# Swarming Autonomous Unmanned Aerial Systems

A Monograph

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Swarming is a tactic long employed by military forces to offset military advantages by leveraging emergent technologies. This monograph explores the potential for the employment of swarming on the modern battlefield. The development and operationalization of autonomous unmanned aerial vehicles (UAVs) and emergent technologies have increased the versatility and lethality of swarm UAVs. Successful integration of this technology into the US military operations requires theory, operational concepts, and tactics that the military has yet to construct. Adversaries of the United States continue to make advances in the use of semi-autonomous and autonomous weapon systems that are quickly reducing the technological gap currently held by the US military. As such, this monograph suggests that the Department of Defense needs to make greater efforts in prioritizing the employment of swarming autonomous UAVs.

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# Abstract

Swarming Autonomous Weapons Systems, by MAJ B. Paola Benson, US Army, 49 pages.

Swarming is a tactic long employed by military forces to offset military advantages by leveraging emergent technologies. This monograph explores the potential for the employment of swarming on the modern battlefield. The development and operationalization of autonomous unmanned aerial vehicles (UAVs) and emergent technologies have increased the versatility and lethality of swarm UAVs. Successful integration of this technology into the US military operations requires theory, operational concepts, and tactics that the military has yet to construct. Adversaries of the United States continue to make advances in the use of semi-autonomous and autonomous weapon systems that are quickly reducing the technological gap currently held by the US military. As such, this monograph suggests that the Department of Defense needs to make greater efforts in prioritizing the employment of swarming autonomous UAVs.

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# Acronyms

| | |
|---|---|
| DARPA | Defense Advanced Research Projects Agency |
| DoD | Department of Defense |
| GPS | Global Positioning System |
| ISIS | Islamic State of Iraq and Syria |
| ISR | Intelligence, Surveillance, and Reconnaissance |
| JCRAS | Joint Concept for Robotic and Autonomous Systems |
| LOCUST | Low-Cost Swarming Technology |
| OFFSET | Offensive Swarm-Enabled Tactics |
| RAS | Robotic and Autonomous Systems |
| TRA | Teledyne-Ryan Aeronautical |
| TRADOC | Training and Doctrine Command |
| UAS | Unmanned Aircraft Systems |
| UAV | Unmanned Aerial Vehicles |
| UCAV | Unmanned Combat Aerial Vehicle |
| UGS | Unmanned Ground Systems |

# Introduction

> It is not possible fully to separate the art and science of war from technology; they are too tightly bound in with each other and stand too closely alongside each other in their very strong and unbreakable mutual effects.
>
> — General Mac Schwarte, *Technik des Kriegswesens* (Leipzig, 1913)

The 2017 *Slaughterbots*, a film produced by students at the University of California Berkeley, warns of the rapid development of military technologies. In the film, a fictitious company develops an armed microdrone capable of executing precision strikes against preprogrammed targets utilizing artificial intelligence, facial recognition technologies, and tactical sensors. In the film, the industrial sponsor of this technology makes the claim that this technology marks the transition to a new age of warfare, making nuclear weapons obsolete as the tiny robots provide a scalable weapon of mass destruction that is precise, effective, efficient, and, most importantly, unstoppable.[1] Although *Slaughterbots* is a science fiction dystopia intended to propagate anti-autonomous lethal weapons rhetoric, the film illustrates the potential capability of automated weapon system swarms and the effects capable of combining technologies that are currently available for military use. The concept of using unmanned aerial autonomous weapons to eliminate targets is not only realistic but a reality. Countries like China, Israel, and Russia currently invest in the research and technology necessary to produce and employ autonomous weapons systems, in particular autonomous unmanned aerial vehicles (UAVs), as part of their military arsenal.[2] Similarly, non-state organizations like Hezbollah and the Islamic State of Iraq

[1] *Slaughterbots*, dir. Stewart Sugg, screenplay by Stuart J. Russell and Matt Wood. Slaughterbots, November 17, 2017, accessed January 30, 2018, https://www.youtube.com/-watch?v=9CO6M2HsoIA.

[2] US Naval War College, "Autonomous Weapon Systems Brief: Lt. Col. Jeffrey S. Thurnher: Legal Implications of AWS," YouTube, June 05, 2013, accessed March 26, 2018, https://www.youtub-e.com/watch?v=muQFmY8HvUA.

and Syria (ISIS) search for new methods deliver lethal strikes such as the utilization of low cost drones to attack their opponents.[3]

The use of unmanned aerial systems (UAS) coupled with the military application of current technologies presents a significant perceived threat to society throughout the world. Viewers throughout the world can already see the effects of airstrikes enabled by semi-autonomous UAVs, like the Predator, in Iraq, Afghanistan, Yemen, and other countries. The implications of developing and harnessing weapons systems which combine current and emergent technologies have caused such concern that in 2015, renowned scientist Stephen Hawking, artificial intelligence researcher Stuart Russell, and other scientists signed an open letter to the United Nations requesting the ban of autonomous weapons systems designed for lethal purposes. In this letter, scientists refer to autonomous weapon systems as the “third revolution in warfare” after gunpowder and nuclear weapons. The letter discusses the moral, ethical, and physical risks posed by these weapons and the necessity to ban such capability. In addition to simple, easy to use and produce characteristics of UAV technology, manufacturers can produce these weapons at a fraction of the cost of nuclear weapons with scalable and accurate effects. Swarming autonomous weapon systems could potentially be the next weapons of mass destruction, scalable in size and effectiveness as well as efficiently reliable.[4]

Over eighty-five countries possess semi-automated weapon systems, including the United States, Russia, and Israel that have used the technology in combat operations and openly pursue the technological capability to employ swarms of autonomous weapon systems.[5] Understanding

[3] Paul Scharre, “Why You Shouldn’t Fear ‘Slaughterbots’,” IEEE Spectrum, December 22, 2017, accessed January 12, 2018, https://spectrum.ieee.org/automaton/robotics/military-robots/why-you-shouldnt-fear-slaughterbots.

[4] "Open Letter on Autonomous Weapons," Future of Life Institute, July 28, 2015, accessed January 13, 2018, https://futureoflife.org/open-letter-autonomous-weapons/.

[5] New America Foundation, "Machines That Kill: Will We Rely on Autonomous Weapons," YouTube, March 02, 2015, accessed March 27, 2018, https://www.youtube.com/watch?v=g2P1KaQ4AC4.

the implications and applications of swarming UAV technology offers insight on how the military can attain an operational advantage on the battlefield as well as counter an adversary's ability to utilize this technology. This technological pursuit constitutes a race, seeking a technological advantage that could potentially shift the balance of power in global military supremacy. The significance of swarming UAV tactics and the potential military application of emergent, autonomous technologies directly correlates to the impact of these systems at the operational level of warfare. At the operational level, these systems could have the capability to shape the battlefield by providing greater coordination, survivability, intelligence, and speed to overwhelm the adversary. As such, exploration into the operational implications of swarming autonomous UAVs at the operational level is significant as it could potentially prevent strategic defeat in the next conflict. Understanding these implications and developing a doctrinal framework to maximize the capability of this technology have the potential to offset any advantage held by an adversary.

The time for the US military to develop ways to offset an adversary's technological advantage by employing and defending against swarming autonomous UAVs is now. The technologies to conduct swarm attacks already exist and could pose significant challenges in the very near future. This technology is cheap and available to many non-state actors as well as state adversaries that could employ a swarm of autonomous UAVs against any US formation overseas or over a populated area within the United States homeland. These attacks, similar to the January 2018 Syrian rebel drone attack against a Russian airbase in Syria, could potentially constitute high yield, low risk operations that would significantly alter the balance of technological superiority traditionally held by the US military.[6] Therefore, it is important to acknowledge the

[6] Raf Sanchez, 2018, "Russia Uses Missiles and Cyber Warfare to Fight Off 'Swarm of Drones' Attacking Military Bases in Syria," *The Telegraph*, January 9, 2018, accessed January 12, 2018, https://www.telegraph.co.uk/news/2018/01/09/russia-fought-swarm-drones-attacking-military-bases-syria/.

immediate threat as well as the potential for rapid growth and military application of the technology in this field.

As other nations currently pursue semiautonomous and autonomous weapons and the capability to swarm, the US Army should have a more concerted approach to develop a doctrinal framework to employ and defend against swarming autonomous weapons systems to maintain global military supremacy. Furthermore, both the development of this doctrine and consideration of the effects of swarms of autonomous UAVs on the battlefield lead to the discussion of shaping the requirements for autonomous and semi-autonomous weapon systems. Unmanned autonomous technology, combined with swarming tactics, could harness a critical advantage to US military leaders in an operational fight both offensively and defensively. Swarming autonomous UAVs could provide a division commander with opportunities to achieve and exploit success on the battlefield by simultaneously shaping the deep fight, countering adversarial initiatives, collecting intelligence, and aiding target identification. Additionally, the employment of these weapon systems could enable greater coordination, survivability, intelligence, and speed required to overwhelm the adversary in all contested domains.

To provide context as to how this technology can assist commanders achieve and exploit success at the operational level, an understanding of swarming theory assists military practitioners with a fundamental concept for employment and integration of technology at the tactical and operational level. An examination of historical uses of swarming tactics reveals the impact and effects that swarming has had on the battlefield and demonstrates the potential for future use. A review of the historical employment of UAVs exhibits the modern evolution and progression of the concept of military swarming. Lastly, a consideration of emergent technologies and swarming concepts aids military practitioners in assessing the planned implementation of emergent technologies, the timeline associated with these programs, and the frameworks constructed by the Department of Defense (DoD) to procure and integrate these systems.

Considering these lines of research informs commanders on the efforts needed to employ and maximize the capability of these weapons on the battlefield to maintain an operational advantage.

## Swarming Theory

> It is not enough for theory to describe and analyze, it must itself be an event in the universe it describes.
>
> — Jean Baudrillard, "Why Theory?", *The Ecstasy of Communication*

In today's complex world full of numerous technological advancements and information systems, swarming stands as an emergent concept that provides a means to cope and, potentially, thrive in it. To fully understand how swarm technologies can impact the battlefield, it is important, firstly, to generally understand what a swarm is and, secondly, to understand its origins and theory for potential use in the military. Understanding this contextual background provides a foundation for the military practitioner to explore swarming's potential in cross-domain disciplines. This understanding further enables the exploration of potential uses and applications for the US Army to couple technological advances and swarm theory to gain an operational advantage on the battlefield.

### Swarming in Nature

A swarm is a network formed by groups of individuals that engage in an activity benefitting the group as a whole by relying on the interactions between individuals and their environment. A key feature of a swarm is decentralized or distributed control to ensure the cohesion of the swarm is never lost.[7] These interactions are a result of local stimuli. The basic premise of swarming is evident in natural life. Nature provides examples of swarms and a general understanding of the necessary components and requirements for swarms to function effectively in harmony.

[7] David Hambling, *Swarm Troopers: How Small Drones Will Conquer the World* (Lexington, KY: Archangel Ink, 2015), 186.

Swarming is a complex behavior commonly observed in social animals such as a flock of birds, a herd of gazelles, a school of fish, and a pack of wolves. These animals perform simple tasks that, when conducted in a sequence, form a coordinated motion that provides an evolutionary advantage in the survival of the species. Stigmergy, a self-organization behavior exhibited by these animals, underlies the cooperative behavior, coordinated motion, and division of labor exhibited by these animals. For example, flocks of ducks fly in a V-shaped formation to improve aerodynamic efficiency, ensuring all members of the flock survive migration. Schools of fish also demonstrate similar complex behaviors of simple, coordinated motions. This behavior in fish is a self-defense mechanism, an anti-predator adaptation that serves as cover and concealment. The school of fish forms large swarms that can seem to be a larger animal, providing the individual fish with a hydrodynamic advantage to evade potential predators. This coordinated motion allows a school of fish an ability to change shapes in an effort to confuse the attacking predators.[8] While swarming provides examples of defensive behaviors to assist animals react to their environment and overcome complex issues to ensure the survival of the species, swarming in nature also demonstrates offensive capabilities such as the collaborative hunting for prey by pack animals such as wolves or lions. Swarming is not only evident in animals; humans also display swarming behaviors that enable the survival of the group.

## Swarming in a Complex Social World

Advanced technologies, decentralized networks, complex social relationships, and an infinite amount of information make adaptation and interacting within the environment difficult. Some theorists like Antoine Bousquet, Everett C. Dolman, and Peter Singer suggest that swarming logic is a helpful and efficient way to react, navigate, and adapt to the chaotic and

[8] Joao Hespanha and Francis Doyle, III, "Bio-Inspired Network Science," in *Bio-Inspired Innovation and National Security* (Washington, DC: United States National Defense University, 2010), 281-290.

complex environment today's technological advances and social requirements have imposed.[9] Similar to the actions of social animals in nature to use swarming behavior to survive, humans also demonstrate swarming techniques. An example of natural swarming pertains to feeding the population of New York City. No single entity controls or requests food for New York City. Instead, requisitions, shipments, and the concept of supply and demand explain why the population of the city continues to have food readily available for consumption. Numerous individuals, performing simple actions in a concerted effort with little hierarchical control, seemingly solve this complex problem. Another example is the self-organization of crowds, rallies, or protests. While leaders initiate the activities of smaller bodies, these small bodies can grow exponentially with no further direct interaction between leaders and observant individuals who respond to the stimulus of the crowd.[10]

Swarming transcends disciplines from nature to business corporations to the military. Additionally, swarming transcends domains from physical to air, sea, space and cyber. Swarming can be either a natural or acted upon behavior that helps individuals to survive in a complex environment. Examples of human swarming are just as apparent now that humans rely on artificially networked systems and broadband internet, achieving coordinated actions from large groups of people.[11] While social media serves as the most popular form of human swarming and the exchange of ideas, the use of all-points bulletins and the Amber Alert system also provide examples of using networked systems to organize human activity for a single purpose.

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[9] Antoine Bousquet, *The Scientific Way of Warfare: Order and Chaos on the Battlefields of Modernity* (New York: Columbia University Press, 2009), 210-215; Everett C. Dolman, *Pure Strategy: Power and Principle in the Space and Information Age* (London: Frank Cass, 2005), 171-172; P.W. Singer, *Wired for War: The Robotics Revolution and Conflict in the Twenty-First Century* (New York, Penguin Books, 2009), 230-234.

[10] P.W. Singer, *Wired for War*, 232.

[11] Hespanha and Doyle, "Bio-Inspired Network Science," 281.

Swarming behavior is the simplest, most effective and efficient way in interact to a complex and chaotic environment. Author Yaneer Bar-Yam states that the more complicated and larger the system is, the interactions and relationships between individuals become simpler.[12] This allows a swarm to exist effectively and efficiently adapt to its environment overcoming any threats or challenges the environment may pose.

## Swarming in Military Theory

Nature provides valuable insights as to how the military can use swarming. Collaborative and anti-predatory swarming emulates principles of offensive maneuvers and divisions of labor that resemble shaping and decisive operations. These operations center on the principle that simple interactions between individuals and appropriate reactions to local information or environment will improve the chances of survival for the entire group.

Theorists John Arquilla and David Ronfeldt claim that swarming tactics are the next step in warfare. Swarming, however, has been a military tactic used throughout history. Armies used large numbers of personnel to conduct multi-directional and repetitive attacks to overwhelm and defeat an opponent. Arquilla and Ronfeldt define swarming as a way of war as a systematic approach to attack an opponent with interconnected units pulsing fire or force from all directions simultaneously.[13] Swarming is a tactic where large numbers of systems coordinate actions and self-organize to attack an adversary. Swarms are effective in achieving operational outcomes by massing cohesive but decentralized network-system against an adversary.[14]

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[12] Yaneer Bar-Yam, *Making Things Work: Solving Complex Problems in a Complex World*. (Cambridge, MA: NECSI, Knowledge Press, 2004), 91.

[13] Arquilla and Ronfeldt, *Swarming and the Future of Military Conflict,* 8.

[14] US Department of Defense, Joint Chiefs of Staff, *Joint Concept for Robotic and Autonomous Systems (JCRAS)* (Washington, DC: United States Department of Defense, 2016), 8.

Arquilla and Ronfeldt also identify that swarming provides an outnumbered force an advantage in terms of manning, firepower, or technological capability an opportunity to offset the advantage. For swarming to be successful, the commander relies of the elements of surprise, mobility, and situational awareness to weaken the opposing force. Additionally, connectivity is important as it allows stigmergy to happen within the units of the swarm. Swarming is a decentralized network that will required a decentralized command and control structure, relying on mission command and commander's intent to facilitate flexibility and provide purpose.[15] Military swarming requires the unit to be able to sustain "pulsing" of either force or fire against an opponent.[16] Military swarming requires a large number of small maneuverable units that can communicate across the operating environment.

In the past, armies employed swarming techniques to offset advantages in numbers and sometimes weaponry. Arquilla and Ronfeldt draw three types of swarming from nature that they believe would be helpful for the military: blanketing, hunting like packs, and mobbing. Blanketing refers to the covering or claiming of territory by a large swarm foraging outside the hive or nest. Arquilla suggests that this swarming technique describes the actions of units patrolling an area and massing to destroy any threats within the area. Another form of organization is hunting in packs, like wolves and hyenas. Packs travel in semi-dispersed formations and come together to target a herd, attack the weakened members, and again disperse. Guerilla warfare demonstrated by the Spanish guerrillas against the French during the Napoleonic War or by the Communist Chinese in Mao's "Peoples War" demonstrates this applicability. The German U-Boat campaign of WWII provides another example of the wartime application of

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[15] Dan Gettinger, "What You Need to Know About Drone Swarms," Center for the Study of the Drone, December 28, 2014, accessed March 27, 2018, http://dronecenter.bard.edu/what-you-need-to-know-about-drone-swarms/.

[16] Arquilla and Ronfeldt, *Swarming and the Future of Military Conflict*, 21, 23.

hunting in packs. Arquilla describes the third form of swarming as “mobbing” to describe the overwhelming massing of people focused on a single objective. An example of mobbing in warfare is the Chinese deployment of the volunteer force used to push back the American advance during the Korean War. However, with the exception of the U-boat example, these examples represent swarming with a direct correlation to human swarming. Like Arquilla and Ronfeldt, modern military theorists suggest that swarming applied for military use can win wars by providing the capability to offset any technological advantage and effectively operate in a complex environment against a capable adversary.[17]

As human swarming denotes risk of high casualties, the application of swarming techniques as it applies to the employment of technology is a more feasible application of the theory. Animal swarming behavior inspired the heuristic model that made unmanned aerial system swarms a reality. The characteristics of cooperative behavior, coordinated motion, and division of labor are a result of stigmergy, a self-organization behavior that robotic engineers and artificial intelligence researchers wanted to replicate with robotic and autonomous systems. The autonomous systems operate on three governing rules: cohesion, separation, and alignment that, allows the individual units to fly together without crashing onto each other.[18] Using these governing rules, robotic and autonomous systems can replicate stigmergy and swarm behavior leading to a major military advantage at the strategic, operational, and tactical level.

Considering technological advances such as smartphone technology, global positioning system (GPS), and artificial intelligence along with the miniaturization of UAVs also make swarming a capability the US military can exploit to maintain its global military supremacy. The

[17] John Arquilla and David Ronfeldt, *Swarming and the Future of Military Conflict,* (Santa Monica, CA: RAND, 2000), 25-27.

[18] Hespanha and Doyle, “Bio-Inspired Network Science,” 288.

US military continues to conduct research and set conditions to fight future wars, attempting to conduct warfare with more autonomous weapon systems to maximize effects and minimize risk to the warfighter on the battlefield. As technology advances and modes of threat change, so should the theories of how to defeat such emergent and potentially disruptive technologies and threats. Swarming in the battlefield using small autonomous weapon systems will require a new army doctrine. Modern military theorists take into consideration the technological advancements and couple them with swarming tactics to propose new theories on how the military should employ a swarm of autonomous UAVs.

Paul Scharre defines swarm warfare as “the combination of highly decentralized nature of melee combat with the mobility of maneuver and a high degree of organization and cohesion, allowing a large number of individual elements to fight collectively.”[19] Scharre posits that swarming UAVs can provide the military a wider range of operational reach and tempo for combat operations. Additionally, Scharre suggests that a swarm of UAVs can improve the military capabilities of massing fires and forces, coordination, intelligence collection, and surveillance of the battlefield at a considerable low financial cost.[20]

Scharre recommends the US military adopt a new operational concept and a paradigm shift to adopt and implement swarming tactics. Scharre submits that the US military heavily invests in existing operational paradigms that make it hard for procurement and implementation of the new technology and tactic of swarming. To assist in reshaping the US military’s current paradigm regarding swarming UAVs, Scharre provides five different examples of how robotic systems using swarming tactics can assist US forces on the battlefield. He suggests that UAVs

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[19] Paul Scharre, "Unleash the Swarm: The Future of Warfare," War on the Rocks, March 04, 2015, accessed August 20, 2017, https://warontherocks.com/2015/03/unleash-the-swarm-the-future-of-warfare/.

[20] Ibid.

can provide coordinated offensive attacks and defense similar to Iran's naval swarming tactics. UAVs with adaptive technology can establish self-healing networks and provide a higher mission success rate. The adaptive technology of swarming UAVs allows the swarm to reconfigure and reorganize itself to overcome any challenges, losses of individual vehicles, and continue mission execution. Another way a swarm of UAVs provides an advantage in the battlefield is to distribute sensing and attacks in the electronic domain. Finally, Scharre posits that UAVs serve as an excellent asset to conduct deception operations and collect intelligence.[21] While Scharre's examples provide excellent applications of UAV technology to the battlefield, he also points out that non-state actors are already developing techniques to employ swarms of low-cost UAVs that can accurately seek out targets without detection, creating an opportunity for a shift in tactical dominance. Scharre implores military leaders to develop a framework that allows the timely procurement of technology and implementation of new concepts of operations and doctrine to successfully employ swarming UAVs on the battlefield and ensure the United States maintains its military supremacy.

Another military theorist that writes about swarming UAVs and its military applications is David Hambling. He describes a swarm as a group of autonomous drones in which the drones cooperate to work together while dispersed over a wide area.[22] Hambling likens a swarm to an organism that cannot be killed by destroying a specific part, stating swarms have no center of gravity as a swarm has the capability to overcome battle and mechanical losses and still be capable of executing all the same actions.[23] Suggesting that UAVs should operate as swarms,

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[21] Paul Scharre, "Counter-Swarm: A Guide to Defeating Robotic Swarms," War on the Rocks, March 31, 2015, accessed July 18, 2017, https://warontherocks.com/2015/03/counter-swarm-a-guide-to-defeating-robotic-swarms/.

[22] David Hambling, *Drone Swarms will Change the Face of Modern Warfare,* 6.

[23] Hambling, *Swarm Troopers,* 187.

Hambling lists the capabilities of swarm UAVs in three categories: offensive, defensive, and intelligence support. Offensively, a swarm of UAVs can leave an enemy unit vulnerable by destroying the radars, missile launchers, and any other key systems required to defend itself. Defensively, a swarm can form a protective barrier to defend against physical and electromagnetic attacks. Lastly, Hambling discusses the efficiency that swarm UAVs provide for intelligence collection and target identification, exacting more precision and efficiency than using just one UAV. Hambling suggests these capabilities provide a clear advantage on the battlefield for the military leaders that can figure out how to employ this technological capability effectively. Hambling, like Scharre, suggests that the US military should develop a doctrine for the employment of swarm UAVs in order to sustain its technological and military advantage over other technology-seeking states such as China and Russia. Hambling suggests that military leaders do not have enough trust on the reliability and effectiveness of swarm robotics to develop a doctrine for unmanned warfare. Hambling states that swarming UAVs have the potential to change the battlefield geometry and the conduct of war; therefore, the US military should seek to employ this technology as soon as possible.[24]

Peter Singer is another military theorist that sees advantages in the employment of swarming autonomous weapon systems for military purposes. Similar, to Arquilla, Singer suggests that swarming entails a dispersion of combat power. Singer states that the swarming tactics that Arquilla postulated are now a reality due to advances in technology. Swarming autonomous UAVs can provide depth, speed, and accuracy in identifying and attacking targets on the battlefield. Furthermore, swarms can produce "psychologically debilitating" effects on the enemy. Singer proposes that swarming autonomous weapons systems will replace soldiers on the battlefield, reducing the risk to humans whilst providing redundancy and flexibility to ensure

[24] Hambling, *Drone Swarms will Change the Face of Modern Warfare*, 7.

mission success. Singer also calls for military leaders to develop a framework to master the technological innovations and ensure proper integration and employment of emergent military technologies.[25]

Another theorist, Irving Lachow, posits that swarms of autonomous weapon systems create a tactical and operational advantage. According to Lachow, swarming UAVs can be employed to defend; attack; provide support operations such as intelligence, surveillance, and reconnaissance; and conduct logistic operations. Lachow suggests swarms of UAVs can overwhelm enemy defenses with a large number of potential targets that are resilient and harder to destroy providing a tactical advantage to exploit. Swarms have the potential to act as anti-access and air defense weapons by swarming over an airfield to prevent an adversary's aircraft from taking off or to conduct air-to-air attacks against adversarial aircraft, colliding with planes to cause mechanical damage, and forcing planes to land.[26] The ability of the swarm to disperse makes it difficult and costly to defeat. Lachow observes that the only way to defeat a swarm of drones may be with another swarm of drones. He states that a swarm of UAVs is more cost effective because it is cheaper to replace a small UAV than it is to replace a manned or unmanned airplane or anti-air missiles used on US Navy ships. Additionally, Lachow comments that swarms are useful in psychological warfare, instilling fear in the enemy. The versatility of the swarm exceeds expectations beyond direct action, potentially coordinating motions to create decoys that can deceive enemy radar systems. Lachow states that the US military can gain much from

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[25] P.W. Singer, *Wired for War: The Robotics Revolution and Conflict in the Twenty-First Century*, 234-235; Ronan Doare et. al, *Robots on the Battlefield: Contemporary Issues and Implications for the Future* (Fort Leavenworth, KS: Combat Studies Institute Press, 2014), xx.

[26] Irving Lachow, *The Upside and Downside of Swarming Drones*, published online 28 February 2017, accessed on 15 November 2017, http://dx.doi.org/10.1080/00963402.2017.1290879.

developing a framework that allows for quick procurement and implementation of swarming UAVs.[27]

The commonality of military theorists currently writing about swarm theory is the inherent belief that swarming UAVs have the potential to change warfare. The rapid evolution of technology presents offensive, defensive, and combat support capabilities that these theorists suggest the US military needs to quickly appropriate, cautioning that failure to do so will equate to relinquishing the technological advantage held by the US military since the 1980s.

## Historical Uses of Swarming

To understand the past and to judge the present is to foresee the future.

— JFC Fuller at the Royal United Service Institute's Chesney Gold Medal in 1919

According to John Arquilla, the evolution of warfare consists of four methods of attack: the chaotic melee, massing rigid formations, maneuver, and swarming. Maneuver replaced the linear formations of an undisciplined force. Advances in technology and organization led to smarter ways to defeat an opponent. Outnumbered and outgunned armies then recognized that swarming offset the comparative advantage of an adversary. These armies defeated their opponent by massing fires and forces to conduct pulsing and dispersed attacks, a distinct characteristic of swarming tactics. The massing of fires and forces by the swarming unit required a strong communication network and organizational structure to coordinate the attacks. Advances in information operations and technology throughout the years continue to make swarming a reality on the battlefields. The success of swarming and the growing availability of low cost technologies have resulted in a wider variety of actors employing this tactic. This expansion of

[27] Laurent Beaudoin et al., "Potential Threats of UAS Swarms and the Countermeasures Need," *ResearchGate*, March 16, 2015, accessed November 15, 2017, https://hal.archives-ouvertes.fr/hal-01132236/document**.**

swarming on the battlefield requires the US military to develop a basis for development of offensive and defensive swarming doctrine.[28]

Throughout history, however, swarming has been a common tactic in war. Militaries of ancient empires utilized horses to provide mobility while the bow added a capability to attack at standoff ranges. The Persians used this tactic of swarming with horses to conquer a vast majority of the Middle Eastern empire. Alexander the Great used similar tactics while also becoming the first military commander to develop and employ counter-swarming measures against the Scythians in 329 BC.[29]

Militaries have traditionally coupled prevalent technologies of the time with mass to employ swarming techniques both offensively and defensively at the tactical and operational levels of war in many different environments. In the thirteenth and fourteenth centuries, the Mongols mastered swarming in land warfare. The ability to use the composite bow, horses, and forward scouts enabled Genghis Khan to apply swarming successfully on the battlefield, conquering Eurasia in less than one hundred years. The Mongols used the available technology of arrows, bows, and horses to increase mobility and reduce risk to forces by creating a standoff fire capability. Utilizing a decentralized command structure, the Mongols enabled subordinate commanders to make timely and effective decisions as microcosms of a larger echelon. Additionally, the Mongols implemented a spy network reinforced by forward scouts to conduct reconnaissance and develop detailed knowledge of the environment and the opposing forces, providing the Mongols with a better understanding of the operational environment and signaling coordinated and widely dispersed attacks.[30]

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[28] Arquilla and Ronfeldt, *Swarming and the Future of Conflict*, 7, 36.

[29] Ibid., 29.

[30] Edwards, *Swarming and the Future of Warfare*, 209-212.

Continuing into the twentieth century, the combat tactics of World War II also demonstrated examples of defensive and offensive swarming. During the Battle of Britain in WWII, the Royal Air Force (RAF) employed squadrons of Hurricanes and Spitfires to create a protective barrier between key infrastructure and Germany's Luftwaffe raids. The Royal Air Force coordinated this defensive swarm by integrating a smaller fleet of aircraft by radios and relying on a decentralized command and control system, effectively synchronizing attacks. Although the German air forces arguably had better equipment than did the outnumbered British, the RAF deterred German invasion of the British Isles.[31]

As swarming requires situational awareness and a decentralized network to coordinate and synchronize attacks effectively on the battlefield, the British leveraged those systems and the technologies of the time to effectively employ swarming at the operational level during the 1940 Battle of Britain.[32] The British Fighter Command established an effective and decentralized organizational system that gave the British an operational advantage. The British command and control system included headquarters elements at multiple echelons, radar stations, the public telephone system, an observer corps, and radio interception stations that worked in concert to provide early warning of incoming German attacks and synchronize a defensive attack. The radar stations identified incoming German fighters at approximately eighty miles and provided the information to the tactical headquarters via telephone. Once the British determined the distance and direction of the German fleet, the radar stations relayed the information to the group and sector headquarters to continue to track inbound German sorties. The observer corps, along with low radio-intercept teams, confirmed and provided further detail about the range and type of incoming German aircraft to the group and sector commanders. The decentralized network

[31] Edwards, *Swarming and the Future of Warfare*, 248.

[32] Ibid.

provided intelligence from multiple sources that enabled the British Fighter Command to develop great situational awareness and therefore, avoid surprise by the Luftwaffe.[33]

The British Fighter Command's decentralized command and control system was effective at providing great situational awareness. The British staff managed the information flow from multiple sources within an operations center designed to maintain a common operating picture for the entire command. This common operating picture enabled the group commanders to decide which squadrons to scramble by assigned sector. The sector station commanders then decided how to deploy their fighters to intercept the German bombers. This decentralized command and control system allowed for different sectors to assume command temporarily depending on mission requirements. Squadrons from one sector could operate freely in another sector's airspace. When one sector was bombed, another took over seamlessly. The decentralized command and control and effective communications network enabled the British to interdict the German Luftwaffe's air raids.[34]

To counter German efforts to bomb British airfields, the Royal Air Force allowed German reconnaissance aircraft to gather intelligence and observe activity at selected airfields. Once the German Luftwaffe identified the desired target and launched a formation of bombers, British radar stations identified the German bombers. The RAF then sent out planes from widely dispersed air bases to counter and destroy the German bombers.[35] While swarming at the operational level facilitated the massing of British forces, swarming at the tactical level enabled the RAF's fighters to concentrate on destroying the Luftwaffe's bomber formations using swarming tactics to break the formation and separate the bombers from their fighter escorts.

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[33] Edwards, *Swarming and the Future of Warfare*, 249- 251.

[34] Ibid., 251-252.

[35] Arquilla and Ronfeldt, *Swarming and the Future of Conflict*, 33.

Multiple British squadrons' fighters worked together in the air to conduct swarming attacks against the German bombers. The British fighters massed to attack the Luftwaffe's bomber formation from the front and the flanks causing catastrophic damage to the Luftwaffe's bombers. Then, British fighters disengaged and scattered to avoid destruction in detail. The RAF inflicted major damage on the Luftwaffe's bomber formations and denied the Germans the ability to set the necessary conditions to invade England.[36]

Despite the parity of technology, the RAF defeated the German air raids with swarming tactics. The British decentralized and flexible command and control system, intelligence network, and use of the prevalent technology of the time to gain great situational awareness enabled the successful implementation of swarming tactics. The RAF's swarming tactics proved successful in the Battle of Britain so much that the Germans adopted these tactics in their defense against future Allied air campaigns.[37]

Most swarming theorists propose that swarming is most useful in the offense. Like wolves in a pack hunting for prey, military swarms are effective at attacking and destroying the desired target from multiple directions by using a well-establish communication network to obtain great situational awareness and speed to mass at the appropriate time and location. In WWII, the available technology allowed militaries to disperse battle formations and mass occasionally against an identified target – swarming on the battlefield. The best example of offensive swarming during WWII is Germany's use of the U-boat wolfpack tactics to defeat the Allies during the Battle of the Atlantic (1939-1945).[38]

[36] Edwards, *Swarming and the Future of Warfare*, 255.

[37] Arquilla and Ronfeldt, *Swarming and the Future of Conflict*, 33.

[38] Edwards, *Swarming and Future of Warfare*, 258.

In 1939, Germany deployed submarines in a dispersed fashion covering a wide area across the Atlantic looking to destroy convoys of Allies' transport ships and destroyers. Identifying a convoy, the U-boats attacked from multiple directions until they destroyed the targeted convoy. Then, the submarines dispersed, only coming together again when another target presented itself.[39] The Germans' wolfpack typically consisted of five or more U-boats that communicated with one another and the U-boat headquarters located in France via radio.[40]

Key to effective swarming tactics for the U-boats was timely and accurate intelligence of the location and direction of travel of the Allies' transport ships. Germans developed great situational awareness through a network of reconnaissance planes, scout U-boats, and electronic espionage. The U-boat command routed packs of U-boats to reported locations of targets by radio. Like the Mongol scouts of the thirteenth century, U-boat scouts surveyed expected convoy routes searching to identify the target. The U-boat scout would elusively pursue the identified target with caution while reporting the location and direction of travel of the target to the U-boat Command and rest of the pack. The U-boat wolfpack would then assemble near the targeted convoy and navigate at full speed to a firing position to fire four torpedoes before disengaging and surfacing to reload and reattack. Like the RAF in the Battle of Britain, the U-boats had a decentralized command and control system. Each U-boat commander attacked the target without coordinating with a higher command for approval that would have only decreased its effectiveness and speed. The U-boat wolfpack tactics are an example of swarming that was effective mainly due to the ability to gain better situational awareness, disseminate information via radio to coordinate and synchronize an attack on a desired target at the right time and location, and the U-boat's elusiveness. The U-boats were successful until 1943 when the Allies used

[39] Arquilla and Ronfeldt, *Swarming and the Future of Conflict*,33.

[40] Edwards, *Swarming and Future of Warfare*, 258.

aircraft armed with radar to identify the location and depth of the U-boats, taking away the German offsetting the advantage of stealth and situational awareness.[41]

The swarm tactics used by the German U-boat wolfpack demonstrate how successful a swarming unit can be in the offense. The stealth of the U-boats, the decentralized command and control system, along with good intelligence enabled the Germans to achieve great situational awareness and therefore, maximize the military advantage and execute well-coordinated and synchronized attacks against convoys of Allies' transportation ships and destroyers. Radar and wireless communication intercepts enabled the commanders to develop a situational awareness that facilitated the swarming forces to attack the right target. Wireless communication made the coordination of such attacks possible. Advances in communication technologies in artificial intelligence, wireless, and smartphone communications have a greater impact on the possibility of establishing decentralized networks making swarming of unmanned aerial vehicles a reality today.

During the Vietnam War, militaries experimented with unmanned aerial vehicles for ISR and targeting. Although the US military did not attempt swarming with UAVs or other semi-autonomous weapon systems in Vietnam, the introduction of the technology and concept for autonomous and semi-autonomous systems to swarm on the battlefield had begun.[42] Since the Vietnam War, the national militaries have used UAVs and semi-autonomous systems to maintain an operational advantage and seek operational results against adversaries. In 1982, Israel employed UAVs to defeat Lebanon's anti-air defense umbrella and penetrate defenses to achieve decisive effects that enabled the defeat of Lebanese forces within seven days.[43] Beginning in the

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[41] Edwards, *Swarming and Future of Warfare*, 258- 259.

[42] Edwards, *Swarming on the Battlefield*, 9-10, 14-20, 80.

[43] Steven J. Zaloga and Ian Palmer, *Unmanned Aerial Vehicles: Robotic Air Warfare 1917-2007*, (Oxford: Osprey, 2008), 22.

1990 Gulf War, the US military has employed the Predator UAV to conduct precision strikes against leaders of violent extremist organizations operating in Afghanistan, Pakistan, Yemen, and Libya.[44] Most recently, in January 2018, Syrian rebels used a swarm of UAVs to attack a Russian airbase in Syria.[45] The last thirty years have demonstrated that the technologies have progressed to a point that would enable the employment of swarming tactics by semi-autonomous and autonomous weapon systems such as autonomous UAVs to significantly impact today's battlefield.

## History of Military Unmanned Aerial Vehicles

The US Navy employed the first unmanned aircraft during World War II. Initially used as target practice for anti-aircraft gunners, the Navy armed these radio-controlled platforms and used them as an early version of precision-guided munitions during the Battle of Guadalcanal.[46] Referred to as "American kamikazes" by the Japanese, these aircraft successfully attacked the Japanese freighter Yamazuki Maru in May 1944.[47] During the Korean War, the US military continued to develop unmanned technologies. In 1952, the US Navy converted six obsolete fighter aircraft into radio-controlled kamikazes. Again using these aircraft as primitive precision missiles, these aircraft destroyed targets previously unscathed by US heavy bombing efforts.[48]

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[44] Hambling, *Swarm Troopers*, 37-52.

[45] Raf Sanchez, 2018, "Russia Uses Missiles and Cyber Warfare to Fight Off 'Swarm of Drones' Attacking Military Bases in Syria," *The Telegraph*, January 9, 2018, https://www.telegraph.co.uk/news/-2018/01/09/russia-fought-swarm-drones-attacking-military-bases-syria/.

[46] Zaloga and Palmer, *Unmanned Aerial Vehicles*, 8.

[47] Hambling, *Swarm Troopers*, 14.

[48] John F. Keane and Stephen S. Carr, "A Brief History of Early Unmanned Aircraft," *Johns Hopkins APL Technical Digest*, 32, no. 3 (2013): 558- 565, 565; John David Blom, *Unmanned Aerial Systems: a Historical Perspective* (Fort Leavenworth, KS: Combat Studies Institute Press, US Army Combined Arms Center, 2010), 1.

The success of this unmanned platform, although limited, furthered American interest in developing technologies capable of accurately identifying and destroying enemy targets.

The Vietnam War was the first technologically intensive conflict where the US military utilized UAVs extensively.[49] During the Vietnam War, the US Navy and Air Force used UAVs developed in the 1950s and early 1960s as intelligence, surveillance, and reconnaissance platforms. The UAVs were able to fly high and low altitude flights in contested areas without risking the loss of human life. The US Navy and Air Force performed over 3,400 UAV missions from 1964 to 1975. UAVs collected electronic signal intelligence, provided real-time information, and used electro-optical technology, infrared technology, and radars to acquire information on enemy forces. The US Navy employed the DSN-3 UAVs, which provided live video feedback to the ship to direct naval gunfire.[50]

The Vietnam War was the turning point in which the role of UAVs transformed from training aids to combat enablers. Due to the extent of enemy anti-air weapons and risk to manned aircraft, the use of UAVs as ISR platforms increased. The most commonly used UAV was the Lightning Bug from Ryan Aeronautical Company.[51] The US Air Force released the Lightning Bugs from airborne C-130s and remotely controlled the platforms to survey the landscape of China and North Vietnam.[52] The Air Force also used the Lightning Bugs to take photos of terrain for later use in planning and to calculate battle damage assessments.[53] Photographs gathered from

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[49] Shaw, "Predator Empire: Drone Warfare and Full Spectrum Dominance," 71.

[50] Blom, *Unmanned Aerial Systems*, 57-58, 62.

[51] Keane and Carr, "A Brief History of Early Unmanned Aircraft," 568.

[52] Ian G.R. Shaw, "History of US Drones," *Understanding Empire: Technology, Power, Politics*, January 23, 2017, accessed March 11, 2018, https://understandingempire.wordpress.com/2-0-a-brief-history-of-u-s-drones/.

[53] Keane and Carr, "A Brief History of Early Unmanned Aircraft," 568.

UAVs helped the United States to counter Communist propaganda regarding the bombing of Hanoi and Hai Phong. In addition to reconnaissance missions, the US Air Force used UAVs as communication relays.[54]

The Ryan Aeronautical Company modified different models of the Lightning Bugs to carry heavier payloads and conduct signals intelligence missions and psychological operations.[55] The modified Lightning Bug payload consisted of electronic intelligence sensors that could record and transmit information pertaining to North Vietnamese SA-2 guidance systems. This information proved to be critical in the development of electronic countermeasures against the SA-2. The payload of future UAV models included the ALQ-51, a counter-missile package. UAVs provided a way to gather intelligence on the enemy's technological capabilities and to test counter-measures without risk to human life.[56]

In 1970, Ryan Aeronautical successfully tested the first unmanned combat aerial vehicle (UCAV). The UCAV consisted of a Lightning Bug with an attached Maverick missile that fired on command.[57] The Lightning Bug design could strike and destroy a ship from a distance of 100 miles. The United States Navy showed little interest in the UCAV, choosing instead to invest in a more versatile weapon system, the Harpoon. The US Air Force and Army similarly showed little interest as manned technology seemed more promising than unmanned technology at the time. After the Vietnam War, the US military's interest for unmanned flight technology waned due to budget cuts and competition with more versatile weapon systems such as the F-15 fighter jet.[58]

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[54] Blom, *Unmanned Aerial Systems*, 63.

[55] Keane and Carr, "A Brief History of Early Unmanned Aircraft," 568.

[56] Blom, *Unmanned Aerial Systems*, 61.

[57] Ibid., 63.

[58] Keane and Carr, "A Brief History of Early Unmanned Aircraft," 568.

In 1971, Ryan Aeronautical Company sold the UCAV to Israel.[59] Teledyne-Ryan Aeronautical (TRA) later developed a UCAV capable of firing a guided air-to-surface missile. In October 1973, Israelis utilized this system to destroy Egyptian missile sites and armored vehicles during the Yom Kippur War.[60] This demonstration of capability served to stoke enthusiasm for the potential of unmanned vehicles.

In the early 1990s, technological advancements in satellites and global positioning systems bolstered Unmanned Aerial Systems (UAS) linkages that could offer beyond the horizon capabilities.[61] Development of the Predator drone in 1994 utilized these technological developments, promising unprecedented reconnaissance capabilities from unmanned assets. After operational testing in Kosovo, the US Air Force fielded its first squadron in 1995.[62] As the platform proliferated through the military branches, DoD fitted the drone with a laser range designator and laser guided munitions, increasing the precision strike capability of the platform.[63]

In early 2000, the United States began using Predators armed with Hellfire missiles to surveil and kill terrorists.[64] After the attacks of 11 September 2001, the production and employment of armed "hunter-killer" Predators increased.[65] The first successful use of an armed Predator in combat was on 14 November 2001 in Afghanistan when a Predator-launched Hellfire

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[59] Keane and Carr, "A Brief History of Early Unmanned Aircraft," 568.

[60] Zaloga and Palmer, *Unmanned Aerial Vehicles,* 21-22.

[61] Ibid., 30.

[62] Ian Shaw, "Understanding Empire: Technology, Power, Politics," accessed March 11, 2018, https://understandingempire.wordpress.com/2-0-a-brief-history-of-u-s-drones/.

[63] Hambling, *Swarm Troopers,* 37.

[64] Elisa C. Ewers et al., "Drone Proliferation: Policy Choices for the Trump Administration," *Center for a New American Security* (June 2017), accessed 13 January, 2018, http://drones.cnas.org/wp-content/uploads/2017/06/CNASReport-DroneProliferation-Final.pdf, 7.

[65] Zaloga and Palmer, *Unmanned Aerial Vehicles,* 35.

missile killed six terrorists involved in the planning of the September 11, 2001 attack.[66] Theorist Paul Scharre suggests this attack ushered in a new way of war.[67]

In combat, the military uses UAVs to provide close air support, ISR, and communication relays in support of ground forces. The military also uses UAVs to conduct target strikes against key infrastructure and insurgent leaders, conduct target identification and clearance, and assess battle damage in support of the joint targeting process.[68] Since 2002, armed Predators have become the preferred semi-autonomous weapons system to combat insurgents in places like Afghanistan, Iraq, Somalia, and Yemen. In 2007, DoD purchased the Reaper, a drone that has a longer station time than the Predator as well as the ability to carry up to fourteen Hellfire missiles. The US Army also bought a version of the Predator, the MQ-1C Grey Eagle, to serve as an operational-level armed surveillance asset.[69]

Since the beginning of the Global War on Terror, DoD has significantly invested in many types of UAS, utilizing them in an offensive manner to execute precision strikes. While these assets cost less than manned aircraft, the cost of these systems deters the military from using them as swarms. However, prolonged operations in Afghanistan and Iraq provided a testing site for the inception and implementation of new and smaller tactical UAVs. The Army has since employed the RQ-7 Shadow while the Marines utilize the RQ-1 Pioneer for tactical level reconnaissance. The US military and NATO partners also use mini-UAVs such as the RQ-11 Raven and the

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[66] Fred Kaplan, “The First Drone Strike,” *Slate* Magazine, September 12, 2016, accessed November 20, 2017, http://www.slate.com/articles/news_and_politics/the_next_20/2016/09/a_history_of_the_armed_drone.html

[67] Elisa C. Ewers et al., "Drone Proliferation: Policy Choices for the Trump Administration," 7.

[68] Mike Fowler, "The Future of Unmanned Aerial Vehicles," *Global Security and Intelligence Studies* 1, no. 1 (2015): 1-13, accessed October 31, 2017, http://digitalcommons.apus.edu/-gsis/vol1/-iss1/3.

[69] Hambling, *Swarm Troopers,* 53.

Dragon Eye as robotic scouts, serving to provide ground forces with situational awareness and understanding.[70]

Technological advances in smartphone and Bluetooth technology have also led to the miniaturization of UAVs.[71] Popular demand for "smaller and more powerful" things contributes to the trending of miniaturization of UAVs. Mini-UAVs have since become popular and widely available to militaries and civilian businesses. The mini-UAVs are developing increasingly fast due to their multi-purpose use. Aside from commercial use in film, farming, and scientific research, militaries have also expressed interest in the development of this technology. A 2014 RAND experiment found that smaller remotely controlled aircraft with fewer capabilities performed better than larger ones with more capabilities. This testing as well as a resurgence of swarm theory suggest that swarms of inexpensive mini drones could efficiently and effectively cover a larger and wider area than just a single, more expensive UAV, increasing mission effectiveness while reducing risk to high cost military technologies and human life.[72]

The evolution of the electronics industry, smartphone technology, and biomimetic technology has contributed to the proliferation of mini-UAVs. Additionally, the low cost of UAV development makes it easier and faster for anyone from electronic companies to engineering students to garage inventors to generate new models with different and more diverse capabilities. According to David Hambling, these mini-UAVs are the "smallest and smartest weapon yet."[73] Miniaturized technology of smaller payloads and sensors make mini-UAVs survivable and more

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[70] Zaloga and Palmer, *Unmanned Aerial Vehicles,* 39.

[71] Patrick M. Miller, *Mini, Micro, and Swarming Unmanned Aerial Vehicles: A Baseline Study* (Washington, DC: Library of Congress, 2006), 1.

[72] Hambling, *Swarm Troopers*, 185.

[73] Ibid., 152, 210.

versatile, accurate, and more lethal than larger UAVs or bombers because of their ability to close with the intended target.

From the unmanned aircraft of World War II to the newest models of UAVs currently in the US Army inventory, the contributions of these platforms have increased the Army's ability to gather intelligence, establish communications nodes in austere environments, and destroy enemy targets. These tasks have bolstered situational awareness and extended the operational reach of US forces, adding both tactical and operational value in conflict. With the continued development of electronic and networking capabilities, the importance of these assets will exponentially increase, serving to further expand the effectiveness of US forces on the battlefield.

## Emergent Technology

> The emerging technology with the greatest current capacity to have strategic effect is the unmanned aerial vehicle.
>
> — Hew Strachan, *The Direction of War*

In 1957, Ernst Junger was the first to imagine the concept of a swarm of robots. In his science fiction novel *The Glass Bees*, Junger described a swarm of robotic bees that cross-pollinated flowers to ensure the survival of an ecosystem. From this novel originated the idea that swarms of robots, unmanned aerial vehicles, and semi-autonomous and autonomous systems could have viable legitimacy in serving a purpose in both military and commercial world interests.[74] Relying on his observations of nature, Junger described drones in a swarm as having multiple functions. Similarly, military innovators considered the application of drones to have a primary mission to strike, others to conduct reconnaissance, and still others to serve as the communication nodes within the swarm.[75]

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[74] Dan Gettinger, "What You Need to Know About Drone Swarms," http://dronecenter.bard.edu/-what-you-need-to-know-about-drone-swarms/.

[75] Joseph Foster, "Swarming Unmanned Aerial Vehicles (UAVs): Extending Marine Aviation Ground Task Force Communications Using UAVS" (monograph, Monterey, CA: Naval Postgraduate School, 2015), 39.

While Junger's novel described a technology far beyond the technological capabilities of his time, the technology described is now within reach. Swarm drone development is a project currently assigned to the Strategic Capabilities Office, a sub department of the Pentagon's Third Offset Strategy Office. The third Offset Strategy attempts to leverage America's technological edge by developing new ideas of application in an attempt to maintain dominance against potential adversaries.[76] In that pursuit, the DoD has developed technologies that promise to close the technological gap between science fiction and reality. Examples of the DoD's technologies demonstrate that semi-autonomous and autonomous swarming UAVs have applicability on the modern battlefield and could serve as combat multipliers if properly coupled with the appropriate tasks, doctrine, and strategy. These technologies could provide the United States with a technological advantage over potential adversaries.[77]

In 2008, the US Army began testing combat support applications for emerging UAV technologies. Atair Aerospace pioneered the Onyx Precision Airdrop System, an unmanned parafoil, for the US Army. Deployed from a C-130, the Onyx can facilitate the delivery of over forty thousand pounds of supplies. The unmanned parafoils' flight control system prevents separate loads from drifting into other parafoils, potentially damaging the load. A swarming algorithm ensures the parafoils avoid collisions, minimizing both error and the need for constant human interaction. The Onyx parafoils demonstrate another enabling concept facilitated by unmanned vehicle research and development.[78]

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[76] Defense Updates, "What Are the Capabilities of S 400 and Why Swarm Drones Can Take It Out?" YouTube, October 11, 2017, accessed November 2, 2017, https://www.youtube.com/watch?-v=4o13DPzaAOU.

[77] David Hambling, "Drone Swarms Will Change the Face of Modern Warfare," WIRED, January 07, 2016, accessed June 29, 2017, http://www.wired.co.uk/article/drone-swarms-change-warfare.

[78] Hambling, *Swarm Troopers*, 189.

As technology and capabilities continued to develop, the military began testing more emergent technologies and autonomous UAVs to conduct offensive and defensive tasks as a swarm. One example of this attempt is the Perdix micro-UAV. In October 2016, the DoD employed the largest swarm of micro-UAV on record during test trials. The demonstration consisted of one hundred and three Perdix micro-UAVs deployed from two F/A-18 Super Hornets flying at Mach 0.6 speed.[79] The Perdix micro-UAVs, used for low-altitude ISR and other missions once performed by larger UAVs, are capable of adaptive behavior, self-healing, and collective decision-making.[80] Additionally, Perdix drones are disposable and designed to act as decoys and jammers, and to locate radars to suppress enemy air defenses. The demonstration included four missions of which three required hovering over an identified target. For the fourth demonstration, the Perdix micro-UAVs created a 100-meter-wide circle in the air, presumably to simulate a defensive application of the technology.[81]

The US Navy also developed and tested micro-drone technology, first testing the concept of swarming in 2016. The Low-Cost UAV Swarming Technology (LOCUST) program set out to determine the value and capabilities of large swarm UAVs. The objective of the LOCUST program was to determine the effectiveness of swarming and the cost of potential scalable

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[79] Jürgen Altmann and Frank Sauer, "Autonomous Weapon Systems and Strategic Stability," *Survival* 59, no. 5 (October): 117-42, accessed March 13, 2018, http://dx.doi.org/10.1080/00396338.20-17.1375263, 123.

[80] DoD News, "Department of Defense Announces Successful Micro-Drone Demonstration," *CHIPS: The Department of the Navy's Information Technology Magazine*, January 9, 2017, accessed November 15, 2017, http://www.doncio.navy.mil/(5udzc155ibdgke454epoce55)/CHIPS/Article-Details.aspx?id=8575.

[81] Defense Updates, "What Are the Capabilities of S 400 and Why Swarm Drones Can Take It Out?" YouTube, October 11, 2017, accessed November 2, 2017, https://www.youtube.com/watch?-v=4o13DPzaAOU.

missions executed by swarms in combat.[82] The LOCUST program has successfully deployed low cost UAVs from tube-based launchers in a swarm formation managed by a single operator. This single swarm demonstrated the capability to split into multiple swarms capable of performing reconnaissance and precision attack missions autonomously.[83] The LOCUST program demonstrated the capability of the swarm of UAVs to perform offensive and defensive missions through autonomous collaborative behavior and information sharing between the UAVs in the swarm.[84]

Although successful, the LOCUST has faced some challenges and illuminated needed improvement in defense capabilities. The low-cost drones developed have limited battery life and take a longer time to deploy than desired. The LOCUST program also highlighted deficiencies in the US Navy's anti-access, air defense, and area denial systems. LOCUST demonstrated that the swarm is difficult to defend against because the weapons used today are designed to defend against single, larger aircraft. Experiments have also shown the capability of low-cost defensive techniques that are much more inexpensive than anti-air missiles, making drones a suitable weapon to employ and achieve effective operational and strategic results.

The LOCUST experiments also demonstrated that swarms of autonomous weapon systems are effective offensive, defensive, and reconnaissance platforms. The swarming drones used in the experiment demonstrated a capability to overwhelm simulated adversaries, destroying radars, missile launchers, and other key defensive systems. Conversely, in a defensive role,

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[82] Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics. *Capabilities for Constrained Military Operations*, Report of the Defense Science Board (Washington, DC: Government Printing Office, 2016), 167.

[83] Hambling, *Swarm Troopers*, 190.

[84] David Smalley, *LOCUST: Autonomous, Swarming UAVs Fly into the Future*, Office of Naval Research, April 14, 2015, accessed October 17, 2017, https://www.onr.navy.mil/Media-Center/Press-Releases/2015/LOCUST-low-cost-UAV-swarm-ONR.aspx.

swarms of UAVs demonstrated the capability to form a protective barrier against an opposing force. The LOCUST experiment was successful in demonstrating the capabilities, requirements, and potential uses of swarm UAVs on the battlefield.

From the year 2008 to 2016, military research and development has made major strides in UAV technology and capability. While the Onyx, Perdix, and LOCUST programs represent specific touch points in the evolution of UAV technologies, these systems do not represent the fullest extent of scientific growth in the UAV community. Commercial industries continue to develop UAV and microdrone technology at an exponential rate, creating a technological gap between technologies created by the military and those of civilian corporations.

## Emergent Concepts

> I want a weapon of such a nature because I want to carry out tactics of such a nature, and not, 'Here is a new weapon; what are its tactics?' should be the guiding rule in change.
>
> — JFC Fuller, *The Foundations of the Science of War*

In 2014, Former Secretary of Defense Chuck Hagel introduced a new strategy to ensure the US military maintained its global military supremacy – the Third Offset Strategy. The strategy relies on technological innovation, new operational concepts, and implementation of new technologies to sustain the US military's edge in power projection capabilities with a primary focus on deterring war with Russia and China. The Third Offset Strategy directs research and development of autonomous learning systems, human-machine collaborative decision-making, assisted human operations, advanced manned-unmanned systems operations, and autonomous weapons. However, to maximize the value of this technology, the DoD also needs to develop doctrine to integrate technological advances in order to best leverage these developments.[85]

[85] Adam J. Boyd and Michael Kimball. "The Future Operating Environment and the Third Offset," in *Closer Than You Think: The Implications of the Third Offset Strategy for the US Army* (Carlisle Barracks, PA: US Army War College Press, 2017), 7-10.

In 2014, US Army Training and Doctrine Command (TRADOC) published Pamphlet 525-3-1 "Winning in a Complex World" which stated that for the US Army to maintain its global military supremacy, the force required an institutional reform. The purpose of the institutional reform would be to enable collaboration with other military branches and US government agencies, including national research and development communities, academia, and international partners to facilitate the procurement and integration of new technologies. The US Army's key technological focus areas concerning swarming autonomous UAVs consists of force protection, expeditionary capabilities, obtaining situational awareness, and understanding of the environment.[86]

US Army TRADOC understood that autonomous UAV swarms have potential in future offensive and defensive operations as swarms can enable a commander to develop situational awareness and direct operations accordingly. UAVs already have the capability to destroy enemy air defense assets and indirect fire systems. TRADOC also understood that swarms have the potential to increase the lethality of UAVs, already utilized to extend a unit's operational reach by traversing complex terrain and allowing units to shape the environment to create favorable conditions. The TRADOC pamphlet identified that swarms could be beneficial in increasing a unit's survivability and mobility by identifying threats and overcoming difficult challenges presented by terrain.[87]

In 2016, the Department of Defense published *The Joint Concept for Robotic and Autonomous Systems (JCRAS)*, the base document for the integration of swarm technologies into joint force warfighting concepts. The document provides an understanding that those actors who

[86] US Army Training and Doctrine Command, Pamphlet 525-3-1, *U.S. Army Operating Concept: Win in a Complex World* (Washington, DC: Government Printing Office, 2014), 36-40.

[87] US Army Training and Doctrine Command, Pamphlet 525-3-6, *The U.S. Army Functional Concept for Movement and Maneuver 2020-2040* (Washington, DC: Government Printing Office, 2017), 40.

integrate technology most effectively first will be the most successful operationally. As such, the JCRAS provides a roadmap to integrate robotic and autonomous weapon systems into joint operations by 2035.[88]

While the DoD is actively attempting to integrate robotics and swarming autonomous systems, China and Russia are already testing autonomous weapons that challenge the technological advantage of the US military. Additionally, non-state actors are currently using robotics and semi-autonomous systems to destroy military targets on today's battlefields. Emerging technologies and concepts for swarm autonomous weapons systems are available to the United States and potential adversaries. The United States must integrate new technologies into existing concepts of operation and doctrine or develop new concepts and doctrinal frameworks to employ and defend against adversary swarms of autonomous weapon systems to maintain its military advantage.

In an attempt to encourage bottom up refinement and development, the DoD also published Directive 3000.09. This directive directs Combatant Commanders to employ semi-autonomous and autonomous weapons systems "consistent with their design, testing, certification, operator training, doctrine. . ." and "integrate autonomous and semi-autonomous weapon systems into operational mission planning."[89] While the directive remains vague, the technologies are not readily available, and the design, doctrine, and tactics of these emergent technologies are still under development, this directive provides the framework for integration and reflects the prioritization assigned to incorporating new technologies into operational planning.

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[88] US Department of Defense, Joint Chiefs of Staff, *Joint Concept for Robotic and Autonomous Systems (JCRAS)*, 11.

[89] US Department of Defense, Directive 3000.09, *Autonomy in Weapon Systems* (Washington, DC: Government Printing Office, 2017), 12.

Nested with JCRAS, the Army published *The US Army Robotic and Autonomous Systems (RAS) Strategy* that serves as the Army's plan to integrate new technologies to offset a potential technological advantage of capable adversaries. The US Army's RAS strategy addresses the speed at which adversaries have integrated RAS and the increasing challenges of operating in difficult environments. The RAS strategy aims to improve the US Army's combat effectiveness by incorporating new technologies to increase situational awareness, sustain the force, facilitate movement and maneuver, and protect the force. The strategy, consisting of three phases, outlines near term goals, midterm goals, and long-term goals. Near-term goals, defined as goals to accomplish by the year 2020, consist of investing in and procuring autonomous technology to increase the Army's capability of developing situational awareness and increasing force protection. The focus of the near-term phase is to start to integrate autonomous systems into combined arms maneuver and begin to change how the Army operates.[90]

The mid-term phase, defined as efforts from 2021 to 2030, focuses on the integration of swarming robotics, including mini UAVs, micro-UAVs, and unmanned ground systems (UGS). The miniaturization of UAVs and UGS along with the implementation of artificial intelligence has the potential to provide redundant communications, ISR, and navigation assistance in degraded or contested environments. The artificial intelligence element enables each agent of a swarm to interact with each other and respond to their environment collectively, providing increased coverage, persistence, and duration of ISR over a larger area while sharing information back to the command post to increase situational awareness.[91]

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[90] US Army Training and Doctrine Command, *The US Army Robotic and Autonomous Systems Strategy* (Fort Eustis, VA: Government Printing Office, 2017), i, 1-2, 6.

[91] Ibid., 7.

The far-term phase described by the RAS, anticipated for 2031 to 2040, aims to increase situational awareness by employing swarming UAVs in support of close combat maneuver forces. The Army plans to deliver swarms of fully autonomous UAVs by using simple shipping containers and special-purpose platforms to launch the UAVs similar to the tube-based launcher used in the LOCUST program.[92]

Within the research and development fields, the Defense Advanced Research Projects Agency (DARPA) serves as the primary actor to explore the initiatives outlined in the JCRAS and RAS. As such, DARPA has initiated the Offensive Swarm-Enabled Tactics (OFFSET) program, a venue for different branches of the military to share tactics and procedures to employ swarms of autonomous UAVs in urban environments.[93] The objective of the program is to employ swarm systems with upwards of two hundred and fifty autonomous UAVs capable of operating across multiple domains to support combat forces operating in an urban environment.[94] DARPA recognizes that the use of swarms of autonomous UAVs and UGS can widely amplify military capabilities to increase force protection, ISR, and precision effects.[95] OFFSET provides the opportunity to develop new swarm tactics, evaluate effectiveness, and create capabilities that are scalable and tailorable to the mission and environment to ensure the United States can outmaneuver adversaries.[96]

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[92] US Army Training and Doctrine Command, *The US Army Robotic and Autonomous Systems Strategy*, 10.

[93] Caroline Rees, "DARPA Launches OFFSET Swarm Tactics Program for Unmanned Vehicles," *Unmanned Systems News*, December 14, 2016, accessed November 15, 2017, http://www.unmannedsystemstechnology.com/2016/12/darpa-launches-offset-swarm-tactics-program-unmanned-vehicles/.

[94] Timothy H. Chung, "Offensive Swarm-Enabled Tactics (OFFSET)," Brief , January 30, 2017, accessed November 2, 2017, https://www.darpa.mil/news-events/offset-proposers-day.

[95] Caroline Rees, "DARPA Launches OFFSET Swarm Tactics Program for Unmanned Vehicles," http://www.unmannedsystemstechnology.com/2016/12/darpa-launches-offset-swarm-tactics-program-unmanned-vehicles/.

[96] Ibid.

While the DoD guidance and platforms like the OFFSET systems demonstrate an understanding of the potential impact of swarms of semi-autonomous and autonomous UAVs in the future of warfare, the speed at which these emergent technologies continue to evolve outdistances the development of integration and tactics. However, DARPA and other DoD agencies continue to strive to generate swarm tactics, evaluate the effectiveness of those tactics, and integrate these systems into the force. With the further development of concepts to integrate these technologies, "new scalable, dynamic capabilities" could help the US military maintain a technological edge on the battlefield.[97]

## Conclusion

In determining the operational implications of UAS swarming technology, the significance and potential military application of emergent technologies are great. At the operational level, current platforms, as well as systems currently under testing, have the capability to shape the battlefield to an extent greater than ever before. The question becomes not if, but when will autonomous swarms be employed on the battlefield and by whom. New advancements of autonomous weapon systems could allow tactical and operational commanders to utilize swarming UAVs to achieve advantage and exploit success on the battlefield. The employment of these weapon systems will enable greater coordination, intelligence gathering, and targeting to overwhelm the adversary across the width and breadth of a theater of operations.

The application of the swarming tactic to achieve military effects is not revolutionary. Swarming is a natural phenomenon that has presented itself as a military tactic since the dawn of warfare. Military practitioners of every age, from thirteenth century Mongols to twentieth century superpowers, have leveraged emergent technologies and employed swarming tactics to

[97] Caroline Rees, "DARPA Launches OFFSET Swarm Tactics Program for Unmanned Vehicles," http://www.unmannedsystemstechnology.com/2016/12/darpa-launches-offset-swarm-tactics-program-unmanned-vehicles/.

overwhelm adversaries. The development of combat UAV technology in the 1980s and 1990s has solidified the operational and tactical capability of unmanned platforms. With continued research and development, UAVs, bolstered by weapons systems, artificial intelligence, smartphone technology, and concepts of stigmergy, continue to progress as a promising capability in warfare. Miniaturized UAVs, enhanced by autonomous weapon systems, possess the attributes desired to achieve swarming efficacy. However, the US military, while laying the groundwork for eventual integration, has not yet been able to capitalize on these technological advancements such as the LOCUST and PERDIX drones.

While concepts like the DoD's JCRAS or the US Army's RAS strategy demonstrate an understanding of the potential of autonomous weapon systems, the attempt to integrate these technologies by the year 2035 may be too late. Adversaries of the United States are currently testing swarms of autonomous systems on the battlefield with success. As artificial intelligence and autonomous systems continue to evolve and increase in lethality, the US military ought to ensure that it remains on the cutting edge in order to maintain a technological advantage relative to its peers and adversarial non-state actors by developing ways to detect, use, and counter disruptive emergent technologies.

The DoD and branches of the US military can benefit from the expansion of the framework for integrating emergent technologies. This framework includes a rapid development of doctrine, tactics, techniques, and procedures to employ emerging technologies, counter adversarial employment of similar technologies, and figure out how to fight without the technology. This expansion implies refining procurement, testing, and fielding timelines to ensure that the military can integrate emergent technologies and, just as rapidly, transition to the next, newer technological advancement. As the cost associated with these emergent autonomous technologies are nowhere near the cost of a new conventional weapons platform, the procurement of these weapons systems should not follow the same acquisition process. The US military risks operational and strategic surprise by adversaries prioritizing the development of autonomous weapon systems and potentially employing them sooner than the US military acquisition process will allow. As such, future research should assess the potential for streamlining the process to ensure the US military maintains the technological edge on the battlefield.

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