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Robotics on the Battlefield Part II

The Coming Swarm

By Paul Scharre

Center for a
New American
Security

Also in this series:

"20YY: Preparing for War in the Robotic Age" by Robert O. Work and Shawn Brimley

"Robotics on the Battlefield Part I: Range, Persistence and Daring" by Paul Scharre

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Any errors of analysis, fact or omission are mine alone. CNAS does not take institutional positions.

Cover Image
A flock of auklet birds exhibit swarm behavior.

(U.S. FISH AND WILDLIFE SERVICE)

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Robotics on the Battlefield Part II

The Coming Swarm

I. EXECUTIVE SUMMARY

By Paul Scharre

The unfolding robotics revolution is transforming a range of industries, from manufacturing to transportation, warehouse management, household appliances, toys, elder care and more. Similarly, it will lead to significant and perhaps surprising changes in warfare. Uninhabited vehicles, like the Predator aircraft or the Packbot ground robot, have already proven invaluable in today's conflicts. As uninhabited vehicles incorporate increasing automation and become true robotic systems, they will have tremendous value in future military operations. Individually, they will allow military forces to extend their reach into the battlespace, operating with greater range and persistence than would be possible with human-inhabited systems. With no human on board they can be sent on dangerous or even suicidal missions, allowing more daring concepts of operation. Individually, robotic systems can provide warfighters significant advantages in a range of missions. Collectively, swarms of robotic systems have the potential for even more dramatic, disruptive change to military operations. Swarms of robotic systems can bring greater mass, coordination, intelligence and speed to the battlefield, enhancing the ability of warfighters to gain a decisive advantage over their adversaries.

Secretary of Defense Chuck Hagel has called for a renewed effort to sustain American military technological dominance, and uninhabited and autonomous systems are an important component of such a strategy.[1] Today the U.S. military faces a pernicious cycle of ever rising platform costs and shrinking quantities. As a result, the number of combat ships and aircraft in the U.S. inventory has steadily declined, even during periods of significant growth in defense spending. Today's acute fiscal pressures only exacerbate these trends, forcing a crisis not only in military modernization and readiness, but also in the ability to field sufficient quantities to be relevant in future fights. As precision-guided munitions proliferate to other adversaries – both state and non-state actors – the shrinking numbers of U.S. combat assets becomes a major strategic liability. Adversaries can concentrate their weapons, which are becoming increasingly accurate and capable at ever-longer ranges, on the relatively small number of U.S. ships and bases, overwhelming their defenses. The current trend of attempting to compensate for ever-shrinking numbers of capital assets through increasingly exquisite systems is not sustainable. Clinging to greater quantities by eschewing modernization, however, is not a recipe for success either. A new paradigm is needed, one that sustains the qualitative superiority of U.S. forces in aggregate, but that disperses combat power among a greater number of platforms, increasing resiliency and diversity and imposing costs on adversaries.

Uninhabited systems can help bring mass back to the fight by augmenting human-inhabited combat systems with large numbers of lower cost uninhabited systems to expand the number of sensors and shooters in the fight. Because they can take more risk without a human onboard, uninhabited systems can balance survivability against cost, affording the ability to procure larger numbers of systems. Greater numbers of systems complicates an adversary's targeting problem and allows graceful degradation of combat power as assets are attrited. The disaggregation of combat power into a larger number of less exquisite systems also allows the ability to field a family-of-systems approach, increasing diversity and reducing technology risk, driving down cost. Uninhabited systems need not be exquisite multi-mission systems, but rather can be purpose-built for specific missions at lower cost. For example, uninhabited missile barges, undersea payload modules, airborne "missile trucks" and robotic appliqué kits for ground vehicles can supplement the striking power of existing manned platforms at relatively low cost. The result can be greater combat power on the battlefield, at the same cost. By embracing uninhabited and autonomous systems, the United States can disperse its combat capabilities, increasing resiliency, and expand its offensive striking capacity, all within realistic budget constraints.[2]

The power of swarming lies in more than just greater numbers, however. Today's modern military forces fight as a network, with interconnected human-inhabited platforms passing surveillance and targeting data across great distances. Future military forces will fight as a swarm, with greater coordination, intelligence and speed. Autonomous and uninhabited systems will be networked and cooperative with the ability to autonomously coordinate their actions in response to events on the ground. Swarming, coordinated action can enable synchronized attack or defense, more efficient allocation of assets over an area, self-healing networks that respond to enemy actions or widely distributed assets that cooperate for sensing, deception and attack. Harnessing the power of swarming will require new command-and-control models for human supervision of large swarms. This will mean moving beyond existing paradigms where humans directly control a vehicle's movements to one where human controllers supervise the mission at the command level and uninhabited systems maneuver and perform various tasks on their own.

Increased automation also has the potential to speed up the pace of warfare by helping to shorten decision cycles and, in some cases, remove humans from them entirely. Increased automation can allow humans to process large amounts of data quickly, allowing warfighters to react to changing events on the ground faster than the enemy. In some cases, the fastest reactions might come from removing humans from some tasks entirely, as is already done for some defensive actions like dispensing flares or other countermeasures. While increased automation may have tactical benefits in allowing faster reaction times to enemy actions, it could also have strategic consequences if the speed of action on the battlefield eclipses the speed of decision-making for policymakers. Increased autonomy in the use of force raises the dangerous specter of "flash wars" initiated by autonomous systems interacting on the battlefield in ways that may be unpredictable. While militaries will need to embrace automation for some purposes, humans must also be kept in the loop on the most critical decisions, particularly those that involve the use of force or movements and actions that could potentially be escalatory in a crisis.

> *Humans will still fight wars, but new technology will give combatants, as it always has, greater standoff from the enemy, survivability or lethality.*

Increasingly sophisticated autonomous systems will still fall short of human intelligence in many respects, and uninhabited systems will not be useful or appropriate for all missions. A human-machine teaming approach will be needed to find the optimal mix of human-inhabited and uninhabited platforms and human and machine cognition for various tasks. As one example, the Army has adopted an approach of teaming human-inhabited Apache helicopters with uninhabited Gray Eagle aircraft to perform armed aerial reconnaissance. Developing the doctrine, training, concepts of operation and organization to enable effective human-machine teaming will be critical to leveraging the unique advantages of uninhabited and autonomous systems in a wide range of mission areas.

The introduction of greater numbers of uninhabited and autonomous systems on the battlefield will not lead to bloodless wars of robots fighting robots, but could make more warfare more deadly and dangerous for human combatants. Humans will still fight wars, but new technology will give combatants, as it always has, greater standoff from the enemy, survivability or lethality. Exploiting those advantages will depend principally on the ability to uncover the most innovative applications of robotic swarms, which will require not only increased resources but also an aggressive campaign of experimentation and technology development. Many of the underlying technologies behind increased autonomy are driven by commercial sector innovation, and as a result will be available to a wide range of state and non-state actors. In a world where some of the most-game changing technologies will be available to everyone, uncovering the best uses of that technology – and doing so urgently – will be vital to sustaining American military dominance.

KEY RECOMMENDATIONS

THE OFFICE OF THE SECRETARY OF DEFENSE SHOULD:

- Undertake a study on swarming platforms to examine the potential for low-cost uninhabited systems to impose costs on adversaries.
- Fund a multi-year series of experiments in cooperative multi-vehicle control and swarming.
- Establish a Defense Robotics Systems Office, directly reporting to the Deputy Secretary of Defense, to coordinate ongoing efforts on uninhabited systems across the Department.

THE JOINT STAFF SHOULD:

- Ensure that lessons learned from experiments regarding uninhabited and autonomous systems are centrally collected and widely shared throughout the Department.

THE NAVY SHOULD:

- Build an experimental prototype of an uninhabited missile barge that can demonstrate the ability to remotely control and launch missiles from a large uninhabited vessel.
- Build a proof-of-concept demonstration of an undersea payload module to exploit U.S. sanctuary undersea.
- Move aggressively to field autonomous swarming defensive boats to protect U.S. ships from enemy fast attack craft. This should include further experimentation to refine concepts of operation, a rapid fielding initiative to equip combatants in high-risk areas like the Straits of Hormuz and a program of record for outfitting all Navy surface combatants with optionally-manned small boats that can operate as a defensive swarm.

THE AIR FORCE SHOULD:

- Investigate the potential for low-cost swarming uninhabited air vehicles, including expendable or non-recoverable systems such as missiles or decoys, to conduct a variety of missions including suppression/destruction of enemy air defenses, reconnaissance, battle damage assessment and electronic warfare.

- Conduct an analysis of alternatives of lower-cost uninhabited aircraft to supplement existing manned aircraft with additional sensors and missiles, such as an uninhabited "missile truck."

- Conduct a series of experiments in human control over large numbers of swarming air vehicles.

THE ARMY AND MARINE CORPS SHOULD:

- Develop a concept of operations for using appliqué kits for ground convoy operations and an associated program of record.

- Conduct a series of modern day "Louisiana Maneuver" experiments on "robotic wingman" ground robots for long-range scouting and maneuver operations, in order to inform further technology development and requirements for an eventual program of record.

- Conduct a series of experiments on swarming uninhabited air vehicles for persistent surveillance, close air support, aerial resupply and communications relay to support ground maneuver forces.

THE MARINE CORPS SHOULD:

- Conduct experiments on amphibious swarming robots for reconnaissance and counter-mine operations to clear beaches ahead of an amphibious assault.

II. INTRODUCTION: THE RECONNAISSANCE-STRIKE SWARM

From Fighting as a Network to Fighting as a Swarm

Advances in information technology achieved in the twentieth century allow modern military forces to fight as a network. Sensors can detect enemy forces and pass targeting data through communications links to shooters, who engage enemy targets with precision-guided weapons. The U.S. military was the first to harness the advantages of the information revolution to build a networked force, but other nations are following suit. Adversaries are building reconnaissance-strike networks that can detect U.S. forces at long range and strike them with precision-guided weapons. These developments, often captured under the label of anti-access, area denial (A2/AD) challenges, threaten many traditional U.S. modes of power projection, such as ships, carriers and air bases that can be targeted with long-range weapons.[3] As detailed in CNAS's recent report, "Robotics on the Battlefield Part I: Range, Persistence and Daring," uninhabited systems can help U.S. forces to counter this threat because of their increased range, persistence and ability to take greater risks, enabling new concepts of operation.[4]

But these developments are merely the precursor to a larger shift in warfare.

Emerging robotic technologies will allow tomorrow's forces to fight as a swarm, with greater mass, coordination, intelligence and speed than today's networked forces. Low-cost uninhabited systems can be built in large numbers, "flooding the zone" and overwhelming enemy defenses by their sheer numbers. Networked, cooperative autonomous systems will be capable of true swarming – cooperative behavior among distributed elements that gives rise to a coherent, intelligent whole. And automation will enable greater speed in warfare, with humans struggling to keep pace with the faster reaction times of machines. The result will be a paradigm shift in warfare where mass once again becomes a decisive factor on the battlefield, where having the most intelligent algorithms may be more important than having the best hardware, and where the quickening pace of battle threatens to take control increasingly out of the hands of humans.

Emerging robotic technologies will allow tomorrow's forces to fight as a swarm, with greater mass, coordination, intelligence and speed than today's networked forces.

Keeping Pace with the Unfolding Robotics Revolution

These developments will pose profound operational and policy challenges. Adapting to these challenges will require the development of new capabilities, experimentation with new concepts and development of new doctrine and organizational structures. Despite the U.S. military's dominance today, other nations may be better prepared to capitalize on these coming changes. The U.S. military is heavily invested – both financially and bureaucratically – in today's technologies and methods of fighting. While uninhabited systems have been embraced for some missions like reconnaissance and bomb disposal, across the force they largely remain relegated to niche roles. Only one out of every 20 Department of Defense (DOD) research, development and procurement dollars goes to uninhabited systems.[5] Furthermore, elements of the U.S. military continue to resist technologies that disrupt familiar operational paradigms, such as automation that would change the paradigm of control for human pilots over aircraft.[6] For many missions, uninhabited and autonomous systems are seen as an unproven technology and even potentially threatening when human jobs may be eliminated. In the face of this discomfort, a "go slow" approach might be tempting.

What is a Robot?

Robotic systems combine two key attributes: (1) uninhabited, or unmanned, platforms or vehicles; and (2) autonomous or semi-autonomous operations. While a true "robot" incorporates both attributes, they can be separated. Some uninhabited platforms or vehicles are remote-controlled, and autonomous features can and often are incorporated onto human-inhabited platforms.

Removing the human from a vehicle can have several advantages. Vehicles that are unconstrained by human physical limitations can have increased range, endurance, maneuverability, persistence, speed or stealth. Without a human onboard, commanders can also use the vehicle to undertake more hazardous missions without risking a human life.

Autonomy is the ability of a machine to perform a task without human input. Increased automation or autonomy can have many advantages, including increased safety and reliability, improved reaction time and performance, reduced personnel burden with associated cost savings and the ability to continue operations in communications-degraded or -denied environments.

The problem is that the enemy gets a vote.

By 2018, global spending on military robotics is estimated to reach $7.5 billion per year. At the same time, global spending on commercial and industrial robotics is estimated to top $43 billion a year.[7] As a result, many of the underlying advances in robotics will come from the commercial sector and will be widely available. The U.S. military is used to competing in a world where some of the most game-changing innovations – such as stealth, GPS and precision-guided weapons – come from the U.S. defense sector. It is ill-prepared for a world where such technologies are widely available to all.

> *Elements of the U.S. military continue to resist technologies that disrupt familiar operational paradigms, such as automation that would change the paradigm of control for human pilots over aircraft.*

If the U.S. military is to keep pace with the unfolding robotics revolution, it will need to adopt an aggressive strategy of targeted research and development, experimentation and concept and doctrine development. This will require not only increased resources, but also better institutional processes. Existing acquisition processes are too sluggish to keep pace with rapid technological change and pose a strategic risk to the United States. If they cannot be reformed, then DOD leaders will increasingly have to operate outside the traditional processes in order to rapidly adapt to emerging needs, as they repeatedly did when adapting to urgent needs for Iraq and Afghanistan.

Most importantly, when new technologies upend existing operational paradigms, the alternative

What is a Reconnaissance-Strike Network?

In the 1980s, technological developments in sensors, command-and-control networks and precision-guided munitions enabled the possibility of real-time precision targeting of ground forces, with the potential for strategic effects that were not previously possible without resort to nuclear weapons. Soviet military theorists were the first to recognize the game-changing potential of these technologies and coined the term "reconnaissance-strike complex" to describe the synergistic combination of sensors, networks and precision-guided munitions working together.

The first battle networks actually originated in World War II. During the Battle of Britain, the United Kingdom used a network of radars and spotters, connected with radio and telephone cables, to direct British fighters toward incoming German bombers. Actual engagements were still conducted with unguided weapons, however. During the next several decades, precision-guided munitions increased in accuracy while sensors and network technology also improved. By the early 1990s they had reached a culminating point, and the overwhelming U.S. victory in the Persian Gulf War validated Soviet theories about the value of information technology-enabled reconnaissance-strike networks.[8]

Today, sophisticated nation-states operate reconnaissance-strike battle networks comprised of *sensors*, *command-and-control networks* and *precision-guided weapons*. The combination of these elements allows forces to fight as a networked whole capable of long-range precision strikes. These technologies are not only proliferating to other states over time, but many low-cost versions are within the reach of non-state actors. The United States should expect future adversaries, state and non-state alike, to be able to operate battle networks capable of targeting U.S. forces with great precision.

Uninhabited and autonomous systems will enable the next evolution, as forces shift from fighting as a *network* to fighting as a *swarm*, with large numbers of highly autonomous uninhabited systems coordinating their actions on the battlefield. This will enable greater mass, coordination, intelligence and speed than would be possible with networks of human-inhabited or even remotely controlled uninhabited systems. Human judgment will still be essential for many decisions, but automation will help humans to process large amounts of data rapidly, control large numbers of vehicles simultaneously and shorten decision cycles, accelerating the tempo of operations.

concepts they enable should be embraced through experimentation and innovation. The history of revolutions in warfare has shown they are won by those who uncover the most effective ways of using new technologies, not necessarily those who invent the technology first or even have the best technology. This report is an attempt to chart out what those new uses might be, and how they could change operations on the battlefield.

III. MASS

The United States outproduced its enemies in World War II. By 1944, the United States and its Allies were producing over 51,000 tanks a year to Germany's 17,800 and over 167,000 planes a year to the combined Axis total of just under 68,000.[9] Even though many of Germany's tanks and aircraft were of superior quality to those of the Allies, they were unable to compensate for the unstoppable onslaught of Allied iron.[10] Paul Kennedy writes in *The Rise and Fall of Great Powers*:

> … by 1943-1944 the United States alone was producing one ship a day and one aircraft every five minutes! … No matter how cleverly the Wehrmacht mounted its tactical counterattacks on both the western and eastern fronts until almost the last months of the war, it was to be ultimately overwhelmed by the sheer mass of Allied firepower.[11]

The Cold War saw a shift in strategy, with the United States instead initially relying on nuclear weapons to counter the growing Soviet conventional arsenal in Europe. By the 1970s, the Soviets had achieved a three-to-one overmatch against NATO in conventional forces and a rough parity in strategic nuclear forces. In response to this challenge, the U.S. military adopted an "offset strategy" to counter Soviet numerical advantages with qualitatively superior U.S. weapons. The result of this approach was the invention of stealth technology, advanced sensors, command and control networks, and precision-guided weapons.[12]

Quantity has a quality all of its own.

APOCRYPHALLY ATTRIBUTED
TO JOSEPH STALIN

The full effect of these weapons was seen in 1991, when the United States took on Saddam Hussein's Soviet-equipped army. Casualty ratios in the Gulf War ran an extremely lopsided 30-to-1.[13] Iraqi forces were so helpless against American precision airpower that the White House eventually terminated the war earlier than planned because media images of the so-called "highway of death" made American forces seem as if they were "cruelly and unusually punishing our already whipped foes," in the words of Gulf War air commander General Chuck Horner.[14] Precision-guided weapons, coupled with sensors to find targets and networks to connect sensors and shooters, allowed the information-enabled U.S. military to crush Iraqi forces fighting with unguided munitions.

The proliferation of precision-guided weapons to other adversaries is shifting the scales, however, bringing mass once again back into the equation. The United States military can expect to face threats from adversary precision-guided munitions in future fights.[15] At the same time, ever rising platform costs are pushing U.S. quantities lower and lower, presenting adversaries with fewer targets on which to concentrate their missiles. U.S. platforms may be qualitatively superior, but they are not invulnerable. Salvos of enemy missiles threaten to overwhelm the defenses of U.S. ships and air bases. Even if missile defenses can, in principle, intercept incoming missiles, the cost-exchange ratio of attacking missiles to defending interceptors favors the attacker, meaning U.S. adversaries need only purchase more missiles to saturate U.S. defenses.

Uninhabited systems offer an alternative model, with the potential to disaggregate expensive multi-mission systems into a larger number of smaller, lower cost distributed platforms. Because they can take greater risk and therefore be made low-cost and attritable – or willing to accept some attrition – uninhabited systems can be built in large

Artist depiction of Chinese DF-21D anti-ship missile widely circulated on Chinese defense-related web forums.

numbers. Combined with mission-level autonomy and multi-vehicle control, large numbers of low-cost attritable robotics can be controlled en masse by a relatively small number of human controllers.

Large numbers of uninhabited vehicles have several potential advantages:

- Combat power can be *dispersed*, giving the enemy more targets, forcing the adversary to expend more munitions.
- Platform survivability is replaced with a concept of *swarm resiliency*. Individual platforms need not be survivable if there are sufficient numbers of them such that the whole is resilient against attack.
- Mass allows the *graceful degradation* of combat power as individual platforms are attrited, as opposed to a sharp loss in combat power if a single, more exquisite platform is lost.
- Offensive salvos can *saturate enemy defenses*. Most defenses can only handle so many threats at one time. Missile batteries can be exhausted. Guns can only shoot in one direction at a time. Even low cost-per-shot continuous or near-continuous fire weapons like high energy lasers can only engage one target at a time and generally require several seconds of engagement to defeat a target. Salvos of guided munitions or uninhabited vehicles can overwhelm enemy defenses such that "leakers" get through, taking out the target.

Some examples of ways in which these advantages could translate to new, innovative approaches for using uninhabited systems are below.

ATTRITABLE UNINHABITED COMBAT AIRCRAFT

In 2008, a now-infamous study by RAND Project Air Force examined a potential future air-to-air exchange between the U.S. and China over Taiwan.[16] Because U.S. fighters had to fly from protected air bases located in Guam, U.S. numbers in the fight were significantly reduced. Even with the entire U.S. F-22 inventory located at Guam, range and endurance constraints meant that only six F-22s could be maintained over Taiwan continuously. By contrast, because of both greater numbers of fighters and larger, closer air bases, China was able to surge seventy-two aircraft to the fight.

The analysis assumed that every single air-to-air missile that came off of a U.S. F-22 hit a Chinese fighter (probability of kill = 1.0) and that *zero* Chinese missiles hit any U.S. F-22s. Even still, China won the air-to-air engagement because U.S. fighters ran out of missiles. (F-22s can carry eight air-to-air missiles each.) Once the F-22s had run out of missiles, or "gone winchester," the remaining Chinese fighters were free to attack vulnerable U.S. tankers and surveillance aircraft.[17]

An uninhabited "missile truck" that brought additional air-to-air missiles to the fight to supplement human-inhabited F-22s could tip the scales back in the United States' favor. Such an aircraft need not have the full performance characteristics of a 5th or 6th generation fighter aircraft. It would only need to have sufficient stealth to get close enough to launch its missiles against Chinese fighters. If it then perished in the engagement, that would be acceptable provided it took a sufficient number of enemy fighters with it. It would still have accomplished the mission. The uninhabited aircraft would not need advanced autonomy, merely enough to fly in a straight line under a human's control and sufficiently robust communications links for the human-inhabited F-22s to pass targeting data. All targeting and firing decisions would be made by the F-22 pilots. If such an aircraft could be built at relatively low cost, this uninhabited "loyal wingman" could be a tremendous force multiplier for U.S. human-inhabited fighters.

Such a concept is not far from the original vision for the joint unmanned combat air system (J-UCAS), a relatively low-cost "aircraft in a box."[18] The Air Force should begin an analysis of alternatives to determine whether such an uninhabited aircraft could be built that would have sufficient stealth and payload capacity to augment the missile capacity of existing manned aircraft at relatively low cost.

SMALL UNINHABITED AIR VEHICLES AND AIR-MOBILE ROBOTS

The miniature air-launched decoy (MALD) and miniature air-launched decoy – jammer (MALD-J) – loitering air vehicles that are not quite munitions and are not aircraft – hint to the potential of small, loitering uninhabited air vehicles and air-mobile robots. The MALD functions as an aerial decoy to deceive enemy radars, while the MALD-J jams enemy radars.[25] Similar future uninhabited air vehicles, launched from aircraft, ships or submarines, could saturate enemy territory with overwhelming numbers of low-cost, expendable systems.[26] Like D-Day's "little groups of paratroopers" dropped behind enemy lines, they could sow confusion and wreak havoc on an enemy.

Loitering electronic attack weapons could create an electronic storm of jamming, decoys and high-powered microwaves. Small air vehicles could autonomously fly down roads searching for mobile missiles and, once found, relay their coordinates back to human controllers for attack.

Large numbers of cheap, expendable systems could be used to deny an enemy use of an airfield, "mining" the airspace above it by swarming overhead like locusts, risking collisions if enemy aircraft tried to takeoff or land. Air mobile systems could conserve power by landing near an airfield and attacking only periodically, either based on acoustic signatures of landing aircraft or randomly timed sorties, disrupting air traffic for days.

Such aircraft would be small and would require a means of getting to the fight. This could include submarines parked off an enemy's coast, uninhabited missile boats that race to the enemy's coastline before launching their payloads into the air, large bomber or cargo aircraft or even uninhabited undersea pods like DARPA's Hydra program.[27]

The Air Force has recently initiated development of a new "flight plan" for small uninhabited air vehicles. As it begins to scope out the potential for such

THE QUALITY OF QUANTITY

RISING COSTS: AUGUSTINE'S LAW

In 1984, Norm Augustine observed as one of "Augustine's Laws" that the cost of military aircraft was growing exponentially, while the defense budget was only growing linearly. He humorously noted:

> In the year 2054, the entire defense budget will purchase just one tactical aircraft. This aircraft will have to be shared by the Air Force and Navy 3½ days each per week except for leap year, when it will be made available to the Marines for the extra day.[19]

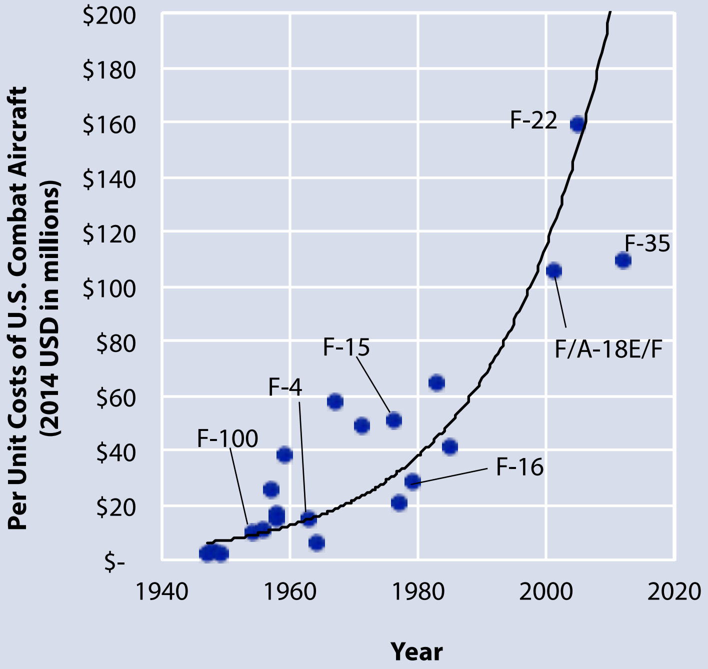
Of course, such a trend becomes a problem long before the Department of Defense gets down to only one aircraft. That time is now.

RISING COSTS, SHRINKING QUANTITIES

Rising costs have pushed down procurement quantities for not only aircraft but also ships. Furthermore, shrinking procurement quantities have the pernicious cyclical effect of further driving up per-unit procurement costs, as developmental costs are spread over fewer and fewer units. This can lead to more cuts in production numbers.

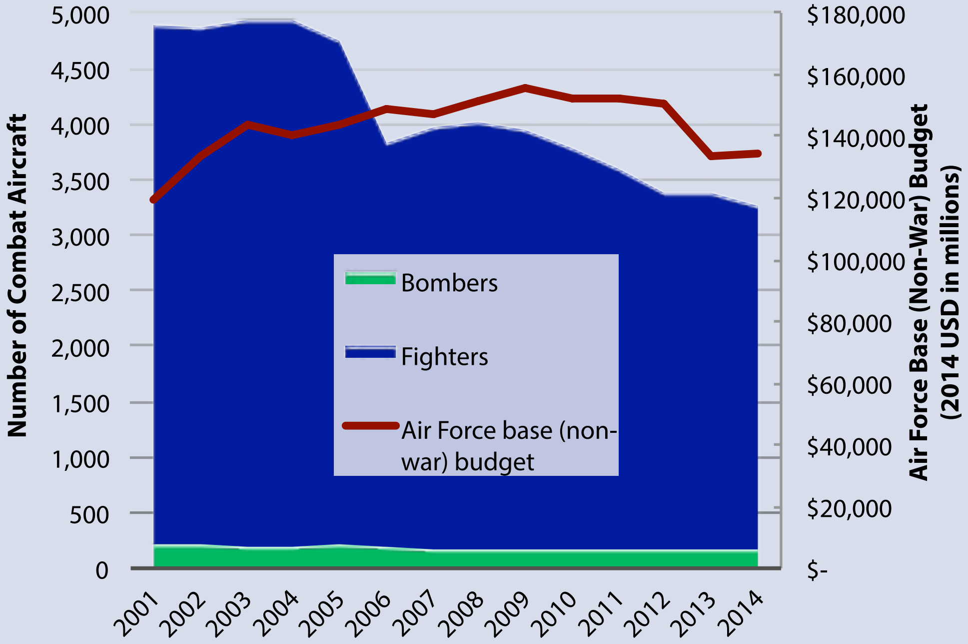
From 2001 to 2008, the base (non-war) budgets of the Navy and Air Force grew 22% and 27%, respectively, adjusted for inflation.[20] Meanwhile, the number of combat ships and aircraft in the U.S. inventory *declined* by 10% for ships and nearly 20% for aircraft over the same period.[21] A number of factors contributed to this decrease in numbers despite an overall budget rise, and this was in part due to a deliberate choice by the Navy and Air Force to emphasize quality over quantity.[22] But better quality can only compensate so much.

AUGUSTINE'S LAW: RISING AIRCRAFT COSTS OVER TIME



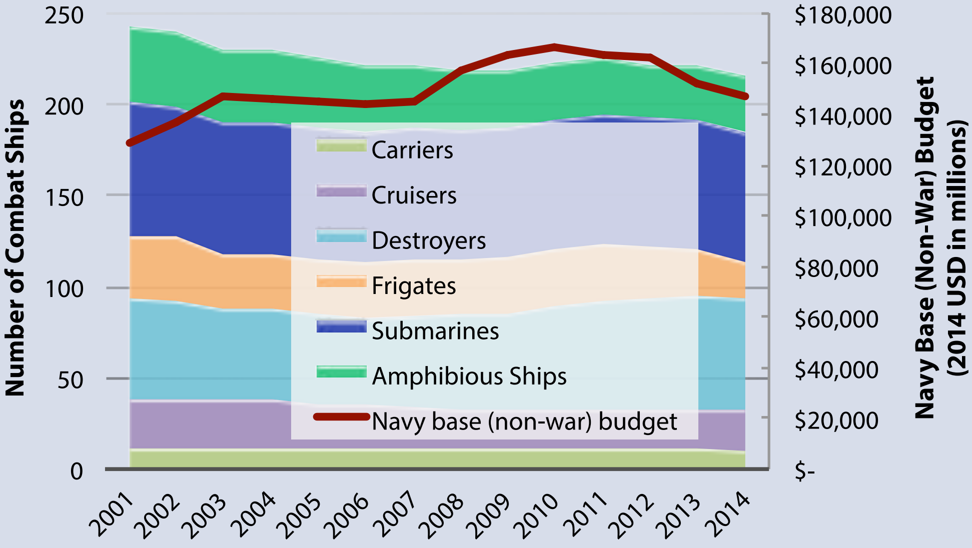
Sources: Marcelle Knaack, Encyclopedia of USAF Aircraft & Missile Systems; Congressional Budget Office, Total Quantities and Costs of Major Weapon Systems Procured, 1974-1993; and DOD: F/A-18E/F SAR (2012), Air Force FY 2011 Budget Estimate and F-35 SAR (2013).

DECLINING AIR COMBAT POWER FROM 2001-2014



Source: International Institute for Strategic Studies. Includes aircraft in store. Budget data from U.S. Department of Defense.

DECLINING NAVAL COMBAT POWER FROM 2001-2014



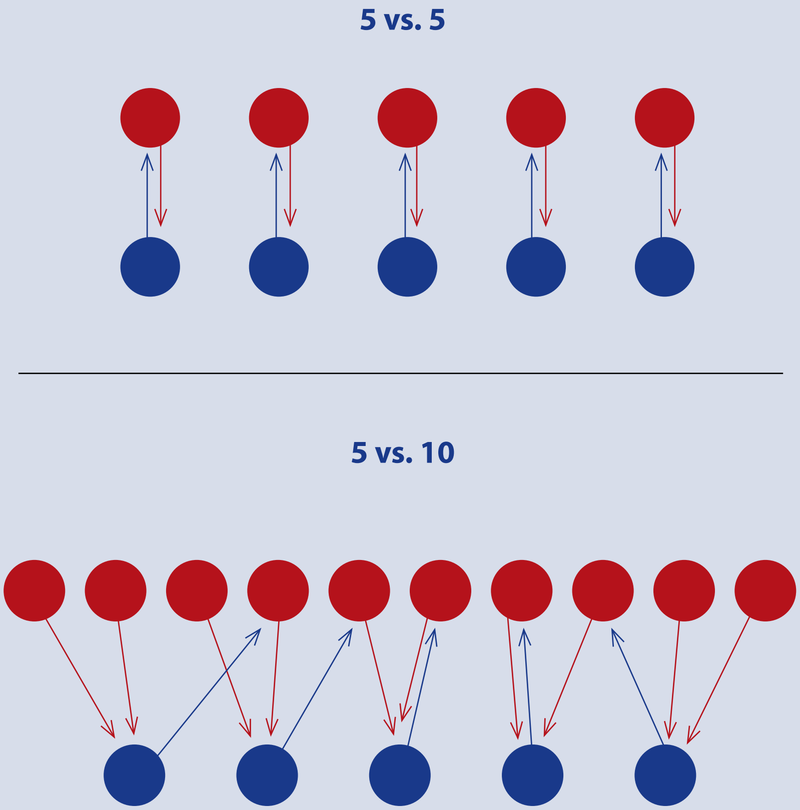
Source: International Institute for Strategic Studies. Includes ships in reserve. Budget data from U.S. Department of Defense.

NUMBERS MATTER: LANCHESTER'S LAW

A standard rule-of-thumb for the advantage of quantity vs. quality in military engagements is Lanchester's Square Law. Lanchester's Square Law states that, all things being equal, having twice as many units in the fight actually translates to a fourfold increase in combat power for units with aimed-fire weapons. This is because the numerically superior force can double up on attacking enemy units, while the numerically inferior force can only attack half of the opposing force at one time. This is in contrast to hand-to-hand combat, where combatants can only attack one person at a time, and a twofold increase in numbers translates to only a twofold increase in combat effectiveness.

A numerically inferior force can compensate with greater qualitative superiority, but a force that is outnumbered by its opponent 2-to-1 must therefore be *four times better* in quality in order to simply match its opponent. There is, in essence, a limit to how much qualitative superiority can compensate for smaller numbers.[23]

LANCHESTER'S SQUARE LAW



Relative combat power is proportional to the square of the relative sizes of opposing forces. A two-fold numerical advantage leads to a four-fold increase in combat power.

As one example, a 2009 RAND study of a hypothetical U.S.-China air war over Taiwan highlighted the value of numbers and the limits of qualitative superiority alone. Analysts conducted a detailed model of aircraft engagements, accounting for qualitative and quantitative advantages. Even though U.S. fighters were assessed to be far more capable than Chinese fighters – 27 times better in the case of the U.S. F-22 – China was able to launch nearly 800 sorties in the first day of fighting and won the battle.[24]

systems, it should be careful to include loitering air vehicles like MALDs, not just recoverable aircraft. The Air Force should also be sure to examine the full range of possible missions including strike and electronic attack, not merely tactical surveillance, as small uninhabited aircraft are used for today.

SQUAD-ORGANIC CLOSE AIR SUPPORT

One particularly notable use for small uninhabited air vehicles is the ability to put organic close air support directly in the hands of ground troops. The Switchblade is a back-packable, loitering precision-strike weapon. Weighing only 5.5 pounds, it can be issued directly to ground troops to carry on patrol. If engaged, they can launch the Switchblade, use its onboard sensors to find enemies, and then destroy them with its low collateral damage warhead.[28] A small, loitering precision-strike air vehicle like the Switchblade is a "firefight ending weapon" that places close air support directly in the hands of ground troops and makes it instantly available.[29]

Because of its low cost and high value, it can be purchased in large numbers and issued to ground troops to provide squad-organic close air support. Switchblade has been deployed to Afghanistan and the Army and Marine Corps are procuring additional systems.[30]

GROUND VEHICLES – ROBOTIC APPLIQUÉ KITS

The Army has thousands of fully functional ground vehicles such as HMMWVs and M113 armored personnel carriers that will not be used in future conflicts because they lack sufficient armor to protect human occupants. At very low cost, however, on the order of tens of thousands of dollars apiece, these vehicles could be converted into robotic systems. With no human on board, their lack of heavy armor would not be a problem.

This could be done at low cost using robotic appliqué kits – sensors and command systems that are applied to existing vehicles to convert them for remote or autonomous operation. Robotic appliqué kits have already been used to convert construction vehicles into remotely operated Bobcats and bulldozers to counter improvised explosive devices.[31]

Applied to existing vehicles, robotic appliqué kits could give the Army a massive robot ground force at extremely low cost. The sheer mass of such a force, and the ability to apply it in sacrificial or suicidal missions, could change how the Army approaches maneuver warfare.

Uninhabited ground vehicles could be the vanguard of an advance, allowing robots to be the "contact" part of a "movement to contact." Robotic vehicles could be used to flush out the enemy, flank or surround them or launch feinting maneuvers. Uninhabited vehicles could be air-dropped behind enemy lines on suicide missions. Scouting for targets, they could be used by human controllers for direct engagements or could send back coordinates for indirect fire or aerial attacks.

The Army is investigating appliqué kits for cargo resupply, which will have significant cost saving advantages, but not yet for maneuver warfare. The Army should begin a series of experiments with uninhabited ground vehicles, akin to the 1940 Louisiana Maneuvers that accompanied the adoption of the tank, to better understand the role uninhabited vehicles could play in maneuver operations.

UNINHABITED ARSENAL SHIPS TO EXPAND MAGAZINE CAPACITY

A U.S. Aegis ballistic missile defense destroyer is an amazing piece of machinery. A flexible and mobile offensive and defensive weapons platform, it can engage and destroy enemy short- and intermediate-range ballistic missiles and can strike targets deep on land with Tomahawk cruise missiles. The Aegis destroyer's sole shortcoming is its limited magazine capacity. A Flight II Arleigh Burke-class destroyer has 96 vertical launching system (VLS) cells, a modular system that can be used to carry a mix of offensive and defensive missiles.[32] VLS space is limited, and once its missiles are exhausted the Aegis's offensive and defensive capabilities are significantly reduced.

Uninhabited arsenal ships could be used to expand destroyer magazine capacity, dramatically enhancing the offensive and defensive capacity of existing destroyers. These could take the form of uninhabited surface barges or undersea pods. The commercial shipping industry is already exploring the possibility of uninhabited ships at sea to reduce costs.[33] By leveraging this technology, the Navy could field additional missile capacity at relatively low cost. Uninhabited arsenal ships could be built much cheaper than additional destroyers because they would not be warships. They would not have radars, guns and other combat capabilities. They would simply need large numbers of VLS cells and reliable communications link to human-inhabited ships, both for targeting and safety purposes. Any additional survivability features would need to be balanced against cost, because such vessels could be attritable in a fight. In fact, all things being equal, a large number of lower-cost missile barges would be preferable to a single high-cost one, since having to target more barges would be cost-imposing to an adversary. Undersea payload modules stocked with missiles would be even better, since they could be parked very close to an enemy's coastline and would be extremely difficult to detect. On warning, they could launch missiles or even uninhabited aircraft into the fight.

The Navy has already tested the basic concept of uninhabited missile boats, demonstrating the ability of a small uninhabited surface vessel to launch missiles to intercept enemy swarming small boats in 2012.[34] A missile barge loaded with VLS cells would be a scaled up version of the same concept. The missile barge is very similar to the concept of a minimally-manned low-cost "arsenal ship," which was floated in the mid-1990s.[35] The Navy should begin experiments to scale up already-demonstrated uninhabited missile boats to larger, VLS-capable surface and subsurface vessels and begin a study of possible designs. As the commercial shipping industry begins to explore uninhabited barges, the Navy may be able to leverage commercial-off-the-shelf technologies to lower cost.

"BILLIONS OF DRONES"

Ultra-cheap 3D-printed mini-drones could allow the United States to field billions – yes, *billions* – of tiny, insect-like drones. Researchers at Harvard have developed a technique for 3D-printing drones cheaply and effectively, without errors, by the sheet. The "Mobee" drone is manufactured by a 3D printer in a two-dimensional sheet, and then pops out of the sheet and folds into a tiny, bug-sized drone.[36] The Mobee is tiny and lacks a power source or sophisticated programming, but computer processing power is becoming smaller and faster at an exponential rate. Just as swarms of insects, which individually are not particularly intelligent, can nevertheless collectively perform complicated tasks, a cloud of tiny drones could similarly be used in novel and inventive ways. "Smart clouds" of 3D printed drones could flood a building, locating and identifying enemy combatants and civilians, or could even be airdropped over a wide area to find enemy personnel and materiel. If a useful tiny drone could be manufactured using 3D printing techniques for less than a dollar apiece, procuring a billion is not out of the Department of Defense's reach.

Cost-Exchange Ratio

The concept of deploying large number of uninhabited systems on the battlespace hinges squarely on the issue of cost. If such systems cannot be made cheaply, they cannot be made in large numbers. But "cheap" is a relative term, as is "expendable." How cheap do systems need to be in order to be useful?

The key metric is not the cost of uninhabited platforms themselves, but rather the *cost-exchange ratio* between adversaries. This ratio is traditionally used in the context of ballistic missile defense, measuring the aggressor's marginal cost of overwhelming enemy defenses as compared to the defender's marginal cost of countering the attack.

In general, the cost-exchange ratio can be thought of as the ratio of the cost of an approach compared to the cost of its countermeasure. The U.S. military should consider its investments within the context of cost-exchange ratios and seek favorable or at least minimally disadvantageous cost-exchange ratios. In some cases, an innovation that operates at an unfavorable cost-exchange ratio but is *less unfavorable* than before may still be an improvement.

Non-material costs and relative cost to an adversary should also be considered. An innovation that can be countered cheaply may still be advantageous if it forces the enemy to expose himself in a dangerous way or consumes other scarce resources for the enemy, such as time or personnel. Similarly, costs should be considered within the context of an adversary's resources. An even cost-exchange or even a slightly unfavorable one may be a perfectly acceptable approach if one has deeper pockets than one's enemy and is willing to outspend them.

A New Paradigm for Assessing Qualitative Advantage

The point of building large numbers of lower cost systems is not to field forces on the battlefield that are qualitatively inferior to the enemy. Rather, it is to change the notion of qualitative superiority from an attribute of the platform to an attribute of the swarm. The swarm, as a whole, should be more capable than an adversary's military forces. That is, after all, the purpose of combat: to defeat the enemy. What uninhabited systems enable is a disaggregation of that combat capability into larger numbers of less exquisite systems which, individually, may be less capable but *in aggregate* are superior to the enemy's forces.

Disaggregating combat power will not be possible in all cases, and large (and expensive) vehicles will still be needed for many purposes. Expensive, exquisite systems will inevitably be purchased in small numbers, however, and so where possible they should be supplemented by larger numbers of lower-cost systems in a high-low mix. Neither a cheap-and-numerous nor an expensive-and-few approach will work in every instance, and U.S. forces will need to field a mix of high and low-cost assets to bring the right capabilities to bear – and in the right numbers – in future conflicts.

THE COST-IMPOSING VALUE OF MASS

The chief value of mass is that it can be used to *impose costs* on adversaries because it forces one's adversary to counter large numbers of systems. The value of mass in a cost-imposing strategy can be illustrated with a simple vignette:

Two adversaries, Red and Blue, are engaged in a technological competition of innovation and countermeasures. In an unguided munitions regime, both seek to maximize the rate of fire of their weapons and the density of the barrage landing on enemy positions. Because the unguided munitions are inaccurate, large numbers are needed to maximize the odds of a successful hit on an enemy target. Blue develops guided munitions first, however, and has a game-changing advantage.

With guided munitions, Blue is able to trade large numbers of unguided weapons for smaller numbers of higher-cost guided munitions. This tradeoff is a winning strategy because the guided munitions have a high probability of kill (Pk), meaning they have a high probability of hitting and destroying their target. Rather than pour thousands of unguided munitions at Red, Blue can invest scarce defense dollars in a mere handful of guided munitions that home in on Red and strike their target. Red is powerless against this approach.

This works great for Blue until Red develops guided munitions as well. Now Red can counter both Blue's munitions and, more importantly, Blue's power projection platforms that launch the munitions with Red's own guided munitions. This is a winning strategy for Red because – in this vignette – there is a fundamental asymmetry between Red's and Blue's strategic approaches. Blue is a naval power attempting to project power around the globe far from its home, while Red is a land power with a large land mass within which Red can hide mobile missile launchers and build scores of dispersed airfields. Blue has many targets to engage and Red has few.

Blue now has two approaches to counter this new challenge from Red. Blue can continue to invest in fewer numbers of ever-higher quality assets or buy larger numbers of lower-cost and therefore lower-quality assets. Blue has a fixed amount of money, so every dollar spent on one type of platform or munition is a dollar robbed from another. Let's consider the value of each approach:

> **Higher-quality:** Let's assume that for its money Blue can buy **1** high-cost, high-quality asset for every given Red target , with a Pk of 0.9.[37] That is, this asset has a **90%** probability of achieving a kill against a Red target.
>
> **High-quantity:** Alternatively, for the same amount of money Blue can invest in **20** lower-cost and lower-quality assets, each with a Pk of 0.11. Each individual weapon has only an **11%** chance of killing a Red target, but the aggregate odds of one of them killing a target if twenty are fired is 90%.[38]

From Blue's perspective, both strategies are equal. They cost the same and achieve the same effect. In one, all of Blue's investment dollars go to a single high-quality asset. In the other, Blue resources are spread over a larger number of lower-cost assets which, in aggregate, achieve the same capability. Both are viable strategies for Blue, but how do they look from Red's perspective?

For Red, countering Blue's high-quantity approach is much more difficult if Red's preferred method of countermeasure is hit-to-kill interception. If Blue adopts a high-quality approach, Red's only challenge is to find a way to hit Blue's single asset. If Blue adopts a higher-quantity approach, on the other hand, then Red needs to hit and kill *all of Blue's assets*, even though most of them will not actually succeed in killing the Red target.[39] From Red's perspective, this is a nightmare. Even though most of Blue's assets are not a threat, Red can't know which will miss and which will hit, making the problem of intercepting Blue's assets twenty times harder.[40] Blue's choice to disperse combat power among a large number of assets is very cost-imposing to Red, since all of Blue's assets effectively act as decoys for the few that get through.

What if Red tried a different approach?

The challenges involved in getting a kinetic hit-to-kill on all of Blue's assets might drive Red to focus instead on reducing the Pk of all of Blue's assets across the board through the use of decoys or some kind of wide-area spoofing attack. What is the effect of such an approach on Blue?

Let's assume that Red adopts a countermeasure that reduces the effectiveness of Blue's assets by 50%.

> For the high-quantity approach, Blue's Pk drops from 0.11 to **0.055** for each asset.[1] In order to get back up to a 90% probability of a hit, Blue must launch **41** assets at Red instead of twenty, or just over *double* what was required before Red degraded Blue's munitions' effectiveness.
>
> For the high-quality approach, Blue's Pk drops from 0.9 to **0.45** for each asset. In order to get the total probability of a hit back up to 90%, Blue must now field **4** assets instead of one, an increase of *fourfold* over its original approach.[41]

Again, numbers matter. Red's countermeasure that reduces the Pk of any given Blue asset by 50% is much more cost-imposing to Blue when Blue relies on high-quality assets. This makes sense, because when Blue was using a low-cost, high-quantity approach, Blue wasn't relying heavily on the quality of its assets individually for securing a kill anyway. Blue's approach favored mass and Blue can counter degraded quality by simply throwing more mass at the problem.

Are larger numbers of low-cost assets always the answer? Of course not. The merits of any given approach in a specific exchange depend heavily on the particular assets at play, their cost, actual Pk, the cost of countermeasures and counter-countermeasures and the cost of any platforms to get them into the fight. The example of trading twenty lower-cost assets with a Pk of 0.11 for one high-cost asset with a Pk of 0.9 is notional and used only to illustrate the value of mass. It is not necessarily indicative of any specific cost-quantity-Pk tradeoff. All things being equal, however, dispersing one's combat power imposes significant costs on the enemy by forcing the enemy to counter many threats, even if individually each of those threats is less capable.

Even if the cost-quantity-Pk tradeoff for a particular asset favors mass, the ability to get additional mass to the fight is essential to the success of this strategy. If Blue relies on $1 billion power-projection platforms that can carry only four missiles each, then Blue ought to go with higher-quality munitions. If Blue can field large numbers of low-cost arsenal ships and missile trucks to get more assets into the fight … Well, then it is another matter entirely.

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[1] See Appendix for a table of Pk values.

IV. COORDINATION AND INTELLIGENCE

A large number of uncoordinated uninhabited systems is not a "swarm;" it is a deluge. A swarm consists of disparate elements that coordinate and adapt their movements in order to give rise to an emergent, coherent whole. A wolf *pack* is something quite different from a group of wolves.[42] Ant colonies can build structures and wage wars, but a large number of uncoordinated ants can accomplish neither. Harnessing the full potential of the robotics revolution will require building robotic systems that are able to coordinate their behaviors, both with each other and with human controllers, in order to give rise to coordinated fire and maneuver on the battlefield.

> *The battlefield is a scene of constant chaos. The winner will be the one who controls that chaos, both his own and the enemy's.*
>
> NAPOLEON BONAPARTE

Swarms in Nature

Swarms in nature are wholly emergent entities that arise from simple rules. Bees, ants, and termites are not individually intelligent, yet their colonies can exhibit extraordinarily complex behavior. Collectively, they are able to efficiently and effectively search for food and determine the optimal routes for bringing it back to their nests. Bees can "vote" on new nesting sites, collectively deciding the optimal locations. Ants can kill and move very large prey by cooperating together. Termites can build massive structures, and ants can build bridges or float-like structures over water using their own bodies.

COLLECTIVE INTELLIGENCE IS AN EMERGENT PHENOMENON

These collective behaviors emerge because of simple rules at the individual level that lead to complex aggregate behavior. A colony of ants will, over time, converge on an optimal route back from a food source because each individual ant leaves a trail of pheromones behind it as it heads back to the nest. More ants will arrive back at the nest sooner via the faster route, leading to a stronger pheromone trail, which will then cause more ants to use that trail. No individual ant "knows" which trail is fastest, but collectively the colony nonetheless converges on the optimal route.

SWARMS USE IMPLICIT AND EXPLICIT COMMUNICATION

Animals communicate through a variety of methods, both explicit and implicit. Bees communicate the degree of interest over their potential food site through a "waggle" dance, while wolves use body language and barks to communicate within the pack.

Implicit communication also plays a significant role. Flocks of birds, schools of fish and herds of animals do not stay together because of explicit communication signals between individual animals, but because each animal keys its movements off of those around it. Once on the attack, a wolf pack operates as a synchronized whole because individual members adapt their behavior based on that of other wolves.[43] This is not dissimilar from military small unit tactics, where "battle drills" allow a well-trained fire team to execute coordinated maneuvers with little or no explicit communication among them, once the decision has been made to execute a particular drill.

A novel and significant method of communication between animals is *stigmergy*, where animals

Ants work together to build a bridge with their bodies.

(SHUTTERSTOCK)

alter their environment and, in so doing, leave signals for other members of the swarm. An ant's pheromone trail is an example of stigmergy, as are the implicit signals termites leave each other in the environment as they construct nests.[44]

SWARMS COMMUNICATIONS CAN BE EXPLOITED BY OTHER ANIMALS

There are many examples in nature of animals exploiting swarm communication signals to deceive members of a swarm, either to hide within the swarm or to hijack it for their own purposes.

Several animals exploit swarm communication signals to hide within a swarm, freeloading on the benefits of security that the swarm brings. The silverfish *malayatelura ponerphila* lives among normally aggressive army ants by rubbing itself on ant larvae and pupae, absorbing their scent. The West African Rubber Frog, on the other hand, directly secretes a pheromone that prevents the normally aggressive stinging ant *paltothyreus tarsatus* from attacking it. The frog then lives inside the colony during the dry season, reaping the benefits of the nest's humidity and protection from prey.[45]

"Slave-making" ants, by contrast, invert this trick by fooling other ants into working for their colony. Slave-making ants raid other rival ant colonies and steal their larvae, taking them back to the slave-making ants' nest and raising them to take care of the slave-making ants' workers. Raised their entire lives in a rival colony, the captured ants are unaware that they have been hijacked by a rival species.[46]

The slave-making ant *polyergus breviceps* takes this method a step further and, in addition to raiding larvae, can hijack an entire colony. A *polyergus* queen can infiltrate a rival colony, kill the queen, and assume control of the colony as its new queen. Her offspring are then raised by the hijacked colony and its workers.[47] Thus, a *polyergus* queen is able to take control of the entire swarm and use it for her purposes by filling one key role.

These examples of animals exploiting communication signals among members of a swarm are analogous to spoofing and cyber attacks in the military domain. Swarm security – ensuring that other members of a swarm can be "trusted," in particular any element that serves as a leader – will be especially important for military swarms.

Robot Swarms Differ from Animal Swarms in Important Ways

Like ants, termites and bees, simple rules governing the behavior of robots can lead to aggregate swarming behavior for cooperative scouting, foraging, flocking, construction and other tasks. Robot swarms can differ from those found in nature in several interesting and significant ways. Robot swarms can leverage a mix of direct and implicit communication methods, including sending complex signals over long distances. Robot swarms may consist of heterogeneous agents – a mix of robots of different types or robots working together to perform a task. For example, the "swarmanoid" is a heterogeneous swarm of "eye-bots, hand-bots, and foot-bots" that collectively work together to solve problems.[48]

Swarm security is an even larger concern for robot swarms than for animals. Robot swarms have the potential to fall victim not only to spoofing attacks like those of the West African Rubber Frog, but also direct cyber attacks that usurp control of an uninhabited system.[49] In December 2012, a hacker demonstrated the ability to take control of a widely used commercially-available drone by hacking its unencrypted wi-fi.[50] "Swarm intelligence" can help individual members be resilient against some forms of cyber attacks. "Voting" mechanisms can allow members to communicate to one when it has fallen victim to a spoofing attack. For example, swarm elements could share position information, allowing some measure of resiliency against GPS spoofing.[51] At the same time, whole swarms could potentially fall victim to hijacking if an enemy is able to spoof the entire swarm as a whole or assume the role of a central node. Cyber vulnerabilities are not unique to uninhabited systems, but the lack of a human on board does introduce additional vulnerabilities. Human-inhabited systems can, in principle, be equipped with physical overrides to be used in the event of a cyber attack, and human "common sense" may afford a measure of resiliency against some forms of spoofing attacks.

The most important difference between animal and robot swarms is that robot swarms are designed while swarm behavior in nature is evolved. Swarms in nature have no central controller or "common operating picture." Robot swarms, on the other hand, ultimately operate at the direction of a human being to perform a specific task.[52]

More research is needed to leverage the potential for emergent swarm phenomena. Researchers have only just begun to understand how simple rules give rise to complex behavior. Simple robot swarms have been demonstrated in laboratory settings, but scientists do not yet have a universal model for understanding what emergent behaviors will arise from simple rules.[53]

While swarms in nature rely on emergent behavior for complex tasks, such as those performed by insects, this may not be necessary for robot swarms or even desirable if it makes swarm behavior less predictable as a result. Instead, robot swarms could leverage cooperative behavior for relatively simple advantages, some of which are explained below.

Concepts for Military Swarming are Largely Unexplored

Military applications for swarming are intriguing but largely unexplored. Examples of fighters employing swarming tactics date back to Genghis Khan, but have often played a less-than-central role in military conflict. In their ground-breaking monograph *Swarming and the Future of Conflict,* John Arquilla and David Ronfeldt articulate an evolution of four doctrinal forms of conflict across history:

- **Melee** – Chaotic combat among groups with individuals fighting non-cohesively
- **Massing** – Large formations of individuals fighting together in ranks and files, such as the Greek phalanx
- **Maneuver** – Multiple formations fighting together, like the Blitzkrieg, coordinating fire and movement across distances to achieve a coherent aim across the battlefield
- **Swarming** – Large numbers of dispersed individuals or small groups coordinating together and fighting as a coherent whole

MELEE VS. MASS

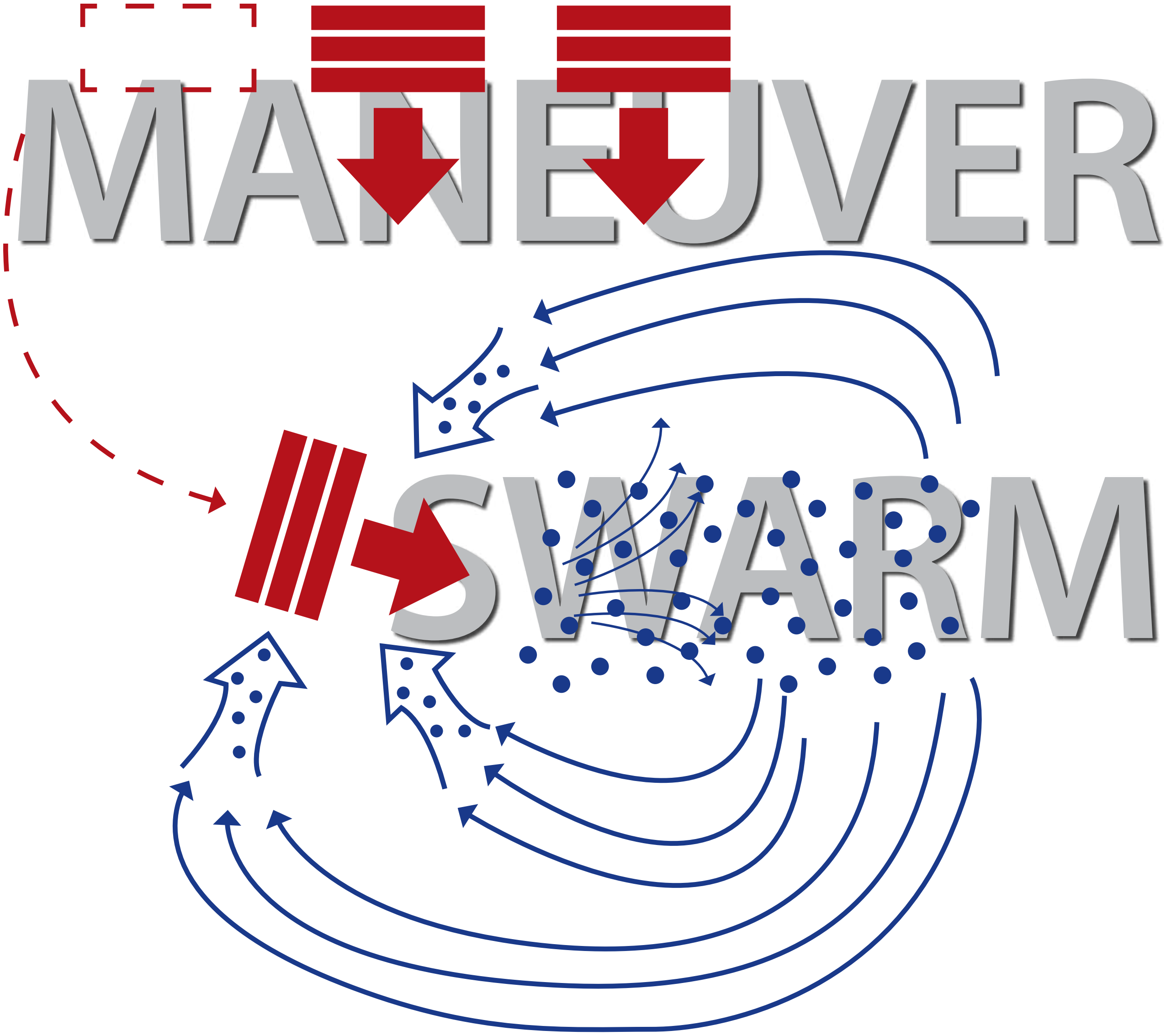
In melee fighting, combatants fight as individuals, uncoordinated. Massed formations have the advantage of synchronizing the actions of combatants, allowing them to support one another in combat. Massing requires greater organization, however, as well as the ability for individuals to communicate to one another in order to act as a whole.

MASS VS. MANEUVER

Maneuver warfare combines the advantages of mass with increased mobility. In maneuver warfare, mutually supporting separate massed formations move as independent elements to outflank the enemy and force the enemy into a disadvantageous fighting position. Maneuver warfare requires greater mobility than massing as well as the ability to communicate effectively between separated fighting elements.

MANEUVER VS. SWARM

Swarm warfare combines the 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. Swarming has much higher organization and communication requirements than maneuver warfare, since the number of simultaneously maneuvering and fighting individual elements is significantly larger.



These types of warfare require increasingly sophisticated levels of command-and-control structures and social and information organization. Examples of all four forms, including swarming, can found dating to antiquity, but widespread use of higher forms of warfare did not occur until social and information innovations, such as written orders, signal flags or radio communication, enabled coherent massing and maneuver.[54]

While low-cost uninhabited systems allow a military to field large numbers of forces, information technology allows them to fight as something more than an uncoordinated deluge. Instead, networking and automation let systems cooperate to fight together as a coherent entity, even while dispersed at great distance. Swarming as a doctrinal concept has the advantage over maneuver in that it distributes one's forces across the battlefield, while still harnessing them to fight as a coherent whole. While this places greater pressures on one's forces for communication and coordination, it also presents the enemy with a much more formidable challenge. Rather than fighting against a formation, the enemy faces an insuppressible collection of targets that are, seemingly, everywhere and nowhere at once.

Intelligent Swarms Have Several Advantages on the Battlefield

Arquilla and Ronfeldt recommend a tactic of swarming as "sustainable pulsing" where forces mass fires, then disperse and come together again to attack.[55] Sean Edwards, in a comprehensive review of swarming tactics, defines swarming as "when several units conduct a convergent attack on a target from multiple axes."[56]

These are tactical definitions, however, relating to but one possible advantage stemming from large numbers of networked, autonomous elements on the battlefield coordinating to achieve a coherent whole. For our purposes, we will define an *intelligent robotic swarm* more broadly as a network of uninhabited vehicles that autonomously coordinate their actions to accomplish a task under some degree of mission-level human direction. The ability to make networked, autonomous systems cooperate has many advantages, including but not limited to coordinated fire and maneuver. Just a few of these potential advantages are explored below.

DYNAMIC SELF-HEALING NETWORKS

Autonomous uninhabited vehicles can coordinate their actions to form self-healing, responsive networks for reconnaissance, communications relay and other activities. DARPA's Heterogeneous Airborne Reconnaissance Team (HART) successfully demonstrated the ability of a network of cooperating uninhabited aircraft to cover an area for reconnaissance purposes, autonomously re-tasking assets to cover areas of interest based on warfighter input.[57] Similar self-coordinating networks could be used for ground and maritime reconnaissance. Uninhabited undersea vehicles, working together in concert with undersea pods, could form a reconnaissance network to cooperatively identify and track submarines.[58] Uninhabited vehicles could autonomously de-mine coastal areas and beaches and, using simple "anti-social" communication means to avoid other uninhabited vehicles, could ensure adequate coverage over a given area. Intelligent minefields, conversely, could shift to re-cover areas that have been de-mined, presenting enemies with an adaptive threat.

Swarming as a doctrinal concept has the advantage over maneuver in that it distributes one's forces across the battlefield, while still harnessing them to fight as a coherent whole.

Intelligent networks of uninhabited vehicles with communications relay payloads could adapt to network disruptions and shift to cover moving forces or areas of high bandwidth. When confronted with jamming, networks could shift and adjust their topology to optimal advantage to avoid interference.[59] Networks of loitering uninhabited aircraft could provide ground forces not only with reconnaissance and communications, but also air-mobile resupply, jamming and close air support all responsive to the needs of warfighters on the ground.

COORDINATED ATTACK AND DEFENSE

Just like wolves in a pack present their enemy with an ever-shifting blur of threats from all directions, uninhabited vehicles that can coordinate maneuver and attack could be significantly more effective than uncoordinated systems operating *en masse*. Waves of kinetic attack weapons could synchronize their strikes to occur simultaneously or from multiple directions to saturate and overwhelm defenses. Decoys, jamming and electronic attack weapons could autonomously coordinate their efforts and time them to be optimally advantageous to support kinetic strikes.

For defensive purposes, clouds of uninhabited vehicles could protect ships or ground troops from attack, autonomously shifting to interdict potential threats. The Navy recently demonstrated the ability of a swarm of autonomous uninhabited surface vessels to intercept and surround an unknown and potentially hostile vessel.[60] Swarms of uninhabited surface, air and undersea vehicles could provide early detection and interdiction of threats to U.S. ships, including from enemy swarming small boats, and the Navy should rapidly move to integrate this capability into a full program of record.

Coordinating attack or defense could allow more intelligent target selection, leading to more targets being effectively engaged. One way this could occur is if munitions had onboard sensors to conduct battle damage assessment *before* attack. In such a case, they could confirm whether a given target had already been destroyed by any previous munitions and, if so, could proceed on to secondary targets. Communication between munitions would thus occur indirectly through a form of stigmergy. This could expand the total number of targets that a sortie could successfully take out. For example, if a missile with a Pk = 0.5 were launched against a target, four missiles would be needed to get a 90% assured probability of kill. If, on the other hand, each missile independently had the ability to look first *before* deciding whether to strike or move on to secondary targets, then four missiles would still need to be launched, but 50% of the time the first missile would strike the target successfully and the remainder would move on to secondary targets. 25% of the time, the first missile would successfully strike the primary target, the second missile would successfully strike the secondary target, and the remaining two missiles would move onto tertiary targets.[61] Sometimes the swarm would take out three or even four targets. Sometimes all of the missiles would be unsuccessful. On average, though, the swarm would successfully take out two targets rather than just one. Thus, in this example, the ability for the missiles to operate cooperatively through stigmergy would *double* striking capacity.

The reverse is also true. If a swarm of munitions were sent after a group of targets and each munition had a very high probability of kill such that only one was needed per target, the munitions could directly communicate in flight to deconflict their targets in order to ensure that multiple munitions were not wasted on the same target.

DISAGGREGATED FUNCTIONALITY FOR LOWER COST, MORE DIVERSE SOLUTIONS

A cooperative swarm of uninhabited systems can distribute its functions across a mix of platforms, allowing more numerous lower-cost systems. Rather than a single exquisite multi-mission platform, a swarm can employ a suite of many low-cost single-mission platforms that are able to work cooperatively to accomplish the same mission. In addition to complicating the enemy's targeting problem, employing a diverse mix of heterogeneous assets has the advantage of forcing the adversary to respond to multiple different kinds of threats. Such an approach can also lower

A swarm of uninhabited surface vessels patrols in formation in a demonstration on the James River.

(U.S. NAVY)

costs by using a "high-low mix" of assets, with a small number of more expensive assets working in concert with a large number of lower-cost assets to solve a problem.

For example, a reconnaissance network might employ a high-low mix of a few expensive, high-quality sensors combined with large numbers of lower-quality sensors. The lower-cost sensors could be distributed over a wide area to find targets and then, upon discovering them, cue a platform with a more expensive sensor to come confirm the target's identity. This could enable wider and more efficient coverage at lower cost.

Similar approaches could be used for inertial navigation systems and communications relay. Inertial navigation systems are used for GPS-independent navigation, an essential capability in anti-access environments. The estimated position of an inertial navigation unit "drifts" over time, however, leading to position inaccuracy that grows with time. More expensive, higher-quality systems can compensate for this problem, as can regular precise position updates from an outside source, such as an element outside a GPS-denied area. A high-low mix of inertial navigation systems among a network of uninhabited vehicles can allow one to act as a "navigator" for others, with other platforms requiring only a capable-enough system to get them through until the next position update. Similarly, higher-cost long-range protected communications systems can be located on a "communicator" within the swarm, with other systems passing their communications through this node.

The capabilities of a single exquisite multi-mission system can be entirely disaggregated among a swarm of low-cost vehicles performing the same functions, but merely as a distributed swarm. This could include surveillance and reconnaissance, electronic attack, decoys and deception, battle damage assessment and strike. By leveraging existing platforms with modular payloads, such a swarm could be built and fielded at relatively low cost. Each individual system need not be and should not be a new, exquisite system in its own right. Instead, each element of the swarm should leverage modular design and existing platforms as much as possible, striving for a simple, low-cost solution to solve one problem. By being simpler, they can be built on shorter timelines with lower technology risk and fewer requirements creep, getting at the underlying conditions behind platform cost growth.[62]

An example of such an approach can be found in the MALD and MALD-J air-launched decoy and jammer. While these platforms do not compete with the functionality of a multi-mission aircraft, they are able to perform their tailored missions – deception and jamming – at low cost. The same concept can be leveraged for an expanded array of missions, and indeed has already been proposed. A proposed MALD-V variant would use a modular design to incorporate a variety of single-mission payloads, from target acquisition to battle damage assessment to strike.[63]

Disaggregating functionality from an exquisite multi-mission system to a family of heterogeneous simpler, special-purpose systems also has other benefits. In addition to forcing the adversary to respond to a range of threats, it can enhance resiliency against enemy innovations and countermeasures. If a weakness is shown in any one system, only that discrete element needs to be replaced or modified, rather than attempting modifications to a large multi-mission system. Monocultures have inherent risk. Malfunctions, like the oxygen system problems that grounded the F-22 fleet, or enemy countermeasures or cyber attacks can have catastrophic consequences in a monoculture.[64] That vulnerability may in fact incentivize adversaries to concentrate their efforts on attacking that single system.[65]

DISTRIBUTED SENSING AND ATTACK

The ability to distribute sensors over a wide area has tremendous advantages for both active and passive sensing and precision geolocation. Multiple cooperative vehicles can accomplish passive precision geolocation by triangulating targets. For example, multiple widely distributed sensors can locate emitters by comparing the differences in time of arrival and frequency due to Doppler shift from relative movement.[66] For active detection, distributed sensors can function like a multi-static radar, with one sensor emitting a radar pulse and multiple sensors detecting the reflection, allowing stealthier and higher-quality radar detection.

The same physical principles can also be used for distributed attack. An array of electromagnetic emitters can deliver focused electronic attack over long distances. This approach depends on precise synchronization of the relative location and timing of the emitters, such that the electromagnetic waves arriving at the target overlap in time and space. If achievable, however, a distributed approach can deliver more precise electronic attack at lower power and with fewer interference problems than blanketing a wide area.[67]

DECEPTION

Swarms of vehicles could be used to deceive an enemy into thinking a larger vehicle or even an entire formation is moving through an area. This could be done through a variety of means, including generating false acoustic, visual or electromagnetic signatures. Cooperative decoys could even be used to generate precisely-timed false radar returns that create the illusion of a radar track moving through integrated air defenses.[68]

SWARM INTELLIGENCE

Distributed voting by numerous systems could also be used to solve problems. Swarm intelligence could be used to improve target identification, with multiple sensors providing estimates of a target’s probable ID and weighing their “votes” based on their estimated confidence.

V. SPEED

Speed is the essence of war.

SUN TZU, THE ART OF WAR

Machines cannot yet match human intelligence in solving ambiguous or novel problems, but they excel at speed. Automation, particularly among networked autonomous systems, enables a much faster pace of military operations. Automation can be used to assist in processing large amounts of information quickly, compressing the decision cycle for human operators. This can result in faster operations, helping commanders to understand the battlespace, then adapt and react before their adversaries. In addition, swarming can delegate control to autonomous elements reacting immediately to events on the battlefield, allowing tactical decision-making closer to the edge of battle.[69] Finally, removing humans entirely from the sense-decide-act loop can result in faster reactions that may be impossible for humans to match.

The Ever-Shifting Swarm

The result could be an accelerated pace and speed of operations that would be impossible for adversaries to match unaided by automation. The sheer volume of information in the future battlespace may be impossible for commanders to understand without automated information processing tools. Moreover, swarming can present enemies with an ever-shifting, constantly-adapting challenge. Just as an adversary is beginning to understand the threat environment, it changes once again.[70] In his explanation of the importance of "getting inside" an adversary's observe-orient-decide-act loop, John Boyd defines the objective of an accelerated action-reaction cycle:

> Goal: Collapse adversary's system into confusion and disorder by causing him to over and under react to activity that appears simultaneously menacing as well as ambiguous, chaotic or misleading.[71]

Automated decision-making may not always be as good as human decision-making, but it need not be if it is faster, and if that speed leads to a sufficient advantage on the battlefield.

"Flash Wars" and Fragile Stability

An accelerated tempo of operations has the potential for significant military advantages, but also raises serious concerns. Just as the introduction of automated trading algorithms has led to "flash crashes," automation in military crises could introduce instabilities. The lure of quicker reaction times or merely the fear that other nations might develop automated weapons systems could spark an automation arms race. This potential "gunslinger" quality of automation is exceptionally dangerous and destabilizing, particularly in cyberspace where operations move at "net speed."

There is a tension between the speed of operations and the speed of decisions. Automation that might make sense tactically would be disastrous strategically if it led to "flash wars." While militaries will need to embrace automation for some purposes, humans must also be kept in the loop on the most critical decisions, particularly those that involve the use of force or movements and actions that could potentially be escalatory in a crisis.

During the Cold War, defense planners faced a similar problem of "fragile stability," whereby vulnerable nuclear arsenals incentivized an enemy to strike first. In response, strategists developed a doctrine of an assured second-strike capacity in order to reduce incentives for a first strike. Similarly, strategists today must focus on resiliency in order to be able to absorb a sudden destabilizing attack and buy time for decision-makers to understand a crisis before deciding how to respond. While automation will be essential for some purposes, it should not take the place of humans for decisions about when and how to use force.

Humans in the Loop

The potential for autonomous systems to increase the speed of operations raises challenges for both policy and strategy. When humans are the weak link in an accelerated decision cycle, there are very real operational incentives to delegate actions directly to machines. Delegation of certain decisions, however, particularly regarding the use of force, raises challenging issues.

Two particularly notable policy concerns are the role of autonomy in decisions regarding the use of force and the role of human cognitive enhancement technologies to assist humans in keeping pace with an accelerating battlefield. The Department of Defense has a policy on the role of autonomy in the use of force, DOD Directive 3000.09, "Autonomy in Weapon Systems," signed in 2012.[72] State parties to the United Nations Convention on Certain Conventional Weapons, which has dealt with "special" weapons in the past like blinding lasers, took up the issue of increased autonomy in future weapons for discussion in the spring of 2014. Discussions on this important topic should continue, and the United States should continue to lead in this area.

The need to keep pace with an accelerated tempo of war also raises difficult issues regarding human cognitive performance enhancement. Human performance modification technologies, including pharmaceuticals such as Ritalin, Adderall and other "study drugs," or other modification techniques, such as transcranial direct current stimulation (tDCS), could allow humans to pay attention, process information and react faster than would otherwise be possible without these aids. These technologies raise difficult legal, policy, ethical and social issues that must be addressed. DOD has a responsibility to take care of its servicemembers, both by ensuring that they are treated in an ethical and responsible manner, and also by giving them access to the best life-saving capabilities. DOD currently lacks a Department-wide policy on human cognitive performance enhancement, however. DOD should take steps to address the policy issues associated with these technologies in order to guide research in this sensitive area.

VI. COMMANDING THE SWARM

Swarming models directly imported from nature are not likely to be ideal for military settings, since animal swarms lack a central commander. At the same time, human controllers will not want to be in a position to micromanage each element of a swarm, nor will they have the bandwidth to do so even if they desired. Human commanders will need to control swarms at the mission level, giving overarching guidance, but delegating a wide range of tasks to autonomous systems. In the near term, this will entail a shift to mission-level autonomy and multi-vehicle control. In the long term, new command-and-control models are needed to allow humans to employ large swarms effectively.

Simple Multi-Vehicle Control is Possible with Even Limited Autonomy

The U.S. military has demonstrated and used multi-vehicle control, where one human controls two or more uninhabited vehicles at the same time, in experiments and limited operational settings. The Air Force has experimented with rudimentary control of multiple uninhabited aircraft while in transit, including in limited real-world operations, although it is not routinely used.[74]

The biggest challenge in adopting multi-vehicle control is not technical, but rather understanding the cognitive demands placed on the human operator and how many vehicles can be effectively controlled. There is no easy answer, and how many vehicles a single person can manage depends on the task at hand, the human-machine interfaces and the level of vehicle autonomy. Early Air Force concepts for multi-vehicle control suggested that a pilot could control up to four vehicles at a time.[75] This is possible for simple missions, like stationary surveillance, jamming or point-to-point transit, even with relatively limited autonomy. In fact, with greater autonomy, human operators might be able to control far more than four aircraft at a time, so long as the demands on the human operator per aircraft are relatively minimal.

> *No plan survives first contact with the enemy.*
>
> HELMUTH VON MOLTKE
> (PARAPHRASED)[73]

If human operators are required to respond to unanticipated events and make decisions, however, then there are limits to how many vehicles a person can effectively control. Switching between tasks introduces inefficiencies, as operators reorient their situational awareness to each new task. The more situation-specific the cognitive tasks are, and the more they differ from each other, the greater the time lag will be. Multiple overlapping events can lead to wait times between the emergence of a need for an operator and his or her ability to respond. Whether or not these wait times are acceptable will depend on the mission. For emergencies, human attention may be needed urgently, but in other situations a vehicle may be able to loiter until the operator is able to attend to it. In addition, some tasks may require an operator to focus his or her attention solely on a single vehicle for some period of time, such as following an emerging target or taking control of a vehicle in an emergency, while others will more readily lend themselves to multi-tasking.[76]

Many of these issues can be addressed through better technology, concepts of operation or training. Multi-vehicle control architectures should be networked, so that primary operators can pass off control of vehicles to other operators in the event that they need to focus their attention on one vehicle. From a concept of operations perspective,

An autonomous rigid hull inflatable boat (RIB) participates in a demonstration on the James River as part of a swarm of thirteen uninhabited autonomous boats.

(U.S. NAVY)

there should be a sufficient number of operators in aggregate to allow for slack in the system to adapt to unanticipated events, so that all operators are not maxed to their cognitive load in steady-state operations. In addition, human-machine interfaces should be designed to assist operators in prioritizing multiple competing tasks. For example, blinking lights might be used to draw attention to an urgent task, while non-urgent tasks could be placed in a queue so as not to distract operators from the task they are presently performing. Improved automation can also help to reduce the human task loading. Finally, training, experience and even psychological orientation may play a significant role in operators' ability to handle multiple, competing cognitive tasks.

Cooperative Multi-Vehicle Control Enables More Complex Tasks

Cooperative multi-vehicle control takes this concept to the next level, with a person tasking a group of vehicles that then coordinate amongst themselves to accomplish the task as a swarm. For example, a human might task a swarm of missiles with a set of targets, but let the missiles coordinate among themselves to determine which missile will hit which target. Or a human might task a group of vehicles to maintain coverage over an area, whether for surveillance, communications relay, electronic warfare or establishing a defensive perimeter, and the vehicles might coordinate to determine how best to cover the area. These vehicles could exist across multiple domains, such as air, sea surface and undersea vehicles operating collectively with one person controlling the group.

Concepts for cooperative multi-vehicle control have been demonstrated in simulations and some real-world experiments, and many applications are technically feasible today.[77] In the summer of 2014, the U.S. Navy demonstrated the ability for one operator to control a swarm of thirteen autonomous uninhabited small boats escorting a high-value ship through a mock strait transit. When a potentially hostile vessel was spotted, the operator tasked the swarm to interdict and surround the vessel, which it executed autonomously. According to naval researchers in charge of the experiment, such a concept could be scaled up to one person controlling twenty or thirty boats at a time.[78] The associated manpower savings and reduction in risk to personnel are tremendous. An interdiction operation that normally would have included forty to fifty sailors closing with potentially hostile actors can be executed by a single sailor safely removed from harm's way. Similar concepts could be used in other domains and for other missions, such as a swarm of air and ground vehicles searching over a wide area to find and positively identify targets. While the Navy is moving out in this area for swarming boats, cultural resistance to multi-aircraft control in the Air Force has hindered progress for air vehicles.

Multi-Vehicle Control Faces Cultural Barriers to Adoption

Early Air Force experiments with multi-aircraft control led to dissatisfaction with human machine interfaces and human task loading, including the inability of pilots to hand over control of their aircraft to other pilots if they needed to focus attention on a single airplane.[79] Rather than improve the technology to allow for networked control and better interfaces, however, multi-aircraft control was deemed an "unfunded requirement."

In 2010, then-Defense Secretary Robert Gates directed the Air Force to develop improved multi-aircraft control interfaces to overcome concerns about the technology as it existed at the time. His direction included nearly $50 million in funding.[80] The Air Force never developed the technology, however, instead arguing that the multi-aircraft control concept needed to be developed further first.

The Air Force is no further along in developing multi-aircraft control today. The Air Force's recently released *Remotely Piloted Aircraft Vector* discusses multi-aircraft control, but it is not funded in the DOD budget.[81] Privately, Air Force officials claim that multi-aircraft control is a "decade after next" technology. The reality is that the technology exists today and has been demonstrated in its basic form by many companies. What will take a decade or longer on the current trajectory is cultural acceptance of a model where pilots are not in direct physical control of only one aircraft at a time.[82]

The belief that a human must control only one aircraft at a time comes from applying an existing paradigm – human-piloted aircraft – to a new technology. Viewing uninhabited air vehicles through this lens is a choice, however. Military forces already routinely employ uninhabited air vehicles that are not directly controlled by human operators. They just aren't called "unmanned aircraft." They are called missiles or decoys. Some, like cruise missiles, fly pre-programmed routes. Others, like homing missiles, are highly autonomous and maneuver to targets on their own. And many can receive new targeting data in flight and respond to human taskings.[83] As uninhabited vehicle technology matures, the lines between uninhabited aircraft, missiles and decoys will continue to blur. If the U.S. military is to fully capitalize on the potential of uninhabited systems, it will need to be willing to change the operational paradigm and embrace new concepts of operation.

Large Swarms Require New Command-and-Control Paradigms

Scaling multi-vehicle control up to large swarms will require even more fundamental shifts in the command-and-control paradigm. The Naval Postgraduate School is working on a 50-on-50 swarm vs. swarm aerial dogfight, and researchers at Harvard have built a swarm of over a thousand simple robots working together to create simple formations.[84] As the number of elements in a swarm increases, human control must shift increasingly to the swarm as a whole, rather than micromanaging individual elements.

How to exercise effective command-and-control over a swarm is an area of nascent research. Possible command and control models, ordered from more centralized to increasingly decentralized control, include:[85]

- **Centralized control**, where swarm elements feed information back to a central planner that then tasks each element individually.
- **Hierarchical control**, where individual swarm elements are controlled by "squad" level agents, which are in turn controlled by higher-level controllers, and so on.
- **Coordination by consensus**, where swarm elements communicate to one another and converge on a solution through voting or auction-based methods.
- **Emergent coordination**, where coordination arises naturally by individual swarm elements reacting to others, like in animal swarms.

Each of these models has different advantages, and may be preferred depending on the situation. While completely decentralized swarms are able to find optimal solutions to complex problems, like how ant colonies converge on the shortest route for carrying food back to the base, converging on the optimal solution may take multiple iterations, and therefore time.[86] Centralized or hierarchical planning may allow swarms to converge on optimal, or at least "good enough," solutions more quickly, but requires higher bandwidth to transmit data to a central source that then sends instructions back out to the swarm. Action by consensus, through voting or auction mechanisms, could be used when low bandwidth communications exist between swarm elements.[87] When no direct communication is possible, swarm elements could still rely on indirect communication to arrive at emergent coordination, however. This could occur by co-observation, like how animals flock or herd, or stigmergic communication by altering the environment.

DECENTRALIZED SWARMS ARE INHERENTLY ROBUST AND ADAPTIVE

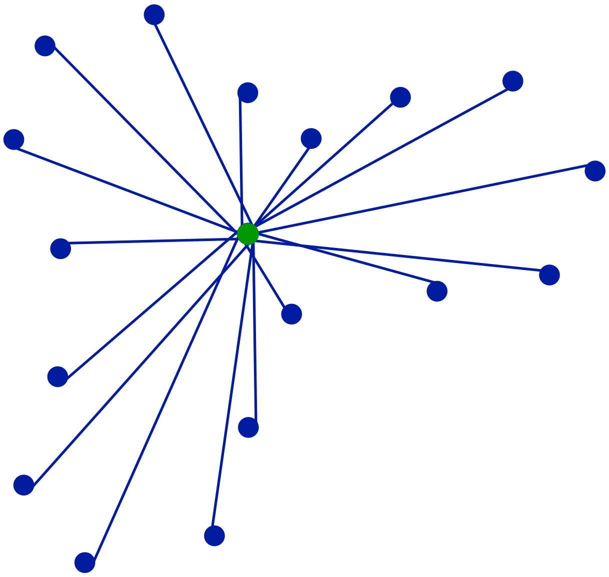
Centralized control is not always optimal even if robust communications exist, since detailed plans can prove brittle amid fast-paced changes to a battlefield environment. Decentralized control, either through localized "squad commanders," voting-based consensus mechanisms or emergent coordination has the advantage of pushing decision-making closer to the battlefield's edge. This can both accelerate the speed of immediate reaction and make a swarm more robust to communications disruptions. Swarms of individual elements reacting to their surroundings in accordance with higher-level commander's intent represent the ultimate in decentralized execution. With no central controller to rely upon, the swarm cannot be crippled or hijacked *in toto,* although elements of it could be. What a decentralized swarm might sacrifice in terms of optimality, it could buy back in faster speed of reaction. And swarms that communicate indirectly through stigmergy or co-observation, like flocks or herds, are immune to direct communication jamming.[88]

Hordes of simple, autonomous agents operating cooperatively under a centralized commander's intent but decentralized execution can be devilishly hard to defeat. The scattered airdrop of

SWARM COMMAND-AND-CONTROL MODELS

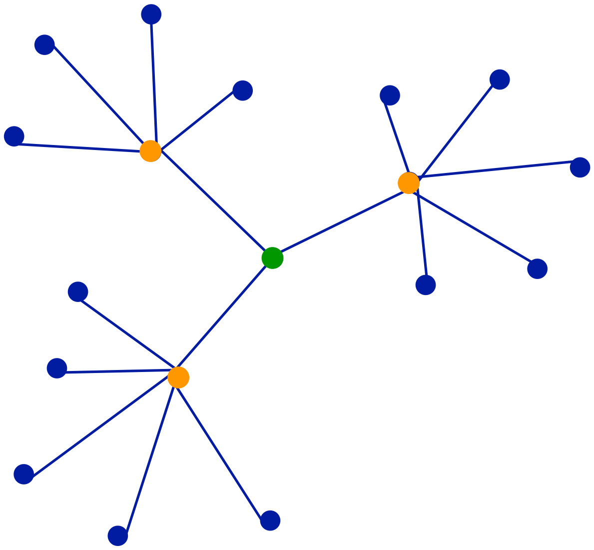
Centralized Coordination

Swarm elements communicate with a centralized planner which coordinates all tasks.



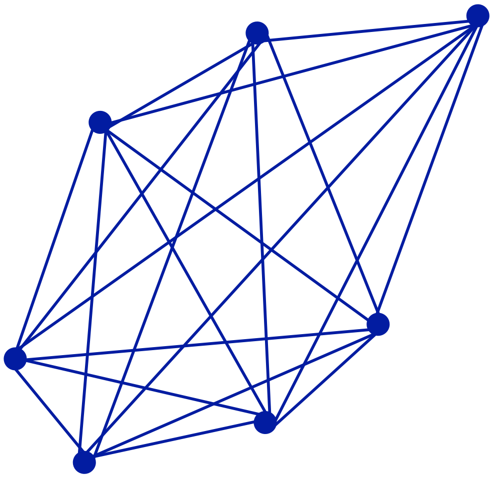
Hierarchical Coordination

Swarm elements are controlled by "squad" level agents, who are in turn controlled by higher-level controllers.



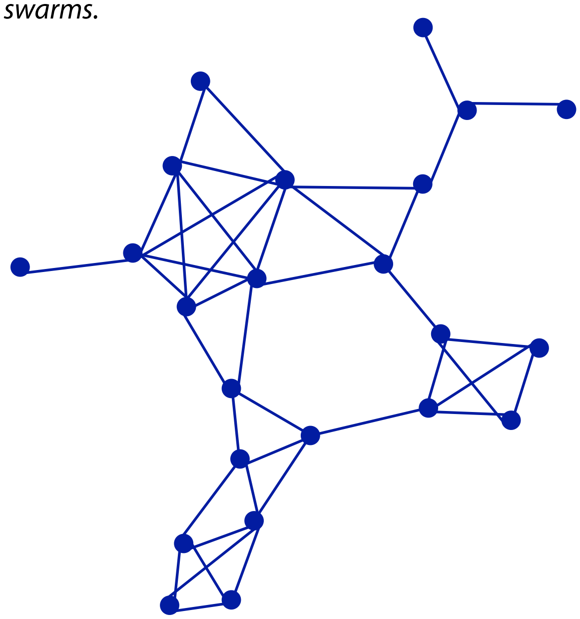
Coordination by Consensus

All swarm elements communicate to one another and use "voting" or auction-based methods to converge on a solution.



Emergent Coordination

Coordination arises naturally by individual swarm elements reacting to one another, like in animal swarms.



paratroopers over Normandy during the D-Day invasion wrecked detailed Allied plans, but had the unintended effect of making it nearly impossible for Germans to counter the "little groups of paratroopers" dispersed around, behind and inside their formations. Simple guidance like "run to the sounds of gunfire and shoot anyone not dressed like you" can be effective methods of conveying commander's intent, while leaving the door open to adaptive solutions based on situations on the ground. The downside to an entirely decentralized swarm is that it could be more difficult to control, since specific actions would not necessarily be predictable in advance.

COMMAND-AND-CONTROL MODELS MUST BALANCE COMPETING OBJECTIVES

Choices about command-and-control models for swarms may therefore depend upon the balance of competing desired attributes, such as speed of reaction, optimality, predictability, robustness to disruption and communications vulnerability. The optimal command-and-control model for any given situation will depend on a variety of factors, including:

- Level of intelligence of swarm elements relative to complexity of the tasks being performed;
- Amount of information known about the task and environment before the mission begins;
- Degree to which the environment changes during the mission, or even the mission itself changes;
- Speed of reaction required to adapt to changing events or threats;
- Extent to which cooperation among swarm elements is required in order to accomplish the task;
- Connectivity, both among swarm elements and between the swarm and human controllers, in terms of bandwidth, latency and reliability; and
- Risk, in terms of both probability and consequences, of suboptimal solutions or outright failure.

The best swarm would be able to adapt its command-and-control paradigm to changing circumstances on the ground, such as using bandwidth when it is available but adapting to decentralized decision-making when it is not. In addition, the command-and-control model could change during different phases of an operation, and different models could be used for certain types of decisions.

HUMAN CONTROL CAN TAKE MANY FORMS

Human control over a swarm can take many forms. Human commanders might develop a detailed plan and then put a swarm into action, allowing it to adapt to changing circumstances on the ground. Alternatively, human commanders might establish only higher-level tasks, such as "find enemy targets," and allow the swarm to determine the optimal solution through centralized or decentralized coordination. Or human controllers might simply change swarm goals or agent preferences to induce certain behaviors. If the cognitive load of controlling a swarm exceeds that of one person, human tasks could be split up by breaking a swarm into smaller elements or by dividing tasks based on function. For example, one human controller could monitor the health of vehicles, with another setting high-level goals and yet another approving specific high-risk actions, like use of force.

Ultimately, a mix of control mechanisms may be desirable, with different models used for different tasks or situations. For example, researchers exploring the use of intelligent agents for real-time strategy games developed a hierarchical model of multiple centralized control agents. Squad-based agents controlled tactics and coordination between individual elements. Operational-level agents controlled the maneuver and tasking of multiple squads. And strategy-level agents controlled overarching game planning, such as when to attack.[89] In principle, cooperation at each of these levels could be performed via different models in terms of centralized vs. decentralized decision-making or human vs. machine control. For example, tactical coordination could be performed through emergent coordination; centralized agents could perform operational-level coordination; and human controllers could make higher-level strategic decisions.

To harness the power of swarms, militaries will not only need to experiment and develop new technology, but also ultimately modify training, doctrine and organizational structures to adapt to a new technological paradigm.

In order to optimize their use of swarms, human controllers will need training to understand the behavior and limits of swarm automation in real-world environments, particularly if the swarm exhibits emergent behaviors. Human controllers will need to know when to intervene to correct autonomous systems, and when such intervention will introduce suboptimal outcomes.[90]

Basic research on robotic swarms is underway in academia, government and industry. In addition to better understanding swarming behavior itself, more research is needed on human-machine integration with swarms. How does one convey to human operators the state of a swarm simply and without cognitive overload? What information is critical for human operators and what is irrelevant? What are the controls or orders humans might give to a swarm? For example, a human controller might direct a swarm to disperse, coalesce, encircle, attack, evade, etc.[91] Or a human might control a swarm simply by using simulated “pheromones” on the battlefield, for example by making targets attractive and threats repellent.[92] To harness the power of swarms, militaries will not only need to experiment and develop new technology, but also ultimately modify training, doctrine and organizational structures to adapt to a new technological paradigm.

VII. ENEMY SWARMS AND COUNTERMEASURES

Many of the game-changing innovations that enable swarming – low-cost uninhabited systems, autonomy and networking – are driven by commercial sector, not military, innovation. They will be widely available to a range of actors, and many states and non-state groups may be more eager to embrace them than the U.S. military, which is invested heavily in current operational paradigms.

Strategists should not be deceived by the apparent lack of sophistication of the cheap drones currently in the hands of non-state groups like Hamas, Hezbollah or the Islamic State of Iraq and Syria. Fully autonomous GPS-programmable drones can be purchased online today for only a few hundred dollars. Large numbers of them could be used to field an autonomous, jam-proof swarm carrying explosives or even crude chemical or biological agents. Just as cheap improvised explosive devices wreaked havoc on U.S. forces operating in Iraq and Afghanistan, low-cost drones could similarly be extremely disruptive and cost-imposing. U.S. forces must begin to think now about how to counter these threats and in cost-effective ways.

Reversing the Cost Equation

It is not enough merely to find a way to destroy an enemy's drone; it must be done in a cost-effective manner. If taking out a $1,000 enemy drone requires a $1 million missile, then every drone shot down is a win for the enemy, because it imposes tremendous costs on the defender.

LOW COST-PER-SHOT WEAPONS

Developing low cost-per-shot weapons will be critical to countering enemy swarms. These consist of exotic technologies like lasers and electromagnetic rail guns as well as more traditional technologies like machine guns. The Navy is currently developing laser weapons and rail guns , and will test a laser weapon at sea in 2014 and a rail gun at sea in 2016.[93] Lasers and rail guns are appealing counter-swarm weapons because they are electrically powered and therefore have relatively low costs for each shot – significantly lower than a missile – assuming the power sources are available. The Navy has already demonstrated the ability of a laser to shoot down an enemy drone, although defeating an entire swarm of drones is a more significant challenge. Machine guns, like the sea-based Phalanx and land-based counter-rocket, artillery and mortar (C-RAM) system are also effective at defeating incoming projectiles or drones at low cost. High-energy lasers, if they could be operationalized successfully, would have even longer range.

COUNTER-SWARM

One method of taking out a swarm could be with another swarm. As long as the counter-swarm was cheaper and/or more effective than the enemy swarm, it could be a relatively low-cost way to defend against enemy swarm attacks. The Naval Postgraduate School is currently researching swarm-on-swarm warfare tactics, with the intent of testing a 50-on-50 aerial swarm fight.[94] Basic research in swarming tactics will be critical, as winning in swarm combat may depend upon having the best algorithms to enable better coordination and faster reaction times, rather than simply the best platforms.

ELECTRONIC ATTACKS

Electronic warfare countermeasures, such as spoofing, jamming, cyber-weapons and high-powered microwaves are particularly attractive for countering swarms since they can, in theory, be applied over a wide area without requiring one to target individual swarm elements. If a swarm relies on communications for its coordination, then jamming or cyber attacks could be quite effective if they disrupted communications and forced swarm elements to fight individually, devolving a swarm fight into a melee. Spoofing attacks that trick a swarm with false data or cyber attacks that potentially even take control of a swarm are also appealing ways to counter large numbers of systems.

Uninhabited systems are not uniquely susceptible to electronic warfare, cyber attacks and spoofing, but the consequences of some types of attacks could be greater in some cases.[95] Because machine cognition lacks the "common sense" capabilities of a human, there is a higher risk that the system might fail badly if manipulated with false data. Whereas humans can adjust and adapt to new and unanticipated situations, machines can be "brittle" if presented with situations for which they were not programmed, leading to unpredictable outcomes.

Counter-countermeasures

The difficultly in tricking a person with false data points to one possible safeguard against spoofing or cyber attacks.[96] Maintaining a human "in the loop" – not for every swarm action but for particularly high-risk ones, such as target authorization – is one potential fail-safe. By building in "human firebreaks" within a swarm's decision-cycle, militaries can ensure that even if an adversary were to be able to insert false data, there would be limits to what the swarm could do without human approval.[97] While humans are not incapable of mistakes, a human firewall would ensure that there was at least a common sense check before authorizing high-risk swarm actions. [98] At the very least, a human firewall would ensure that in order for an adversary to take control of a swarm, the enemy would have to actually exercise some direct human control and replicate the human control interfaces, not merely insert malicious code.

VIII. CONCLUSION: BUILDING THE SWARM

A New Paradigm for Technological Superiority

We need not wait until 2054 when the Department of Defense will only have sufficient dollars to fund one aircraft, split between the Air Force, Navy and Marine Corps, for Augustine's Law of rising costs to take its toll. The crisis in rising costs and shrinking quantities that Norm Augustine warned about is here today. Quantities for next-generation systems are so low that even dramatic qualitative advantages over adversaries, on the order of 27-to-1, are not sufficient to overcome the challenges inherent in projecting power at long range and with limited numbers of assets. The solution is not to stop modernizing, however, or to retain legacy force structure at the expense of higher-quality systems. Instead, we need a new paradigm that allows the United States to field high quality systems *and* in large quantities. And this strategy must work in the midst of a constrained fiscal environment. Accommodating rising costs through massive growth in the defense budget in perpetuity is neither feasible nor responsible.

Distributing functionality from single, exquisite multi-mission systems to large numbers of lower cost, less complex systems is one approach to help address this problem. Because uninhabited systems have no person on board, survivability can be balanced against cost, replacing the concept of platform survivability with swarm resiliency. Large numbers of systems can be built to be attritable. If some are destroyed, the remainder can carry on the mission, allowing graceful degradation of combat capability rather than risk the catastrophic loss of a single expensive platform. A large number of diverse assets also imposes costs on adversaries, dramatically expanding the number and diversity of the targets they must strike, and enhances resiliency by avoiding monocultures.

Perhaps most importantly, because they would be less complex than exquisite multi-mission systems, adopting a distributed approach could begin to reign in rising costs. Increasing complexity of systems and, in particular, shifting requirements is a major factor behind ever-rising platform costs.[99] This need not be the case, however. Many commercial technologies, including computers and automobiles, are as complex as modern weapon systems in terms of numbers of parts and lines of code, and yet do not face the same challenge of exponentially rising costs.[100] Economies of scale are a factor – another advantage of adopting a cheap-and-many approach – but development timelines are also a major contributor to the problem. DOD frequently develops major weapon systems on twenty or thirty year timelines, which creates perverse incentives to generate unrealistic requirements based on unproven technology. Long development timelines also virtually guarantee that requirements will change over time as adversary capabilities evolve, which further increases costs. In the worst cases, even with shifting requirements, platforms are unable to keep pace with adversary or commercial sector innovation and risk being obsolete before they are even fielded.

A smarter approach would be to break down exquisite systems into smaller components. One typical way in which this is done is to disaggregate modernization across time, building modular platforms with incremental improvements in each procurement "block" over time.[101] With only marginal changes between each "block," this approach reduces technology risk and, as a consequence, cost. Another approach would be to disaggregate a system spatially into many components, adopting a family-of-systems approach. This would consist of a number of single-mission systems working together to accomplish a task, rather than a single exquisite multi-mission system. Because single-mission systems would be less complex than multi-mission systems, they could be produced with lower technology risk and at lower cost. In addition, provided that network architectures are designed with sufficient interoperability up front, such an approach is inherently modular. Concerns about size, weight and power that traditionally bedevil modular design approaches no longer matter when combat functions are disaggregated spatially among many platforms. Provided they can plug into the network, new systems are inherently "plug and play."

Disaggregating complex multi-mission systems into a family of lower-cost single-mission systems has not been particularly appealing to date since, without automation, human operators were ultimately needed to control them, either physically onboard the platform or remotely. People cost money, and rising personnel costs have placed steady downward pressure on end-strength for all of the military Services. In a world where Services envision having fewer aircraft, ships and ground vehicles because they have fewer people to control them, highly capable multi-mission systems make sense.

Autonomous uninhabited systems offer the potential for a different approach. They can be used to augment existing human-inhabited systems, putting additional sensors and missiles into the fight at relatively low cost. The onboard automation need not be intelligent enough to replace human operators entirely, but need merely be sufficient to reduce the cognitive load for a human supervisor such that he or she can control many vehicles at one time. This breaks the current relationship between people and platforms, and allows a force small in personnel to field and control a very large force in platforms. Some human-inhabited platforms may be needed forward in the battlespace for various functions, including to "quarterback" the fight. There also may be little benefit to removing humans from very large and expensive systems like ships or bombers. But augmenting these human-inhabited assets with larger numbers of lower cost uninhabited systems may dramatically increase the ability of those humans to accomplish their mission.

Human-Machine Teaming

The Army's manned-unmanned teaming concept for its aviation assets is an instructive example of this approach. The Army's recent decision to retire its aging Kiowa armed reconnaissance helicopter without a replacement allowed the Army to adopt an alternative approach: teaming the human-inhabited AH-64 Apache helicopters with its uninhabited MQ-1C Gray Eagle aircraft. The uninhabited Gray Eagles do not on their own replace every task the Kiowa once performed, but in aggregate the Gray Eagles and Apaches do. Not only is this approach less expensive, it also enables new concepts of operation, since Gray Eagles can be sent forward to undertake more dangerous missions without risking human lives. Gray Eagles also incorporate a high degree of automation, which reduces the human task loading for simple missions. As a result, the Gray Eagle can even be controlled directly from the Apache's cockpit.

In this model, human-inhabited and uninhabited systems are both leveraged for their relative strengths, as are human and machine cognition and automation. This is not to say that uninhabited and autonomous systems are without significant limitations. An uninhabited vehicle is a poor choice for demonstrating political will to an adversary, when one wishes to show the resolve to suffer and die for a piece of terrain. Removing a person from a vehicle also means removing the most advanced information processing system on the planet – the human brain – and placing it at another location. Cognition for uninhabited systems depends instead on some combination of onboard autonomy and a communications link to offboard human controllers, both of which have limitations. Communications can be disrupted and degraded, and even under the best conditions bandwidth today is insufficient to convey all of the sensory information a person can take in when physically present. Machine intelligence has limitations as well. While machines exceed human cognitive capacities in some areas, particularly speed, they lack robust general intelligence that is flexible across a range of situations. Some decisions, particularly those requiring judgment or creativity, will be inappropriate for autonomous systems. Those who can field a mix of human and machine abilities, maximizing the advantages of both, will be best suited to capitalize on the potential of the robotics revolution.

As uninhabited systems become increasingly autonomous, this balance of tasks will shift over time. In some cases, trusting automation will be difficult. Humans may be unwilling to cede control for some tasks over to machines. Debates over autonomous cars are an instructive example. Human beings are horrible drivers, killing more than thirty thousand people a year in the United States alone, or roughly the equivalent of a 9/11 attack every month. Self-driving cars, on the other hand, have already driven nearly three quarters of a million miles, including in crowded city streets, without a single accident.[102] Autonomous cars have the potential to save literally tens of thousands of lives every year, yet rather than rushing to put self-driving cars on the streets as quickly as possible, adoption is moving forward cautiously.[103] At the state of the technology today, even if autonomous cars are far better than human drivers overall, there would inevitably be situations where the autonomy fails and humans, who are better at adapting to novel and ambiguous circumstances, would have done better in that instance.[104] Even if, in aggregate, thousands of lives could be saved with more autonomy, humans tend to focus on the few instances where the autonomy could fail and humans would have performed better. Ceding human control to automation requires trust, which is not easily given.

Increased autonomy can run into similar obstacles in military contexts, especially when cultural issues related to identity compound the issue. While Army uninhabited aircraft incorporate a high degree of automation, equivalent Air Force aircraft do not, even though they are built by the same contractor. In fact, Air Force MQ-9 Reapers do not include automated takeoff and landing functionality, even though the vast majority of MQ-9 accidents occur on takeoff and landing.[105] Automating takeoff and landing would require ceding control, however, changing the relationship of the human controller to the aircraft. For Army soldiers, who see uninhabited aircraft as just another piece of equipment, ceding control is not problematic. In the Air Force, however, piloting is central to the collective sense of identity. Tellingly, the Air Force insists upon identifying uninhabited aircraft as “remotely piloted,” even applying this term to future aircraft which, in principle, ought to have a high degree of automation.[106] Conversely, not only does the Army refer to its uninhabited aircraft as “unmanned aircraft systems,” the people controlling them are called “operators,” not pilots.[107] Terminology aside, the paradigm that equates “piloting” to direct physical control of the aircraft, rather than human supervision and mission command, leads to resistance to automation that could prevent accidents and increase efficiencies.

Culture matters, both to individuals and organizations. It cannot be blithely swept aside, but nor can it be accepted when it hinders necessary change. When existing cultural paradigms prevent the adoption of new approaches that could have game-changing results on the battlefield, change is required. Cultures must adapt. The Army cavalry is a fine example in this regard. While tanks and motorized fighting vehicles have long replaced horses in modern combat, the cavalry ethos lives on in Army “cavalry” units today. Cavalry soldiers honor their heritage with Stetsons and tall boots for dress uniforms. New cavalry soldiers must “earn their spurs.” But the definition of what it means to be a cavalry soldier has evolved. Similarly, the definition of what it means to be a “pilot” will change over time. The significance of physically controlling an aircraft by stick and rudder will fade, to be replaced with greater emphasis on areas where human cognition is still needed, such as mission-level command and decisions over the use of force.

While pilots may be the first to grapple with this paradigm shift, autonomous systems will raise the same issues across many military positions, from truck drivers to tank commanders. As uninhabited and autonomous systems are increasingly introduced into the force, the skills that we require of military personnel may change. Physical prowess for some tasks, like piloting an aircraft, driving a vehicle or firing a rifle will be less important in a world where aircraft fly themselves, vehicles drive on their own and smart rifles correct for wind, humidity, elevation and the shooter’s movements all on their own. The cognitive skills that are most in demand for humans will change as well, perhaps in surprising ways. As machine intelligence becomes increasingly capable, the tasks that are required of humans will change, to include not only the tasks that machines do poorly, but also the supervision of complex autonomous systems in combat.[108] This places new burdens on the selection, training and education of military personnel.

The Rapid Pace of Technological Advancement

DOD will need to move swiftly to harness the advantages of swarming if it is to retain its current fragile lead in military robotics.[109] The technology that enables swarming is generally not new platforms, vehicles or munitions, but rather improved autonomy for existing hardware. For some applications, such as swarming boats, the degree of autonomy required to enable swarming exists today. For others, improved autonomy is needed, and the gulf between what is possible today and what is needed for some applications can be quite large. However, the underlying technologies that enable more advanced autonomy, such as improved computer processing power, are advancing at an exponential rate. As a result, many information-based technologies that may have seemed like science fiction only a few years ago, like “smart” glasses and watches, self-driving cars or bionic exoskeletons, exist today.[110] The rate of their diffusion into our highways, homes and businesses is a product of price, business models, market availability and legal and policy issues, but the capabilities exist today.

Likewise, the ability to field fully autonomous, cooperative vehicles and munitions may be realized sooner than anticipated. Many swarming applications have already been demonstrated in simple form. Beyond the military domain, there are strong commercial incentives for investments in cooperative robotic systems, given their potential to develop solutions for area coverage, self-healing networks, optimal transport and other tasks. DOD may have to import into the defense sector swarm algorithms first developed for non-defense applications, reversing the traditional paradigm of DOD exporting advanced technology into the commercial space.[111]

Whether the U.S. military successfully capitalizes on swarming’s potential will depend upon bureaucracy and culture. To tap into commercial sector innovation in robotics, DOD will need to lower the barriers to entry that currently exist for non-traditional defense companies and make itself a more attractive customer, or risk freezing itself out of an important market. DOD’s sluggish requirements and acquisition process is also a strategic risk. If DOD continues to develop “next-generation” weapon systems on thirty-year timelines, it will be hard-pressed to maintain the most cutting-edge computer hardware and software.[112] Shorter acquisition timelines and more modular system designs are needed. The cultural lens through which technology is viewed also matters. When acquisition challenges are combined with a desire to "go slow" in areas where automation raises uncomfortable cultural issues, the U.S. military may find itself at risk of falling behind.

The Human Element

Cultural resistance to robotic systems often stems from a perception that they are replacing humans, and terminology that refers to robotic systems as "unmanned" can feed this perception. The reality, however, is a future of human-machine teaming. Many of the tasks humans perform in warfare will change, but humans will remain central to war, for good or ill. The introduction of increasingly capable uninhabited and autonomous systems on the battlefield will not lead to bloodless wars of robots fighting robots, with humans sitting safely on the sidelines. Death and violence will remain an inescapable component of war, if for no other reason than that it will require real human costs for wars to come to an end. Nor will humans be removed from the battlefield entirely, telecommuting to combat from thousands of miles away. Remote operations will have a role, as they already do in uninhabited aircraft operations today, but humans will be needed forward in the battlespace, particularly for command-and-control when long-range communications are degraded.

Even as uninhabited and autonomous systems play an increasing role on the battlefield, it is still humans who will fight wars, only with different weapons. Combatants are people, not machines. Technology will aid humans in fighting, as it has since the invention of the sling, the spear and the bow and arrow. Better technology can give combatants an edge in terms of standoff, survivability or lethality, advantages that combatants have sought since the first time a human picked up a club to extend his reach against an enemy. But technology alone is nothing without insight into the new uses it unlocks. The tank, radio and airplane were critical components of the blitzkrieg, but the blitzkrieg also required doctrine, organization, concepts of operation, experimentation and training to be developed successfully. It was people who developed those concepts, who drafted requirements for the technology, who restructured organizations and rewrote doctrine and who ultimately fought. In the future, it will be no different.

It is still humans who will fight wars, only with different weapons.

War will remain a clash of wills. To the extent that uninhabited systems allow an actor to reduce the costs of war, they can be a major advantage. Those who master a new technology and its associated concepts of operation first can gain game-changing advantages on the battlefield, allowing decisive victory over those who lag behind. But technological innovation in war can be a double-edged sword. If this advantage erodes a nation's willingness to face squarely face the burden of war, it can be a detriment. The illusion that such advantages can lead to quick, easy wars can be seductive, however, and those who succumb to it may find their illusions shattered by the unpleasant and bloody realities of war.[113] Uninhabited systems can lead to greater standoff from the enemy, but the millennia-long evolution of weapons and countermeasures suggests that such weapons will proliferate: no innovation leaves its user invulnerable for very long. Similarly, automation has the potential to accelerate the pace of warfare, but not necessarily in ways that are conducive to the cause of peace. An accelerated tempo of operations may lead to combat that is more chaotic, but not more controllable. Wars that start quickly may not end quickly.

Uninhabited and autonomous systems raise challenging operational, strategic and policy issues, the full scope of which cannot yet be seen. The nations and militaries that see furthest into the future to anticipate these challenges and prepare for them now will be best poised to succeed in the warfighting regime to come.

Conclusion

The past decade of conflict has seen the introduction of uninhabited systems in warfare in important ways, saving lives and money, but their use has to-date been confined largely to niche roles. This is merely the precursor to a larger shift in warfare where large numbers of autonomous uninhabited systems play significant roles on the battlefield.

Autonomous and uninhabited systems have the potential to give tremendous advantages to actors who figure out how best to employ them. As detailed in "Robotics on the Battlefield Part I: Range, Persistence and Daring," uninhabited systems can operate with longer endurance and therefore greater range and persistence. This is particularly important in countering anti-access threats where long-range missiles threaten U.S. ships and bases. Uninhabited systems can also enable more daring concepts of operation, allowing commanders to take risks with uninhabited assets that they would not with human-inhabited ones.

Large numbers of uninhabited systems can bring greater mass onto the battlefield, and with it greater resiliency and diversity. Cooperative, autonomous systems can operate as self-healing networks and self-coordinate to adapt to events as they unfold. And automation can accelerate the pace of battle, compressing decision cycles and constantly altering the adversary's threat picture before he can respond.

For actors who are able to harness the advantages of uninhabited and autonomous systems, their forces will be able to operate with greater:

- Range and persistence
- Daring
- Mass
- Coordination and intelligence
- Speed

In aggregate, these advantages will lead to the evolution from today's reconnaissance-strike networks to tomorrow's reconnaissance-strike swarm.

Perhaps most significantly, the underlying technology that will enable these innovations does not stem from secret U.S. defense labs, but in many cases will be widely available. Moreover, much of the technology that will enable autonomous operations and swarming is better algorithms and software, not necessarily new platforms. There is an urgent need to innovate faster than adversaries, and to discover the best ways of employing swarms first. To do so, the United States must invest in a robust plan of experimentation, prototyping, and iterative concept and technology development. Where these technologies raise challenging policy concerns, such as increased automation in the use of force or human cognitive performance enhancement to keep pace with faster machines, the United States should grapple forthrightly with the issues and craft sensible policy guidelines to guide technological development.

IX. RECOMMENDATIONS

Elements of the Department of Defense are conducting experiments on swarms and other applications of uninhabited and autonomous systems, but DOD currently lacks a comprehensive plan to take full advantage of their potential.

Developing the technology alone is not sufficient, as the truly game-changing innovations come from the ways in which a new technology is ultimately used. The best path forward for developing these applications is an iterative process of experimentation with new technologies and concepts, which then informs further technology development. Simulations can be useful, but concepts of operation ultimately must be tested in the field. Actual experimentation with real users also can solicit new ideas, as well as feedback on what avenues for research are promising, or where a concept or technology does not work well.

The chief stumbling block in DOD is the "valley of death" between cutting edge research and development and formal programs of record. Through organizations like the Defense Advanced Research Projects Agency (DARPA), Office of Naval Research (ONR) and other labs, DOD does an excellent job of undertaking high-risk / high-reward proof of concept research. Transitioning new, promising concepts to actual funded DOD programs, however, is uneven at best. Experimentation and technology development can help bridge the gap by clarifying what is possible, what is promising and what is not.

To sustain the U.S. military's current, but fragile, lead in robotics:

The Office of the Secretary of Defense should:

- Undertake a study on total lifecycle costs for uninhabited systems, including the potential for automation to reduce costs by reducing the need to train operators to physically control vehicles. The study should focus particular attention on aircraft, where pilot training costs run high.
- Undertake a study on swarming platforms to examine the potential for low-cost uninhabited systems to impose costs on adversaries. The study should include an evaluation of platform survivability, total cost, amount of vehicles fielded per dollar and costs to adversaries to respond.
- Investigate the potential for uninhabited systems to increase resiliency and reduce costs by disaggregating complex systems into a larger number of smaller, simpler systems.
- Ensure future military systems are built with modular designs and open architectures to allow upgrades and plug-and-play interoperability into a family of systems.
- Fund a multi-year series of experiments in cooperative multi-vehicle control and swarming.
- Establish a Defense Robotics Systems Office, directly reporting to the Deputy Secretary of Defense, to coordinate ongoing efforts on uninhabited systems across the Department.[114]
- Undertake a comprehensive policy review of human cognitive performance enhancement technologies.
- Continue to lead in international discussions on autonomy in weapon systems.

The Joint Staff should:

- Ensure requirements for all new programs are written so as not to exclude uninhabited or autonomous solutions or partial solutions as part of a family of systems.
- Include cost – and not only platform costs but also total lifecycle costs – as a factor in balancing new program requirements.
- Ensure that lessons learned from experiments regarding uninhabited and autonomous systems are centrally collected and widely shared throughout the Department.

The Navy should:

- Build an experimental prototype of an uninhabited missile barge that can demonstrate the ability to remotely control and launch missiles from a large uninhabited vessel.
- Build a proof-of-concept demonstration of an undersea payload module to exploit U.S. sanctuary undersea.
- Move aggressively to field autonomous swarming defensive boats to protect U.S. ships from enemy fast attack craft. This should include further experimentation to refine concepts of operation, a rapid fielding initiative to equip combatants in high-risk areas like the Straits of Hormuz and a program of record for outfitting all Navy surface combatants with optionally-manned small boats that can operate as a defensive swarm.
- Conduct a series of further experiments in multi-domain swarms of air, surface and subsurface vehicles for a variety of missions.
- Sustain development of low cost-per-shot counter-swarm weapons such as high-energy lasers and electromagnetic rail guns.

The Air Force should:

- Investigate the potential for low-cost swarming uninhabited air vehicles, including expendable or non-recoverable systems such as missiles or decoys, to conduct a variety of missions including suppression/destruction of enemy air defenses, reconnaissance, battle damage assessment and electronic warfare.
- Conduct an analysis of alternatives of lower-cost uninhabited aircraft to supplement existing manned aircraft with additional sensors and missiles, such as an uninhabited "missile truck."
- Fund development of improved multi-aircraft control interfaces for existing uninhabited aircraft.
- Conduct a series of experiments in human control over large numbers of swarming air vehicles.

The Army and Marine Corps should:

- Develop a concept of operations for using appliqué kits for ground convoy operations and an associated program of record.
- Conduct a series of modern day "Louisiana Maneuver" experiments on "robotic wingman" ground robots for long-range scouting and maneuver operations, in order to inform further technology development and requirements for an eventual program of record.
- Conduct a series of experiments on swarming uninhabited air vehicles for persistent surveillance, close air support, aerial resupply and communications relay to support ground maneuver forces.
- Include ground robotics as part of the set of possible solutions as part of a family of systems for all future programs, such as a light airborne tank or new ground combat vehicle.

The Marine Corps should:

- Conduct experiments on amphibious swarming robots for reconnaissance and counter-mine operations to clear beaches ahead of an amphibious assault.

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9. Paul Kennedy, The Rise and Fall of Great Powers (New York: Random House, 1987), 353-354.

10. The standard metric for weighing the value of quantitative advantages of aimed-fire weapons is Lanchester’s Square Law, which states that the military advantage of increased numbers increases with the square of the combat ratio. So, for example, a two-fold superiority in numbers actually translates to a four-fold military advantage. This is because aimed-fire weapons can focus their attacks, bringing all firepower to bear at the same time. This is in contrast with the linear-scaling advantage in additional numbers in an era of hand-to-hand combat, where phalanxes of fighters could only engage one person at a time. Under Lanchester’s Square Law, German tanks would have had to have been nine times better than Allied tanks to compensate for their three-fold numerical disadvantage.

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37. For reference, historical Pk values for various air-to-air missiles: AIM-7 (estimated pre-Vietnam) = 0.7; AIM-7 (actual in Vietnam) = 0.08; AIM-9 (estimated pre-Vietnam) = ~0.65; AIM-9 (actual in Vietnam) = 0.15; AIM-9L (actual in Falklands) = 0.73 (19 kills for 26 missiles fired); AIM-9M (actual in Desert Storm) = 0.23 (11 kills for 48 missiles fired); AIM-120 (actual to-date) = ~0.59 (10 kills for 17 missiles fired in combat). Source: John Stillion and Scott Perdue, Air Combat Past, Present, and Future, slides 19-28.

38. Total probability of a hit for a salvo is given by the following formula: Probability of hit = 1 – (1 – Pk)^N where Pk is the probability of kill for a single munition and N is the number of munitions fired in a salvo.

39. Of course, reducing the number of Blue's assets has some value for Red, even if Red does not eliminate all of them. Partially reducing Blue's salvo reduces the likelihood of Red's target being taken out, even if it does not eliminate it entirely.

40. This is not the case for unguided munitions, for example in the case of Hamas' rocket attacks against Israel. Because Hamas uses unguided rockets, Israel can calculate the rockets' trajectory and determine which are likely to strike populated areas, and therefore only target those that are threats. Guided munitions that home in on targets move, however, considerably complicating the problem of distinguishing which will miss.

41. This does not at all consider the critical question of "shot doctrine," or how many munitions Blue should shoot before stopping to assess whether the target has been taken out and whether or not to shoot more munitions. In an ideal scenario, one would have both the time and the means to "shoot-look-shoot," that is, fire one munition, observe whether it has taken out the target, and only fire a second munition if it has not. This would maximize the effectiveness of each munition and ensure that none were wasted against already destroyed targets. In practice, time is a factor, as is the practical matter of actually conducting a real-time battle damage assessment. In some situations it is more advantageous to shoot two munitions, then observe, then shoot again if necessary (shoot-shoot-look-shoot). Other combinations are also possible. Suffice to say, shot doctrine plays a significant role.

42. Some researchers distinguish between "swarming" and "teaming," only using the term swarming to refer to cooperative behavior with large numbers of agents and where the agents themselves are not particularly intelligent. In this report, we use the term "swarming" to cover cooperative behavior regardless of the number of agents or their degree of individual intelligence.

Rather, the term swarm is used to refer to cooperative behavior of a number of individual agents where their cooperation leads to a whole greater than the sum of its individual parts.

43. For a vivid illustration, see this video of a pack of wolves fighting a grizzly bear over a kill, “Wild Kingdom – Wolves vs. Grizzly,” https://www.youtube.com/watch?v=jY7Xmt4HzV0.

44. For an excellent overview of animal swarming, see Eric Bonabeau, Guy Theraulaz, Marco Dorigo, Swarm Intelligence: From Natural to Artificial Systems (New York: Oxford University Press, 1999).

45. Matt Soniak, “3 sneaky chemical tricks used by animals,” Mental_Floss, March 3, 2014, http://mentalfloss.com/article/55203/3-sneaky-chemical-tricks-used-animals.

46. Rumsaïs Blatrix, Claire Sermage, “Role of Early Experience in Ant Enslavement: a Comparative Analysis of a Host and a Non-Host Species,” FrontiersinZoology.com, August 2, 2005, http://www.frontiersinzoology.com/content/2/1/13.

47. Howard Topoff, Ellen Zimmerli, “Colony Takeover by a Socially Parasitic Ant, Polyergus Breviceps: the Role of Chemicals Obtained During Host-Queen Killing,” The British Journal of Animal Behaviour, 46 no. 3 (September 1993), 479-486.

48. “Swarmanoid: towards humanoid robotic swarms,” http://www.swarmanoid.org/.

49. The natural world does have examples of direct cognitive hijacking, akin to cyber attacks. The protozoan parasite toxoplasma gondii, or “toxo”, alters the behavior of mice it infects by making them less afraid of cats. Once the mice are eaten, toxo reproduces in the cat’s intestines and infects other mice through cat feces. The “zombie ant” fungus ophiocordyceps unilateralis is even more inventive. It infects ants’ brains and directs them to very specific spots in the rain forest that are the optimal humidity and temperature for fungal growth. The infected ants then climbs to the underside of a leaf of a particular height off the ground on the northern side of the plant and bites down. The ant’s jaws lock in place in a “death grip” and the ant dies. Then the fungus grows stalks from the ant’s body, which it uses to rain down spores on other ants passing by. Matt Simon, “Absurd Creature of the Week: The Zombie Ant and the Fungus That Controls Its Mind,” wired.com, September 13, 2013, http://www.wired.com/2013/09/absurd-creature-of-the-week-zombie-ant-fungus/. For a delightful overview of some of the more colorful examples in nature, see Ed Young, “Suicidal crickets, zombie roaches, and other parasite tales,” TED, March 2014, http://www.ted.com/talks/ed_yong_suicidal_wasps_zombie_roaches_and_other_tales_of_parasites#.

50. Hack a drone yourself using SkyJack freeware: Samy Kamkar, “Skyjack,” samy.pl, December 2, 2013, http://samy.pl/skyjack/.

51. Sharing position data from inertial navigation systems among vehicles can also modestly mitigate the problem of inertial navigation “drift” in accuracy over time, although it does not solve the problem.

52. This need not be real-time supervision, of course.

53. For example, see “Self-Organizing Systems Research Group,” Harvard University, http://www.eecs.harvard.edu/ssr/.

54. John Arquilla and David Ronfeldt, Swarming and the Future of Conflict (Santa Monica: The RAND Corporation, 2005), vii, http://www.rand.org/content/dam/rand/pubs/documented_briefings/2005/RAND_DB311.pdf. Some modern-day examples of swarming with human agents can be found in the tactics of protestors and rioters, particularly when empowered with information technology that allows them to rapidly communicate and synchronize their actions. Bill Wasik, “#Riot: Self-Organized, Hyper-Networked Revolts – Coming to a City Near You,” wired.com, December 16, 2011, http://www.wired.com/2011/12/ff_riots/all/.

55. Arquilla and Ronfeldt, ibid, page vii.

56. Sean Edwards, Swarming and the Future of Warfare (Santa Monica: The RAND Corporation, 2005), xvii, http://www.rand.org/content/dam/rand/pubs/rgs_dissertations/2005/RAND_RGSD189.pdf.

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59. Patrick Tague, “Improving Anti-Jamming Capability and Increasing Jamming Impact With Mobility Control” (paper presented at the Mobile Adhoc and Sensor Systems (MASS), 2010 Institute of Electrical and Electronics Engineers 7th International Conference, San Francisco, California, November 8-12, 2010), 501-506.

60. Office of Naval Research.

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66. Sherrill Lingle et al., Methodologiees for Analyzing Remotely Piloted Aircraft in Future Roles and Missions, (Santa Monica: The RAND Corporation, 2012), 18, http://www.rand.org/content/dam/rand/pubs/documented_briefings/2012/RAND_DB637.pdf.

67. "DARPA-BAA-09-65 – Precision Electronic Warfare (PREW)," FedBizOpps.gov, August 24, 2009, https://www.fbo.gov/index?s=opportunity&mode=form&id=85271e56b3b9aa657b2fd26cbeaa3944&tab=core&_cview=1.

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74. Source: U.S. Air Force.

75. Lt Gen Dave Deptula, "Air Force Unmanned Aerial System (UAS) Flight Plan 2009-2047," slide 11, http://www.defense.gov/DODcmsshare/briefingslide/339/090723-D-6570C-001.pdf.

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81. "United States Air Force RPA Vector – Vision and Enable Concepts 2013-2038," (United States Air Force, February 17, 2014).

82. For example, current FAA guidelines that pilots may not perform crew duties for more than one aircraft at a time are often cited as a rationale for not fielding multi-aircraft control technology. FAA guidelines do not apply to military operations outside of U.S. national airspace, however. United States Department of Transportation Federal Aviation Administration, Unmanned Aircraft Systems (UAS) Operational Approval, N 8900.227 (July 30, 2013).

83. For example, see "Tactical Tomahawk Takes Flight," navy.mil, August 27, 2002, http://www.navy.mil/submit/display.asp?story_id=3311.

84. "Dogfighting Drones – Swarms of Unmanned Battle-Bots Take to the Skies," airforce-technology.com, July 23, 2012, http://www.airforce-technology.com/features/featuredogfight-drones-unmanned-battle-bot-swarms/ and Radhika Nagpal, "The Kilobot Project,"eecs.harvard.edu, http://www.eecs.harvard.edu/ssr/projects/progSA/kilobot.html.

85. For a more detailed examination of a wider array of possible command-and-control models, see David Scheidt, Kevin Schultz, "On Optimizing Command and Control Structures," Proceedings of the 16th International Command and Control Research and Technology Consortium (The Johns Hopkins University Applied Physics Laboratory, 2011).

86. This process is called "particle swarm optimization." Another downside to this approach is that it only may result in localized optimization.

87. Coordination is still possible is very low bandwidth environments. For example, DARPA's Collaborative Operations in Denied Environment (CODE) project restricts communications between the swarm and the command element to 50 kilobits per second, or less than a 56k dial-up modem, circa 1997. "Collaborative Operations in Denied Environment (CODE)," fedbizopps.gov, April 25, 2014, https://www.fbo.gov/index?s=opportunity&mode=form&id=2f2733be59230cf2ddaa46498fe5765a&tab=core&_cview=1.

88. One could employ other analogous forms of "jamming" to disrupt their method of implicit communication, however, such as blocking visual co-observation of swarm elements with obscurants. Dave Scheidt, JHU/APL, personal correspondence.

89. Firas Safadi, Raphael Fonteneau, Damien Ernst, "Artificial Intelligence Design for Real-time Strategy Games," Proceedings of NIPS Workshop on Decision Making with Multiple Imperfect Decision Makers, December 16, 2011.

90. John Hawley et al., The Human Side of Automation: Lessons for Air Defense Command and Control, Army Research Laboratory, March 2005.

91. Timothy Chung, Naval Postgraduate School, personal correspondence.

92. John A. Sauter et al., "Distributed Pheromone-Based Swarming Control of Unmanned Air and Ground Vehicles for RSTA," (paper presented at SPIE Defense and Security Conference, Orlando, Florida, March 2008).

93. "All Systems Go: Navy's Laser Weapon Ready for Summer Deployment," Navy.mil, April 7, 2014, http://www.navy.mil/submit/display.asp?story_id=80172; and Allen McDuffee, "Navy's New Railgun Can Hurl a Shell Over 5,000 MPH," Wired.com, April 9, 2014, http://www.wired.com/2014/04/electromagnetic-railgun-launcher/.

94. "Dogfighting Drones – Swarms of Unmanned Battle-Bots Take to the Skies."

95. Additionally, while having a person physically onboard a platform does not render it immune to cyberattacks, having a person physically present could at least prevent the adversary from taking control of the system via cyber attacks, provided there are hardware-level physical overrides. A co-located human operator could physically unplug, for example, a malfunctioning missile battery. When systems are controlled remotely, this additional failsafe does not exist.

96. Humans, of course, are not impervious to deception. Machines actually might be better at detecting data that is manipulated slightly. A person might not notice 1% difference in position data, whereas a machine might catch such a difference. Humans, however, have a level of common sense that can be applied to information that is grossly wrong. If sent the directive to attack friendly forces, for example, a human would intuitively know that the order was either garbled or the result of enemy deception. Some degree of "skepticism" can be programmed into machines – if certain types of failures or enemy attacks can be anticipated. Human intelligence is far more robust, however, to unanticipated circumstances.

97. This, of course, depends on an effective communications link.

98. Andrew Herr, "Will Humans Matter in the Wars of 2030?," forthcoming publication.

99. Mark V. Arena et al., Why Has the Cost of Navy Ships Risen; and Mark V. Arena et al., Why Has the Cost of Fixed-Wing Aircraft Risen?.

100. For example, the F-35 Joint Strike Fighter has over 24 million lines of code. A Mercedes S-class sedan as approximately 100 million lines of code. "A Digital Jet for the Modern Battlespace," f35.com, https://www.f35.com/about/life-cycle/software; and Robert N. Charette, "This Car Runs on Code," spectrum.ieee.org, February 1, 2009, http://spectrum.ieee.org/transportation/systems/this-car-runs-on-code.

101. Admiral Jonathan W. Greenert, "Payloads over Platforms: Charting a New Course," usni.org, July 2012, http://www.usni.org/magazines/proceedings/2012-07/payloads-over-platforms-charting-new-course.

102. Chris Urmson, "The Latest Chapter for the Self-Driving Car: Mastering City Street Driving," Google Official Blog on BlogSpot.com, April 28, 2014, http://googleblog.blogspot.com/2014/04/the-latest-chapter-for-self-driving-car.html.

103. For a good overview of the state of technology today, including current limitations of autonomous vehicles, and likely future trends see "Self-driving cars take a small step closer to reality," TheStar.com, September 15, 2014, http://www.thestar.com.my/Tech/Tech-News/2014/09/15/Self-driving-cars-take-a-small-step-closer-to-reality/.

104. Patrick Lin, "The Ethics of Autonomous Cars," TheAtlantic.com, October 8, 2013, http://www.theatlantic.com/technology/archive/2013/10/the-ethics-of-autonomous-cars/280360/.

105. Takeoff and landing are also the most prevalent conditions for accidents for human-inhabited aircraft as well. The challenge of manually landing an aircraft is compounded in an uninhabited aircraft because the pilot does not get immediate kinesthetic feedback on the aircraft's movement. Thus, there is not only a slight time delay in communications between the aircraft and the controller, but also a time delay in perception by the pilot, who must rely on visual or other cues to perceive movement of the aircraft.

106. For example, the Air Force's vision document for uninhabited aircraft out to 2038 still refers to them as "remotely piloted," "United States Air Force RPA Vector – Vision and Enabling Concepts 2013-2038." For a somewhat humorous overview of the tortured language used to refer to uninhabited aircraft see Joe Trevithick, "Learn to Speak Air Force – A Public Service Announcement Regarding Drones," Medium.com/War-Is-Boring, May 27, 2014, https://medium.com/war-is-boring/learn-to-speak-air-force-e6ebc5614b25.

107. Department of the Army, Unmanned Aircraft System Flight Regulations, Army Regulation 95-23 (July 2, 2010), http://www.apd.army.mil/pdffiles/r95_23.pdf.

108. For more on what this shift to supervisory control will mean and the challenges it will bring, see Hawley, ibid.

109. Michael C. Horowitz, "The Looming Robotics Gap."

110. Ekso Bionics, "Yes, We Said Bionics," http://www.eksobionics.com/ekso.

111. Ben Fitzgerald and Kelley Sayler, "Creative Disruption: Technology, Strategy and the Future of the Global Defense Industry" (Center for a New American Security, June 2013), http://www.cnas.org/sites/default/files/publications-pdf/CNAS_FutureDefenseIndustry_FitzGeraldSayler.pdf.

112. General Mike Hostage, commander of the Air Force's Air Combat Command, has made this point about the software on the F-22, saying "The F-22, when it was produced, was flying with computers that were already so out of date you would not find them in a kid's game console in somebody's home gaming system. But I was forced to use that because that was the [specification] that was written by the acquisition process when I was going to buy the F-22." "Interview: Gen. Michael Hostage, Commander, US Air Force's Air Combat Command," 3 February 2014, http://mobile.defensenews.com/article/302030017.

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114. This echoes a recommendation from Samuel J. Brannen in "Sustaining the U.S. Lead in Unmanned Systems," (CSIS International Security Program, February 2014), 15, http://csis.org/files/publication/140227_Brannen_UnmannedSystems_Web.pdf.

Appendix

APPENDIX: TOTAL PROBABILITY OF KILL FOR SALVO*

By number of munitions fired and probability of kill (Pk) for each munition.

Number of Munitions per Salvo	Single Munition Pk = 0.9	Single Munition Pk = 0.8	Single Munition Pk = 0.7	Single Munition Pk = 0.6	Single Munition Pk = 0.5
1	0.9	0.8	0.7	0.6	0.5
2	0.99	0.96	0.91	0.84	0.75
3	0.999	0.992	0.973	0.936	0.875
4	0.9999	0.9984	0.9919	0.9744	0.9375
5	0.99999	0.99968	0.99757	0.98976	0.96875
6	1	0.99994	0.99927	0.9959	0.98438
7	1	0.99999	0.99978	0.99836	0.99219
8	1	1	0.99993	0.99934	0.99609
9	1	1	0.99998	0.99974	0.99805
10	1	1	0.99999	0.9999	0.99902
11	1	1	1	0.99996	0.99951
12	1	1	1	0.99998	0.99976
13	1	1	1	0.99999	0.99988
14	1	1	1	1	0.99994
15	1	1	1	1	0.99997
16	1	1	1	1	0.99998
17	1	1	1	1	0.99999
18	1	1	1	1	1
19	1	1	1	1	1
20	1	1	1	1	1
21	1	1	1	1	1
22	1	1	1	1	1
23	1	1	1	1	1
24	1	1	1	1	1
25	1	1	1	1	1
26	1	1	1	1	1
27	1	1	1	1	1
28	1	1	1	1	1
29	1	1	1	1	1
30	1	1	1	1	1
…	…	…	…	…	…
39	1	1	1	1	1
40	1	1	1	1	1
41	1	1	1	1	1

* Total probability of a kill for a salvo (Pksalvo) is given by the following formula: Pksalvo = 1 – (1 – Pk)^N where Pk is the probability of kill for a single munition and N is the number of munitions fired in a salvo.

Single Munition Pk = 0.45	Single Munition Pk = 0.4	Single Munition Pk = 0.3	Single Munition Pk = 0.2	Single Munition Pk = 0.11	Single Munition Pk = 0.055
0.45	0.4	0.3	0.2	0.11	0.055
0.6975	0.64	0.51	0.36	0.2079	0.106975
0.83363	0.784	0.657	0.488	0.29503	0.156091
0.90849	0.8704	0.7599	0.5904	0.37258	0.202506
0.94967	0.92224	0.83193	0.67232	0.44159	0.246369
0.97232	0.95334	0.88235	0.73786	0.50302	0.287818
0.98478	0.97201	0.91765	0.79028	0.55769	0.326988
0.99163	0.9832	0.94235	0.83223	0.60634	0.364004
0.99539	0.98992	0.95965	0.86578	0.64964	0.398984
0.99747	0.99395	0.97175	0.89263	0.68818	0.43204
0.99861	0.99637	0.98023	0.9141	0.72248	0.463277
0.99923	0.99782	0.98616	0.93128	0.75301	0.492797
0.99958	0.99869	0.99031	0.94502	0.78018	0.520693
0.99977	0.99922	0.99322	0.95602	0.80436	0.547055
0.99987	0.99953	0.99525	0.96482	0.82588	0.571967
0.99993	0.99972	0.99668	0.97185	0.84503	0.595509
0.99996	0.99983	0.99767	0.97748	0.86208	0.617756
0.99998	0.9999	0.99837	0.98199	0.87725	0.638779
0.99999	0.99994	0.99886	0.98559	0.89075	0.658646
0.99999	0.99996	0.9992	0.98847	0.90277	0.677421
1	0.99998	0.99944	0.99078	0.91347	0.695163
1	0.99999	0.99961	0.99262	0.92298	0.711929
1	0.99999	0.99973	0.9941	0.93146	0.727773
1	1	0.99981	0.99528	0.939	0.742745
1	1	0.99987	0.99622	0.94571	0.756894
1	1	0.99991	0.99698	0.95168	0.770265
1	1	0.99993	0.99758	0.95699	0.7829
1	1	0.99995	0.99807	0.96172	0.794841
1	1	0.99997	0.99845	0.96593	0.806125
1	1	0.99998	0.99876	0.96968	0.816788
…	…	…	…	…	…
1	1	1	0.99983	0.98938	0.889887
1	1	1	0.99987	0.99055	0.895943
1	1	1	0.99989	0.99159	0.901666

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