review*, January 2017. Accessed August 30, 2017. https://www.technologyreview.com/s/603337/a-100-drone-swarm-dropped-from-jets-plans-its-own-moves/.

Creemers, Rogier, Graham Webster, Paul Triolo, and Elsa Kania, trans. *China’s Next Generation Artificial Intelligence Development Plan*. New America Cybersecurity Initiative, 2017. Accessed January 22, 2018. https://www.newamerica.org/cybersecurity-initiative/blog/chinas-plan-lead-ai-purpose-prospects-and-problems/.

Department of Defense. Defense Directive 3000.09, *Autonomy in Weapon Systems*. Washington, DC: Government Printing Office, 2017.

Dombe, Ami R. “China Unveils a Harpy-Type Loitering Munition.” *Israel Defense*, January 2017. Accessed October 6, 2017. http://www.israeldefense.co.il/en/node/28716.

Horward, Donald D., and Michael V. Leggiere, eds. *Napoleon and the Operational Art of War: Essays in Honor of Donald D. Horward*. History of Warfare, Vol. 110. Leiden: Brill, 2016.

Isserson, Georgii S. *The Evolution of Operational Art*. Translated by Bruce W. Menning. Fort Leavenworth, KS: Combat Studies Institute Press, 2013.

Jerusalem Post. "IAI Exhibits Upgraded HAROP 'Suicide Drone' for Clients," *Jerusalem Post*. Accessed October 6, 2017. http://www.jpost.com/Israel-News/IAI-exhibits-upgraded-HAROP-suicide-drone-for-clients-405266.

Jones, Tim. *Artificial Intelligence: A Systems Approach*. Computer Science Series. Sudbury, MA: Jones and Bartlett Publishers, 2009.

Kahneman, Daniel. *Thinking, Fast and Slow*. New York: Straus and Giroux, 2013.

Miere, Jason L. "Russia Developing Autonomous Swarm of Drones in New Arms Race with U.S. and China." *Newsweek*, May 2017. Accessed October 6, 2017. http://www.newsweek.com/drones-swarm-autonomous-russia-robots-609399.

Naveh, Shimon. *In Pursuit of Military Excellence: The Evolution of Operational Theor*y. The Cummings Center Series 7. London: Frank Cass, 1997.

Northrop Grumman. *Understanding Voice and Data Link Networks*. San Diego, CA: Northrop Grumman, 2014

OMelveny, Sean. "Small Diameter Bomb II Completes Live Fire Test Destroying T-72 Tank." *Military.com*. Accessed October 4, 2017. http://www.military.com/daily-news/2015/02/25/small-diameter-bomb-ii-completes-live-fire-test-destroying-t72.html.

Pape, Robert Anthony. *Bombing to Win: Air Power and Coercion in War*. Cornell Studies in Security Affairs. Ithaca, NY: Cornell University Press, 1996.

Rabunal, Juan Ramon, Julian Dorado, and Alejandro Pazos Sierra, eds. *Encyclopedia of Artificial Intelligence*. Hershey, PA: Information Science Reference, 2009.

Rosen, Kenneth H. *Discrete Mathematics and Its Applications*. 4th ed. Boston, MA: WCB/McGraw-Hill, 1999.

Russell, Stuart J., Peter Norvig, and Ernest Davis. *Artificial Intelligence: A Modern Approach*. 3rd ed. Prentice Hall Series in Artificial Intelligence. Upper Saddle River: Prentice Hall, 2010.

Scharre, Paul. *Robotics on the Battlefield Part II: The Coming Swarm*. Washington DC: Center for a New American Security, 2014.

Smith, Jennifer. "Electric Flock." *Daily Mail*, November 2013. Accessed 12 September, 2017. http://www.dailymail.co.uk/news/article-2514252/Incredible-photos-ofhe-moment-TEN-THOUSAND-starlings-fly-formation-Scottish-Borders.html.

Strategic Capabilities Office. *Perdix Fact Sheet*. Washington, DC: United States Department of Defense, n.d.

Theron, Paul. "Cyber-Attack Strategies Against a Massively Collaborative System," March 2, 2016. Accessed 22 January 2018. https://www.linkedin.com/pulse/identifying-potential-cyber-attack-strategies-against-paul.

United States Air Force. “AGM-88 HARM Fact Sheet Display.” Accessed October 4, 2017. http://www.af.mil/About-Us/Fact-Sheets/Display/Article/104574/agm-88-harm/.

US Department of Defense, Joint Staff. Joint Publication 3-0, *Joint Operations*. Washington DC: Government Printing Office, 2017.

US Department of the Army. Army Doctrine Publication 6-0, *Mission Command*. Washington, DC: Government Printing Office, 2012.

———. Army Doctrine Reference Publication 1-02, *Terms and Military Symbols*. Washington, DC: Government Printing Office, 2016.

———. Field Manual 3-90-1, *Offense and Defense Volume 1*. Washington, DC: Government Printing Office, 2013.

U.S. Government Accountability Office. “Defense Acquisitions Assessments of Selected Weapon Programs.” Report to Congressional Committee, March 2017.

Walters, Louis P. *Applications of Swarm Intelligence*. New York: Nova Science Publishers, 2011.

Warden, John. “Air Theory for the 21st Century.” In *Challenge and Response, Anticipating US Military Security Concerns*, edited by Dr. Karl P. Magyar, 351-374. Maxwell Air Force Base, AL: Air University Press, 1994.

Wired. "All About Lady Gaga’s Super Bowl Halftime Show Drones.” *Wired*. Accessed October 6, 2017. https://www.wired.com/2017/02/lady-gaga-halftime-show-drones/.

Sean Williams. "John Warden’s Air Theory and Its Relevancy to Multi-Domain Warfare" Paper, presented at School of Advanced Military Studies, Fort Leavenworth, KS, 2017.

———. *Swarm Weapon Wargaming Simulation Software to Model Systemic Attack*. Java, 2017.