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Robotics on the Battlefield

Part I: Range, Persistence and Daring

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

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CNAS does not take institutional positions, and I alone am responsible for any errors of fact, analysis or omission.

Cover Image
Soldier from the New Zealand Army's 16th Field Regiment launching the Skycam Kahu uninhabited aircraft during field tests.

(New Zealand Army)

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ROBOTICS ON THE BATTLEFIELD
PART I: RANGE, PERSISTENCE AND DARING

By Paul Scharre

I. EXECUTIVE SUMMARY

By Paul Scharre

The U.S. military's conventional superiority is eroding. Anti-access weapons threaten traditional modes of U.S. power projection, and non-state actors are acquiring advanced technologies that will increase their lethal capabilities. On its current trajectory, the U.S. military faces a future in which its freedom of maneuver will be curtailed and where precision strike weapons from state and non-state actors will make the operating environment increasingly hazardous and lethal.

Uninhabited and autonomous systems have enormous untapped potential to help the U.S. military address these challenges. Because of their increased endurance and ability to take risk without placing human lives in danger, uninhabited and autonomous systems can give the military greater reach and persistence into denied areas and can enable more daring concepts of operation.

Uninhabited systems have been used to great effect in current operations but are still in their infancy in terms of their full potential. Like the tank and aircraft at the end of World War I, their use to date has been limited to niche roles, but they have tremendous potential in future conflicts. Cultural and bureaucratic obstacles within the Department of Defense (DOD) are limiting development, however.

Just as the Navy initially resisted the transition from sail to steam-powered ships and elements of the Army dismissed air power and fought against the shift from horses to tanks, some parts of the military continue to resist the expansion of uninhabited systems into traditional combat roles. As a result, the DOD is failing to invest in game-changing technology that could increase efficiencies and save lives. Strong department leadership will be required to overcome these obstacles and ensure that DOD is investing today in these vital capabilities to counter future threats.

Key Recommendations

THE AIR FORCE SHOULD:

- Develop multiaircraft control technology that allows one person to control multiple aircraft at the same time, in order to gain operational efficiencies and increase combat power.
- Begin development of a fleet of high-altitude long-endurance air vehicles to act as a resilient airborne layer for communications and navigation in the event of a widespread disruption to satellites.
- Begin development of low-cost attritable uninhabited aircraft for high-risk missions, such as suppression and destruction of enemy air defenses.

THE NAVY SHOULD:

- Invest in a stealthy deep-strike attack version of its Unmanned Carrier-Launched Airborne Surveillance and Strike (UCLASS) program.
- Study the benefits and risks associated with ultralong-endurance radioisotope thermoelectric power for uninhabited undersea vehicles.
- Begin development of small uninhabited surface vessels to act as picket line defenses to intercept swarming small boats that threaten Navy surface ships.

THE ARMY SHOULD:

- Implement a hybrid remote operations concept for its unmanned MQ-1C Gray Eagle aircraft so operators can fly MQ-1Cs remotely while stateside between deployments, to add operational capacity at low cost.
- Rescind its policy prohibiting uninhabited vehicles for casualty evacuation (CASEVAC) and begin development of uninhabited vehicle options for CASEVAC.

THE MARINE CORPS SHOULD:

- Begin development of a medium-altitude long-endurance uninhabited aircraft, like the Predator or Reaper, to fly from amphibious assault ships to provide Marines with loitering surveillance and close air support.

THE OFFICE OF THE SECRETARY OF DEFENSE SHOULD:

- Establish a senior innovation group, led by the deputy secretary of defense, to ensure DOD invests in key game-changing capabilities, even when such technologies threaten existing cultures and bureaucracies.

II. INTRODUCTION: A REVOLUTION IN WARFARE

Warfare – the tools and methods of war – is ever-changing. Nations must adapt or risk defeat on the battlefield. War is a human endeavor, but the tools of war can be and often are decisive. No amount of élan can overcome a machine gun's bullets. No amount of fortitude can protect exposed ground forces from the relentless barrage of air power.

The militaries that nations field are the product of a desire to stay ahead in an ever-shifting contest of innovations and countermeasures, but they are also shaped by other factors: available technology, society's values, and military bureaucracy and culture. Sometimes these factors lead to innovation – sometimes they can hold it back. When they do so, the battlefield is a harsh judge. The enemy's weapons do not care what congressional district a tank's armor was made in, which military service operates an aircraft or which bureaucratic fiefdom won the battle over requirements for a weapon system. The U.S. military's investments today are shaped by institutional and cultural factors that leave the nation vulnerable to disruptive innovation. Emerging technologies are changing the face of warfare, and the United States must adapt or risk defeat.

Several trends in the global security environment are eroding conventional U.S. military advantages. Long-range, precision anti-access and area denial, or "A2/AD," weapons threaten traditional U.S. modes of power projection and target America's Achilles' heel in space. Long-range missiles that can target U.S. ships and air bases are pushing U.S. power projection assets farther away. Non-state actors have increasing access to guided rockets, artillery, mortars and missiles, or "GRAMM," that can target U.S. ports, bases and formations with high precision and lethality. Readily available commercial information technologies place sensors and ad hoc command-and-control networks literally in the palm of anyone's hand, empowering non-state groups and individuals. And commercial off-the-shelf technologies such as cyberweapons, 3D printers, communications and global positioning system (GPS) jammers and fully autonomous drones give non-state actors and even "lone wolf" terrorists access to potentially powerful disruptive weapons.

"Technological advances will not change the essential nature of war. Fighting will never be an antiseptic engineering exercise. It will always be a bloody business subject to chance and uncertainty. … But the way punishment gets inflicted has been changing for centuries, and it will continue to change in strange and unpredictable ways."

MAX BOOT, *WAR MADE NEW*

Because the power of information-based technologies comes not from industrial capacity but from knowledge, in many ways it begins to level the playing field among states and even with non-state actors. Information flows freely. Stuxnet source code is now available on the Internet and is being teased apart and modified by hackers around the globe. 3D printing designs can be shared freely,

What is a Reconnaissance-Strike Battle 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 vector 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.[2]

Today, sophisticated nation-states operate reconnaissance-strike battle networks composed 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 strike. 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.

adapted and modified. Fully autonomous commercial drones are widely available to anyone.[1] Malware, 3D printed guns and weaponized robotics are "open source" weapons.

As a result, information-based weapons decouple destructive capability from traditional drivers of power, such as population and gross domestic product (GDP). A small but highly capable group of nationalist hackers or cybercriminals can generate sophisticated malware and penetrate government networks. A lone individual could field a swarm of fully autonomous drones laden with explosives. A small but technologically advanced nation-state could field a large robotic military, out of proportion with its population or GDP.

These trends in the democratization of information and the democratization of violence will result in a future operating environment that is more contested, more transparent and more lethal for U.S. forces. Today, the United States and other sophisticated nation-states operate reconnaissance-strike battle networks enabled by advanced sensors, communication technologies and precision-guided weapons. Uninhabited and autonomous systems will enable the *reconnaissance-strike swarm*, with greater range and persistence, taking greater risks and enabling more daring operations, overwhelming adversaries with greater numbers, operating with better coordination and intelligence and reacting at faster speeds than military forces today.

The winner of the robotics revolution will not be who develops this technology first or even who has the best technology, but who figures out how best to use it.

Uninhabited and autonomous systems will enable game-changing advances on the battlefield, but the history of military revolutions suggests that the winner of the robotics revolution will not be who develops this technology first or even who has the best technology, but who figures out how best to use it. The United States has used thousands of air and ground robots in Iraq and Afghanistan, and they have filled valuable roles in overhead surveillance and defusing improvised explosive devices. These uses merely scratch the surface of their potential, however. Just as World War I saw the early introduction of the tank and airplane into combat but their full potential was not realized until World War II, today we are at the infancy of robotic systems. If the United States is to stay ahead in the coming robotics revolution, the first essential element is imagination – to see beyond the "dull, dirty and dangerous" and understand the possible uses for robotic systems across the full array of military tasks and missions. We must put ourselves in the shoes of the early aviators and tank crews in World War I and imagine what might be possible.

This report explores the operational advantages of uninhabited and autonomous systems and the new concepts of operations they enable. In some cases, these systems can be used to perform the same mission as human-inhabited systems but in a better way or at lower cost. In many cases, however, they can be used for entirely new, sometimes radically disruptive, concepts. These concepts are explored according to the five advantages the reconnaissance-strike swarm will have over existing reconnaissance-strike battle networks:

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

This report will examine the first two advantages: range and persistence, and daring. A second report, "Robotics on the Battlefield, Part II: The Coming Swarm," will examine new concepts of operation enabled by greater mass, coordination and intelligence, and speed.

This report will also examine key enablers and obstacles for achieving these advantages and will conclude with recommendations for actions. In some cases, bureaucratic, cultural and institutional shifts will be required. The robotics revolution will not stop and wait for the U.S. military to come around to recognizing the full potential for uninhabited and autonomous systems. Adversaries can and will develop and employ their own robotic systems, sometimes by merely exploiting or modifying commercially available robotics. If the U.S. military is to stay ahead, it must act now.

III. THE BENEFITS OF UNINHABITED AND AUTONOMOUS SYSTEMS

The U.S. Department of Defense's *Unmanned Systems Integrated Roadmap, FY2013-2038* states that unmanned systems are optimized for "dull, dirty, or dangerous missions," but this dramatically understates their potential.[3] Robotic systems can be useful because of two attributes they bring: uninhabited, or unmanned, platforms; and 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.

The Benefits of Uninhabited Platforms

Removing the human from a vehicle or platform has two potential advantages:

- Improved performance, such as increased range, endurance, persistence, speed, stealth or maneuverability, or reduced size
- Increased ability to take risk with the platform

Uninhabited systems in use today leverage these advantages in different ways. Ground robots that are used to defuse improvised explosive devices are prized for their ability to take risk. Uninhabited aircraft such as the Predator, Reaper and Global Hawk are valued because of their ability to loiter over targets for up to 24 hours or more, far longer than manned aircraft are capable of.

For smaller aircraft such as the Predator, improved endurance comes directly from the weight savings gained by removing the human occupant. As uninhabited systems become larger, the direct savings in size and weight from removing the human occupant become less significant, and practical concerns relating to human fatigue become an issue. Even for aircraft whose unrefueled endurance does not exceed human limitations, the ability of an uninhabited aircraft to refuel and stay on station for extended periods can lead to significant operational advantages. The advantages in range and persistence gained from extended endurance are particularly significant for countering anti-access challenges and are explored in more detail in Section IV.

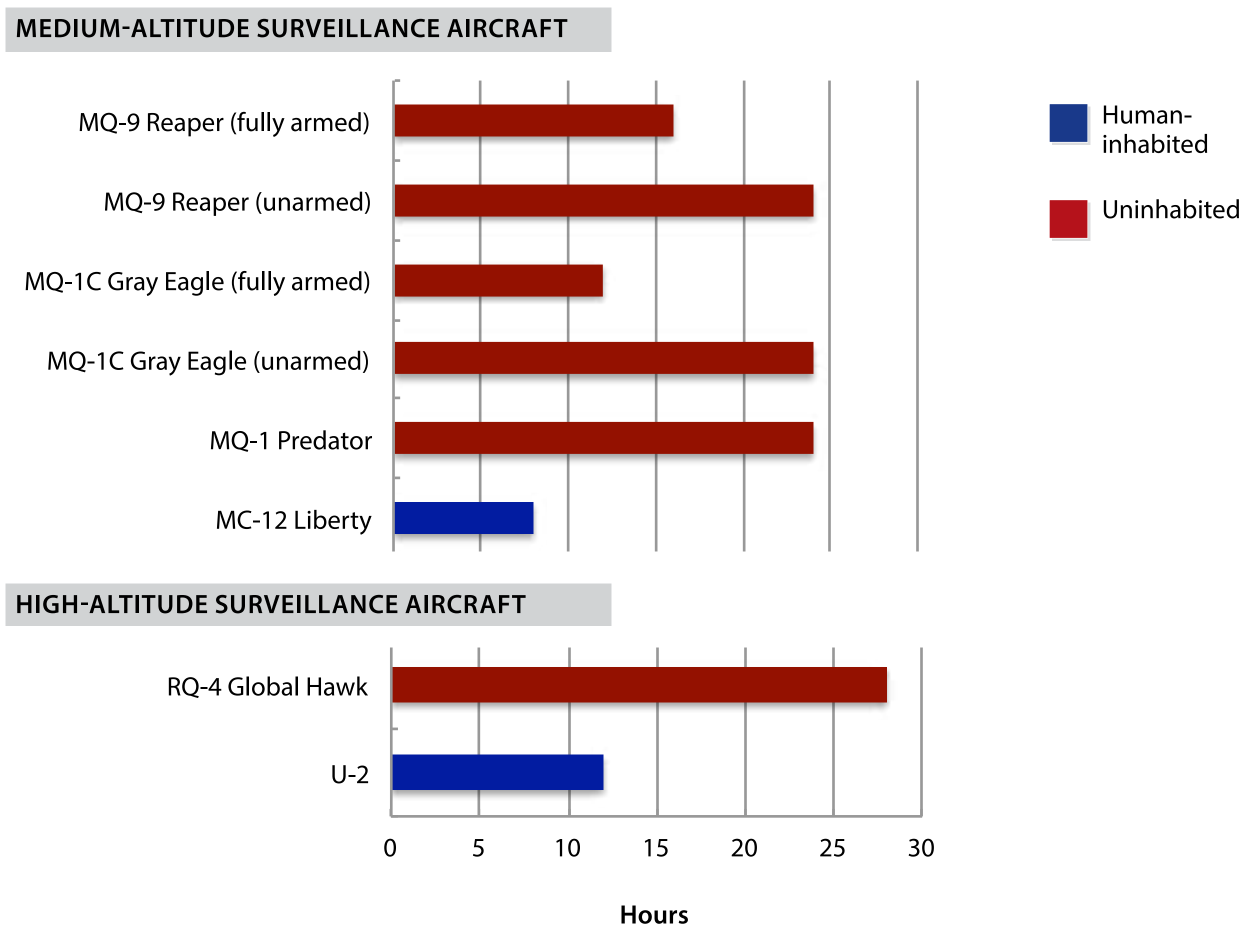
Robot defuses a mock improvised explosive device.

(Photo courtesy of iRobot)

> *"If I had robot technology available to me then, many of those young men and women would be alive today."*
>
> LIEUTENANT GENERAL RICK LYNCH, U.S. ARMY

In many cases, uninhabited systems are valuable because they can do things human-inhabited systems could not do. This can lead to low-cost ways of performing valuable missions or, in some cases, entirely new concepts of operation.

FIGURE 1: ENDURANCE COMPARIONS OF HUMAN-INHABITED AND UNINHABITED AIRCRAFT

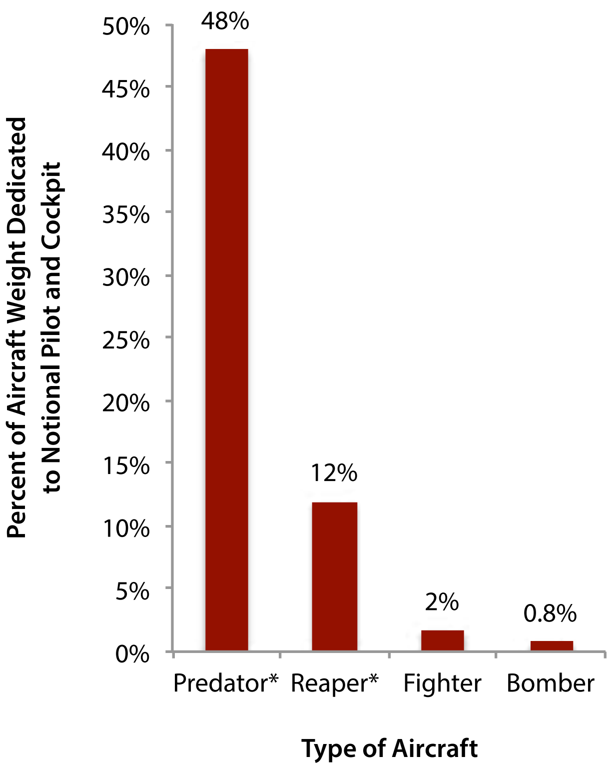


Source: Department of Defense

For example, small uninhabited aircraft such as the hand-launched Raven or Wasp give ground squads an organic airborne surveillance capability that allows them to peer over hillsides and around corners. The aircraft's small size makes them portable on patrol, and their low cost has allowed the Army and Marine Corps to purchase more than 7,000.[4] Performing this mission by stationing manned aircraft above every single ground patrol would simply be so costly it would be infeasible.

Removing the person from a vehicle can also enable greater stealth. Combined with the ability to take greater risk with uninhabited systems, this can open up novel concepts of operation. Small air, ground and sea robots could operate with lower signature than larger human-inhabited systems, allowing more stealthy operations. If they were made entirely with commercial off-the-shelf parts and without identifiable markings, they could be used for clandestine or covert missions where, even if discovered, they could be denied. For large aircraft, simply removing the cockpit reduces signature and improves stealth.[5] The ability to take greater risk enables new, innovative operational concepts, which are explored further in Section V.

FIGURE 2: WEIGHT ADVANTAGE OF REMOVING PILOT DECREASES AS AIRCRAFT SIZE INCREASES



Assumes 1200 lbs "manned design" penalty for pilot and cockpit, relative to aircraft empty weight. Source: Brien Alkire, RAND Corporation

Assumes 2-person crew for bomber.

* Predator and Reaper aircraft are uninhabited. Assumes additional 1200 lbs penalty to add a human occupant if designing a human-inhabited variant.

These are potential advantages and are not realized in all uninhabited systems. An uninhabited platform that was designed the same and used in the same way as a human-inhabited platform would realize none of these advantages. Moreover, an uninhabited platform that is extremely costly may not be considered expendable even though no lives are at risk, although how much risk a commander is willing to take with it may depend on the mission. Finally, uninhabited platforms invariably face design constraints and tradeoffs, like any military platform, which may mean some of these potential performance advantages may not be realized.

The Benefits of Autonomy

Autonomy is the ability of a machine to perform a task without human input. Autonomy can lead to several benefits, including:

- Increased safety and reliability
- Improved reaction time and performance
- Reduced personnel burden, with operational advantages or cost savings
- The ability to continue operations in communications-degraded or -denied environments

Automated features are not limited to uninhabited systems and in fact are included on many human-inhabited systems today. Most cars today include anti-lock brakes, traction and stability control, power steering, emergency seat belt retractors and air bags, while higher-end cars may include intelligent cruise control, automatic lane keeping, collision avoidance and automatic parking. For military aircraft, automatic ground collision avoidance systems (auto-GCAS) can similarly take control of a human-piloted aircraft if a pilot becomes disoriented and is about to fly into terrain. In some cases, such as automatic parking or automated takeoff and landing for aircraft, the advantage of automation is that machines can perform tasks more reliably and with greater precision than humans. In other cases, such as collision avoidance or auto-GCAS, the speed of automation is critical for situations where maneuvers are required faster than is possible with human reaction times.

Autonomous functions can be used to reduce the personnel burden for operating uninhabited platforms, with cost savings as well as operational advantages. Most uninhabited vehicles today are remotely controlled, with one person controlling each vehicle. Even when autonomy is used for routine tasks such as aircraft takeoff and landing or point-to-point navigation, one person stays in

What is Autonomy?

There are three critical dimensions, or aspects, of autonomy: the human-machine command-and-control relationship, the complexity of the system and the type of decision being automated.

Learning thermostat

(Photo courtesy of Nest)

HUMAN-MACHINE COMMAND-AND-CONTROL RELATIONSHIP

Machines that perform a function for some period of time, then stop and wait for human input before continuing, are often referred to as "semiautonomous" or "human in the loop." Machines that can perform a function entirely on their own but have a human in a monitoring role, with the ability to intervene if the machine fails or malfunctions, are often referred to as "human-supervised autonomous" or "human on the loop." Machines that can perform a function entirely on their own and humans are unable to intervene are often referred to as "fully autonomous" or "human out of the loop."

COMPLEXITY OF THE MACHINE

The word "autonomy" is also used in a different meaning to refer to the complexity of the system. Regardless of the human-machine command-and-control relationship, words such as "automatic," "automated" and "autonomous" are often used to refer to a spectrum of complexity of machines. The term "automatic" is often used to refer to systems that have very simple, mechanical responses to environmental input. Examples of such systems include trip wires, mines, toasters and old mechanical thermostats. The term "automated" is often used to refer to more complex, rule-based systems. Self-driving cars and modern programmable thermostats are examples of such systems. Sometimes the word "autonomous" is reserved for machines that execute some kind of self-direction, self-learning or emergent behavior that was not directly predictable from an inspection of its code. An example would be a self-learning robot that taught itself how to walk or the Nest "learning thermostat."[7]

TYPE OF FUNCTION BEING AUTOMATED

It is meaningless to refer to a machine as "autonomous" or "semiautonomous" without specifying the task or function being automated. Different decisions have different levels of risk. A mine and a toaster have radically different levels of risk, even though both have humans "out of the loop" once activated and both use very simple mechanical switches. The task being automated, however, is much different. A machine that might be "fully autonomous" for one task, such as navigating along a route, might be fully human-controlled for another task, such as choosing its final destination.

supervisory control of each vehicle. This concept of operations is extremely personnel intensive, however. Increased autonomy that allows a person to control multiple vehicles at the same time has already been demonstrated and could result in significant personnel cost savings. Multivehicle control is also essential to the employment of large "swarms" of robotics, which could have tremendous operational advantages on the battlefield.

Autonomy also enables operations in communications-degraded or -denied environments. Because of the communications challenges associated with undersea operations, uninhabited undersea vehicles have significantly more autonomy than uninhabited aircraft today. Many uninhabited undersea vehicles incorporate "mission-level autonomy," in which a human tasks the vehicle to conduct a particular mission and the vehicle navigates and conducts the mission all on its own.[6] For anti-access environments, where adversaries may be jamming communications or where emitting signals in the electromagnetic spectrum may give away the vehicle's position, increased autonomy for uninhabited vehicles is essential. The challenges associated with operations in communications-degraded or -denied environments are explored further in Section VI.

Uninhabited and Autonomous Systems Can Lead to Cost Savings

Uninhabited and autonomous systems are not inherently lower-cost, but the performance and operational advantages they enable can translate to significant cost savings.

REDUCED PLATFORM REQUIREMENTS CAN LEAD TO DIRECT COST SAVINGS IN PLATFORM DESIGN

Removing a person from a vehicle can directly lead to cost savings if weight, power, survivability, force protection or other requirements are reduced as a result. Uninhabited ground vehicles could require less armor than human-inhabited vehicles, for example. This could lead to savings directly on platform costs and also in operational costs due to reduced fuel requirements because of lower vehicle weight.

GREATER ENDURANCE CAN SAVE COSTS BY REDUCING THE REQUIRED NUMBER OF PLATFORMS

The performance advantages gained from removing a person can also sometimes translate into significant cost savings. The greater endurance of uninhabited aircraft can not only enable more persistent surveillance at increased range, but also reduced cost compared with human-inhabited aircraft, even if the platform costs and operations costs are roughly comparable. Increased endurance means fewer aircraft are needed to sustain persistent 24/7 orbits over targets. Moreover, these savings increase at greater range, as more of the aircraft's available flight time is used for transit to the target location. For example, no quantity of eight-hour-endurance aircraft can be used to sustain a 24/7 orbit over a target four hours away, as the entire time of flight of the aircraft would be used up in transit to the target and back.

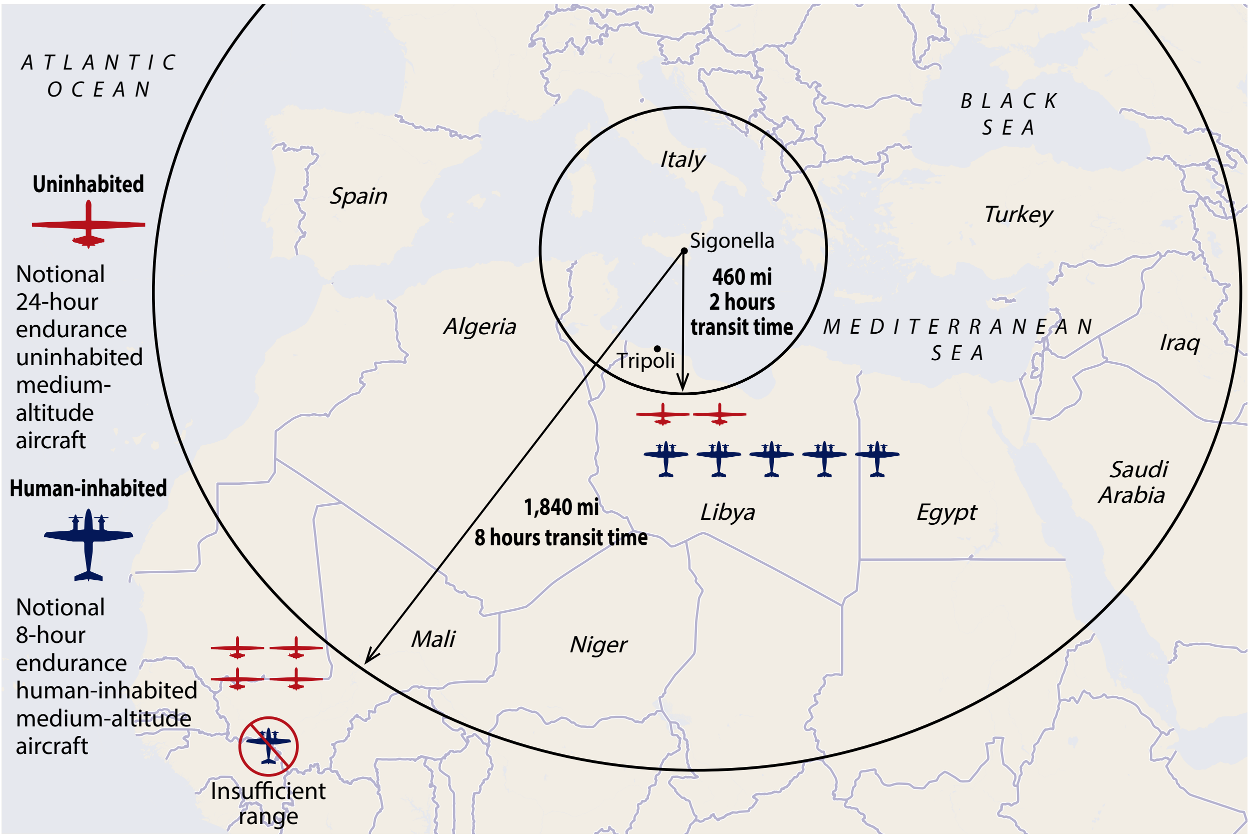
REMOTE OPERATIONS CAN REDUCE PERSONNEL COSTS

Merely the ability to control vehicles remotely can yield significant cost savings. Air Force Predators and Reapers are controlled from the United States, which means that the personnel operating them do not have to deploy to theater to conduct operations.[8] In contrast, Army MQ-1C Gray Eagle aircraft are operated by controllers who deploy to theater on a 1:2 rotational model, which means for every month deployed they spend roughly two months at home between rotations. This has tremendous personnel costs, as the Army effectively pays for three times as many people than if it flew MQ-1Cs remotely from the United States like the Air Force.[9] Cultural and bureaucratic obstacles have prevented the Army from adopting remote operations, however. A 2011 Army study, directed by the Office of the Secretary of Defense, validated the operational efficiencies in remote operations. Even a hybrid approach, where soldiers continued to deploy to theater but also operated MQ-1Cs remotely while in the States between rotations, could expand operational capacity at low cost.[10] Allowing stateside soldiers to augment deployed forces with additional MQ-1Cs flown remotely could increase operational capacity and give nondeployed soldiers real-world operational experience, yet for bureaucratic and cultural reasons the Army has resisted this approach.[11]

MULTIVEHICLE CONTROL CAN REDUCE PERSONNEL COSTS

Autonomy can also reduce the number of personnel required to operate vehicles, with significant savings. Long-endurance uninhabited vehicles can lead to platform savings, but so long as one person controls each vehicle, large numbers of people are still required. Multiaircraft control

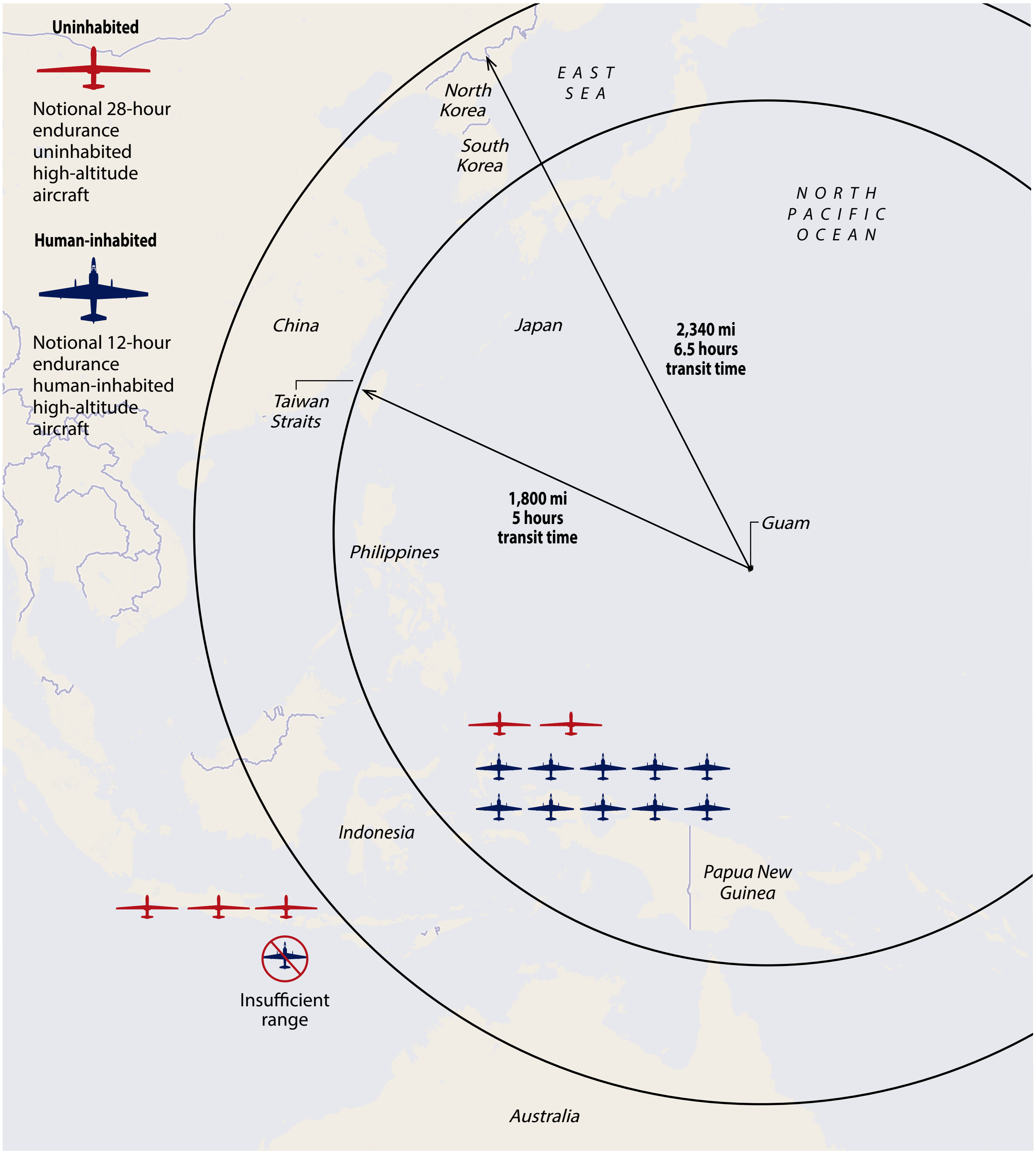
FIGURE 3: THE VALUE OF ENDURANCE: NUMBER OF AIRCRAFT NEEDED TO SUSTAIN 24/7 COVERAGE AT VARIOUS RANGES



Assumes notional medium-altitude aircraft traveling at 230 miles per hour cruising speed. Assumes aircraft require at least 8 hours on the ground between sorties for maintenance. Does not account for personnel. For illustrative purposes only. An actual cost comparison between two specific aircraft would need to include full lifecycle costs, including not only platform costs but also research and development, operations, maintenance, aircraft spares, training, etc.

technologies have been tested and even used in a limited fashion in real-world operations. The cost savings enabled by multiaircraft control would depend on the complexity of the operations, but for static overhead surveillance the savings could be quite large. Air Force concepts from only a few years ago envisioned personnel reductions of 50 percent or greater, with one pilot able to control up to four aircraft at a time.[12] If a large number of aircraft were engaged in dynamic operations, such as tracking moving targets or executing strikes, this would be reduced, but even a modest approach that merely used multiaircraft control for transit operations could generate meaningful savings.[13] Cultural resistance to multiaircraft control in the Air Force has been strong, however. While the Air Force has embraced remote operations, many in the Air Force see aircraft operating under multiaircraft control as "out of control."[14] Early experiments with multiaircraft control led to frustration with human-machine interfaces and task loading. However, the Air Force deemed improving these interfaces and researching human task loading an "unfunded requirement."[15] In 2010, Secretary of Defense Bob Gates directed nearly $50 million to develop improved multiaircraft control

FIGURE 4: THE VALUE OF ENDURANCE: NUMBER OF AIRCRAFT NEEDED TO SUSTAIN 24/7 COVERAGE AT VARIOUS RANGES



Assumes notional high-altitude aircraft traveling at 360 miles per hour cruising speed. Assumes aircraft require at least 8 hours on the ground between sorties for maintenance. Does not account for personnel. For illustrative purposes only. An actual cost comparison between two specific aircraft would need to include full lifecycle costs, including not only platform costs but also research and development, operations, maintenance, aircraft spares, training, etc.

interfaces, but the Air Force has failed to comply with this guidance.[16] Today, the Air Force has no funded plan to move forward with multiaircraft control.[17] The Army, on the other hand, resists remote operations but has embraced multiaircraft control and will field multiaircraft control for MQ-1C Gray Eagle aircraft in 2015.[18]

Increased automation enables cost savings for a wide range of missions beyond aerial surveillance, including lift, resupply and logistics operations in all domains. Autonomous uninhabited resupply helicopters such as the K-MAX have already been used in Afghanistan.[19] The Army is experimenting with autonomous uninhabited ground vehicles for logistics convoys.[20] Commercial shippers have even raised the possibility of uninhabited cargo vessels at sea.[21] Given the tremendous logistical burdens in military operations, uninhabited and autonomous air, ground and sea resupply could potentially save billions of dollars.

AUTONOMY CAN REDUCE TRAINING COSTS

Autonomy can also result in cost savings when automation reduces the need for humans to train for complicated tasks. Naval aviators must spend a significant amount of time practicing carrier landings, even while not deployed, in order to maintain proficiency. Landing an airplane on a moving aircraft carrier is challenging for humans and requires skill and practice. This task is trivial for machines, however. The X-47B has demonstrated a degree of accuracy and precision in landings that is impossible for humans to match.[22] Switching to fully autonomous landings for all aircraft, even piloted ones, would yield significant savings in training and associated flight hour costs. All pilots must maintain currency by flying a minimum number of training hours, on the order of 10 to 20 hours per month.[23] For uninhabited and autonomous systems, the training required to perform complex physical tasks such as landing on carriers could be eliminated, as human controllers would not need to retain the physical reflexes needed to pilot aircraft, which instead would fly autonomously. Training would be required to exercise judgment and decisionmaking in combat, but high-fidelity simulators could replace a great deal of this training, since there would be no "seat of the pants" feel to be gained from flying actual aircraft. Over the life cycle of an aircraft program, the savings reaped from reduced training hours alone could stretch into the billions.

AUTOMATED INFORMATION PROCESSING CAN REDUCE PERSONNEL COSTS

The largest personnel burden for uninhabited vehicles today is the need to process the information gained from their persistent surveillance. The number of people required to operate the sensors and analyze the data for each 24/7 Predator or Reaper "orbit" is an order of magnitude larger than the number of pilots required to operate the aircraft. Ten pilots are needed to operate a single 24/7 orbit at a sustainable tempo, but operating the sensors and analyzing, processing and exploiting the data requires an additional 10 sensor operators, 10 mission controllers and approximately 80 people to manage and process the data.[24] Compounding the problem, wide-area surveillance sensors such as Gorgon Stare and ARGUS-IS aim to multiply the imagery coming off of a single aircraft sixty-five fold.[25] Without automated data processing tools, more than 2,000 human analysts would be required to manage and process this imagery at the level done for each Predator video stream today.[26] Sustaining 24/7 orbits over 10 cities would require more than 20,000 personnel, a completely infeasible personnel burden.

Automation can help. The Defense Advanced Research Projects Agency (DARPA) estimates that automated image-processing tools have the potential to reduce the personnel burden for wide-area sensors to approximately 75 analysts per sensor covering an entire city, a much more manageable burden than 2,000.[27] Computer algorithms cannot yet match human visual processing abilities, but given images with sufficiently high resolution, algorithms can successfully track objects and even identify specific human behaviors such as walking, bending or digging. In fact, intelligent video surveillance systems that automatically monitor surveillance cameras and alert humans to objects of interest are widely available on the commercial market today.

Swarms of uninhabited vehicles patrolling the battle space and scooping up vast amounts of data will not be useful if their data cannot be processed and exploited, and automation will be essential to processing "big data." Moreover, as much processing as possible must occur onboard the vehicle, since networks will not be able to manage the massive bandwidth required to transmit all of the data. A single frame of data from a city the size of Baghdad at the resolution required to track individuals is roughly equivalent to the amount of data transiting the entire U.S. Internet per second in 2009.[28] Motion video at a mere 10 frames per second would require an order-of-magnitude more bandwidth, necessitating onboard processing solutions. The solution to this deluge of data lies not in turning away from wide-area sensors and big data, but in developing better automation.

Uninhabited and Autonomous Systems are Not Suitable for All Missions

Uninhabited and autonomous systems will not bring advantages in every situation and in some cases may be inappropriate for the mission. Removing the person from the platform forces reliance on some combination of communications links to remote operators and onboard vehicle autonomy. For simple missions and environments this may be appropriate, but when decisions are needed that require human judgment in complex, dynamic environments and communications links are challenged, automation may not be feasible or appropriate. Not all decisions can or should be automated.[29]

Furthermore, in some instances having a person on board a vehicle may be important for political signaling or as an ultimate fail-safe against communications or automation failure. Adversaries may have a lower threshold for attacking uninhabited systems in a crisis, an important consideration that should be factored into their use. Uninhabited systems would also not be appropriate for missions that demand an extremely high reliability and where removing a person would have no practical advantages, such as nuclear strike.[30]

Robots Can Perform Missions in Ways Human-Inhabited Systems Cannot

Uninhabited and autonomous systems can be used to save costs or perform some missions better than humans, but their real advantage lies in doing things human-inhabited systems cannot do. Longer endurance enables greater range and persistence, which will allow U.S. forces to reach deep inside anti-access areas and conduct sustained operations within enemy territory. The ability to take greater risk with uninhabited systems without putting a person in danger enables more daring concepts of operation. Because uninhabited systems can be expendable, they can be made cheaper and in greater numbers, flooding the enemy's battle space with mass. Networked autonomous systems can operate with greater coordination and intelligence, fighting as a distributed, coherent whole. Automation can rapidly process large amounts of data, shortening decision cycles and accelerating the tempo of operations.

Each of these advantages will be significant. Together, they will represent an overwhelming advantage on the battlefield as today's reconnaissance-strike networks are eclipsed by the coming reconnaissance-strike swarm. The operational advantages enabled by individual robotic systems – increased range and persistence and more daring concepts of operation – are detailed below.

IV. THE OPERATIONAL ADVANTAGES OF ROBOTICS ON THE BATTLEFIELD: RANGE AND PERSISTENCE

> *"The first virtue in a soldier is endurance of fatigue; courage is only the second virtue."*
>
> NAPOLEON BONAPARTE

Since the first human picked up a rock in anger, the ability to strike one's enemy from a safe distance has been prized in warfare. From the sling to the English longbow to the rifled musket to artillery and air power, military innovations have sought greater standoff. For nearly all of human history the advantages of longer-range weapons were mitigated, however, by the problem of increased inaccuracy. Most unguided munitions miss their target, and their inaccuracy increases with range. As detailed in "20YY: Preparing for War in the Robotic Age," the 20th century saw the advent of precision-guided weapons that, for the first time, allowed accurate strikes independent of range.[31] For a brief period, the United States had a monopoly on precision-strike weapons, but that monopoly is eroding. Precision-guided ballistic and cruise missiles, operating as part of land-based reconnaissance-strike battle networks, can threaten U.S. ships and bases at long range. These weapons will make operating within their threat ring prohibitively costly or simply infeasible, putting a premium on range for U.S. assets. Anti-satellite weapons also threaten the U.S. military's global communications and command-and-control network, which depends heavily on space assets.[32]

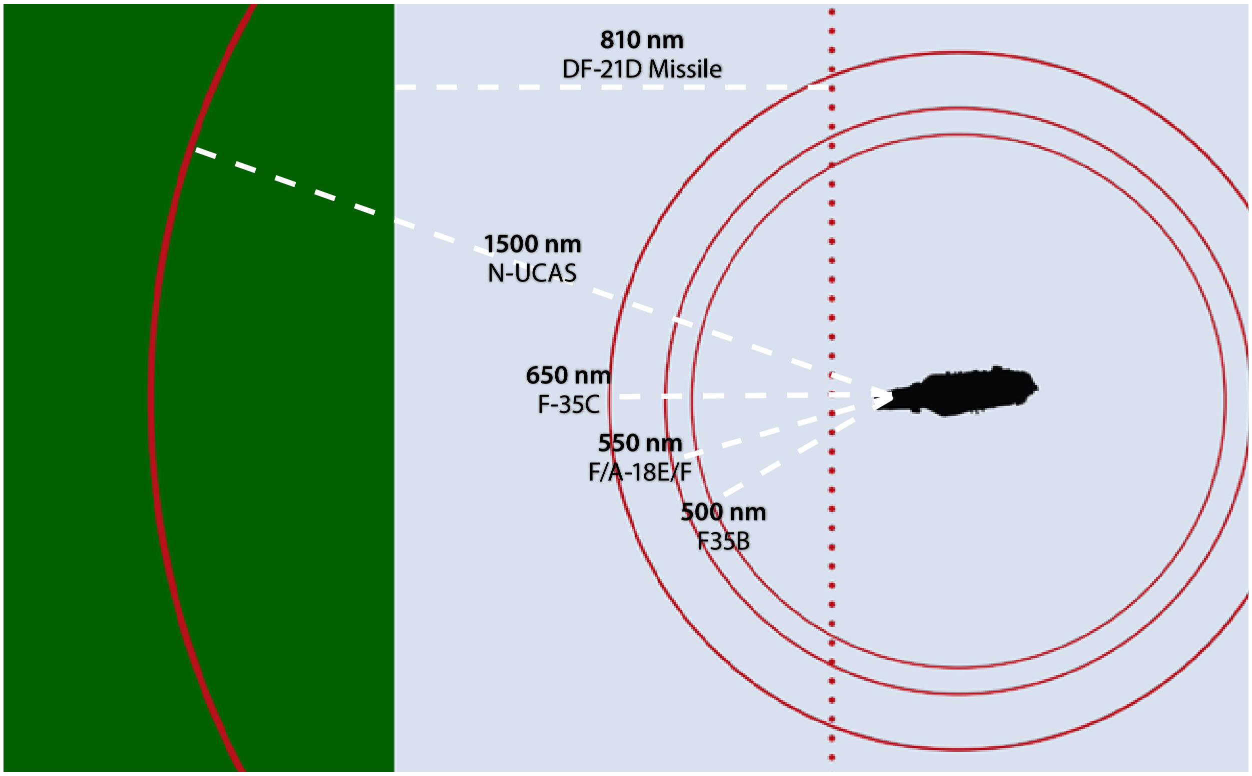
Uninhabited vehicles can help address these challenges. By exploiting their longer endurance, uninhabited aircraft not only have the reach to penetrate anti-access areas, but the persistence to conduct sustained operations inside enemy territory. High-altitude long-endurance uninhabited aircraft can act as pseudo-satellites, or "pseudolites," and function as a backup airborne layer for communications and navigation functions if satellites are disrupted. Long-endurance sea surface and undersea vehicles can operate for months at a time, allowing persistent surveillance of the world's oceans. These and other operational advantages enabled by the extreme endurance of uninhabited vehicles are detailed below.

UNINHABITED CARRIER-BASED AIRCRAFT ENABLE PERSISTENT REACH INTO DENIED AREAS

Greater endurance can translate into greater range, which is essential to countering anti-access threats. A naval uninhabited combat aircraft system (N-UCAS), such as the X-47B unmanned carrier demonstration aircraft, could have significantly greater range and endurance than current carrier-based human-inhabited fighter aircraft such as the F-18 or F-35. A future N-UCAS could have an unrefueled combat radius of up to 1,500 nautical miles (nm), far greater than the unrefueled combat radii of current human-inhabited fighter aircraft, approximately 500 to 650nm, depending on specific aircraft configuration, payload and external fuel tanks.

A long-range N-UCAS would give the carrier the ability to strike land targets from sanctuary beyond the range of enemy anti-ship ballistic missiles. The most severe anti-access threat facing the aircraft carrier is the DF-21D anti-ship ballistic missile, a conventional long-range strike weapon that has a range of 810 nautical miles.[33] From this distance, current carrier-based aircraft will be unable to reach land targets, necessitating either countermeasures to defend the carrier or accepting its irrelevance against sophisticated adversaries. Given the tremendous U.S. investment in aircraft carriers as a tool of power projection and their

FIGURE 5: UNREFUELED COMBAT RADII OF CARRIER-BASED AIRCRAFT



Note: Ranges shown are approximate. Actual combat radius will depend on specific aircraft configuration, including payload and external fuel tanks.

Source: Author interviews, March 2014

inherent flexibility compared with land bases, neither approach is acceptable. Depending solely on methods of defeating the DF-21D and similar threats, with no aircraft capable of striking beyond their range, gambles too much on countermeasures that will be impossible to test thoroughly outside of combat. Resigning carriers only to conflict against less-capable adversaries is equally unacceptable given the enormous U.S. investment in carriers as a tool of future power projection. Next-generation Ford-class carriers cost more than $11 billion apiece and, with a lifespan of 50 years, are expected to last in the fleet until 2070.

While China is currently developing the DF-21D, this technology will proliferate over time.[34] Long-range anti-ship ballistic missiles like the DF-21D will be available in increasing numbers in the coming decades and to a wider array of actors. North Korea and Iran already have anti-ship ballistic missiles in development.[35] If the carrier is outfitted only with short-range aircraft, these threats pose a fundamental problem for the carrier and expose its fragility as a tool of power projection into the middle 21st century.

An N-UCAS could give the carrier greater reach into anti-access environments from beyond DF-21D range. Most importantly, if refueled at tankers operating a safe distance away, an N-UCAS could conduct sustained operations within enemy airspace, refueling multiple times up to its 30- to 40-hour endurance limit. Moreover, since crew rest would not be an issue, an uninhabited aircraft such as the N-UCAS could be turned around within 8 to 12 hours of maintenance before another 30- to 40-hour mission and could sustain this tempo for weeks. Long-endurance uninhabited aircraft can enable a sustained operations tempo far greater than possible with human-inhabited aircraft.

Long-range anti-ship ballistic missiles like the DF-21D will be available in increasing numbers in the coming decades and to a wider array of actors.

Finally, because an N-UCAS could be a tailless aircraft incorporating broadband all-aspect stealth, it could survive in contested air environments.[36] Communications would be a challenge, as adversaries would undoubtedly seek to jam communications. In addition, emitting in the electromagnetic spectrum could give away the position of the aircraft. Approaches for overcoming these challenges are described in Section VI.

The Navy's program to develop a carrier-based uninhabited aircraft is the Unmanned Carrier-Launched Airborne Surveillance and Strike aircraft. Although the Navy is moving forward with the program, it is not clear whether UCLASS will take full advantage of the opportunities provided by uninhabited aircraft. UCLASS has been a victim of internal struggles within DOD over the shape of the program, with some advocating for a lower-cost aircraft focused primarily on surveillance in permissive or lightly contested environments instead of a more capable aircraft for anti-access challenges.[39] As of the time of publication, it was not clear what

Uninhabited Aircraft Are Essential for Carrier-Based Persistent Reach into Anti-Access Areas

The greater range of an N-UCAS compared with an F-18 or F-35 derives principally from the aircraft's design rather than the pilot's weight. The weight saved by removing the pilot is meaningful and can be translated into either greater payload or increased range if more fuel is added as a result. For aircraft in the 30,000- to 40,000-pound range, however, removing the pilot does not yield sufficient savings to account for the range and endurance gap between a hypothetical N-UCAS and the F-18 or F-35. For example, the manned EA-6B Prowler, which was optimized for long-range penetrating electronic attack, had a combat radius of 850 nautical miles, significantly farther than the F-18 and F-35, which are fighter/attack aircraft.[37] A hypothetical human-inhabited carrier aircraft optimized for long-range strike would have slightly less range and unrefueled endurance than an uninhabited N-UCAS.

The refueled endurance, on the other hand, would be dramatically different. An N-UCAS could operate for 30 to 40 hours continuously before returning to the carrier for maintenance. Human-inhabited single-seat fighter aircraft have a refueled endurance of approximately 10 to 14 hours, driven by human fatigue and physical needs. Very large land-based aircraft can overcome these constraints by using larger crews, enabling rest rotations. The B-2 bomber, which has two pilots, can fly more than 40 hours continuously. Aircraft carrier deck size fundamentally limits aircraft size, however, and no aircraft coming even close to the size of a B-2 bomber could land on a carrier.[38]

Long-range, persistent reach from a carrier will be possible only with uninhabited aircraft, which enable ultralong refueled endurance. This reach is not just valuable but essential for meeting anti-access challenges.

Despite the 2014 Quadrennial Defense Review's (QDR) trumpeting of innovation as a core theme, bureaucratic, institutional and cultural obstacles to new concepts and paradigm-shifting capabilities abound within the department.

the final requirements for the UCLASS program would be.[40]

Other problems beset the Navy's ability to field long-range, persistent, penetrating uninhabited aircraft. Even though aerial refueling is a critical enabler of persistent operations at range, the automated aerial refueling component of the Navy's Unmanned Combat Air System Aircraft Carrier Demonstration (UCAS-D) program has faced significant resistance, with stable funding proving elusive. Fully automated aerial refueling has been demonstrated in human-inhabited "surrogate" aircraft but not yet in uninhabited ones.[41] Even though the technology to do so already exists, an actual demonstration of autonomous aerial refueling with an uninhabited aircraft would likely have a significant psychological effect on some who currently see it as a high-risk operation, similar to the psychological impact of the UCAS-D carrier landing.[42]

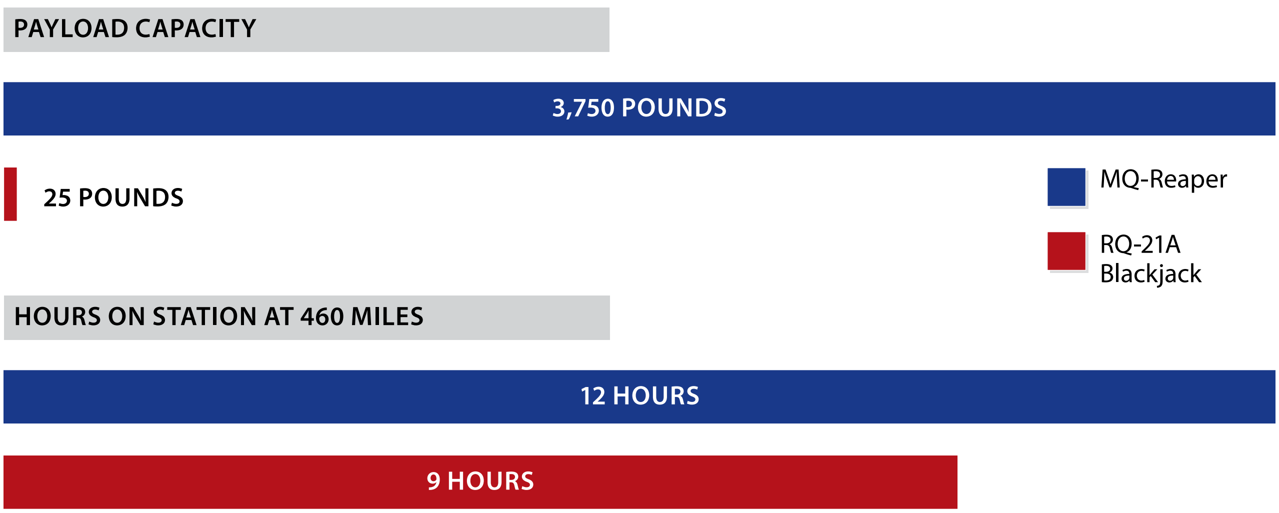
The Navy's problems in funding automated aerial refueling and the fight over UCLASS requirements point to the bureaucratic and cultural challenges innovations face. Even though these innovations are essential to the very future of the aircraft carrier as a relevant means of power projection, they have met resistance. The Navy is not unique in this respect. Similar problems plague other services and indeed DOD's ability as a whole to incorporate and leverage game-changing innovations. Despite the 2014 Quadrennial Defense Review's (QDR) trumpeting of innovation as a core theme, bureaucratic, institutional and cultural obstacles to new concepts and paradigm-shifting capabilities abound within the department.

SEA-BASED LOITERING SURVEILLANCE AND STRIKE FOR EXPEDITIONARY OPERATIONS

Predators and Reapers have been game-changers for ground forces and global counterterrorism operations, yet they are currently limited to land bases. The need for a sea-based long-endurance, medium-altitude uninhabited aircraft like the Predator and Reaper for counterterrorism missions is one of the rationales for a low-cost UCLASS. The need is valid, but the carrier is a suboptimal platform for such an aircraft. Carrier deck space is scarce and should be used for more capable aircraft that can operate in anti-access environments. Moreover, it is hard to imagine that the United States would dedicate a carrier strike group, an extremely scarce asset, solely to a counterterrorism mission. Yet practical range limitations would dictate that a carrier supporting counterterrorism missions in north or west Africa, for example, would be unable to simultaneously support operations in the Strait of Hormuz, much less the Pacific theater.[43] Although the Navy is investing in a limited number of ship-based uninhabited aircraft, they will not have the necessary range and endurance to support persistent expeditionary operations. Moreover, in the Fiscal Year 2015 budget, the Navy discontinued support of sea-based special operations requirements.[44]

Helicopter carrier amphibious assault ships (LHA/LHD), on the other hand, are an ideal platform for medium-altitude uninhabited aircraft such as the Predator or Reaper.[45] The Marine Corps

FIGURE 6: RELATIVE CAPABILITIES OF RQ-21A BLACKJACK AND MQ-9 REAPER



Source: Manufacturer specifications

is investing in a small fixed-wing uninhabited aircraft, the RQ-21 Blackjack, but its range and payload do not come close to the capabilities of a Reaper. The Blackjack has a combat radius of approximately 58 miles and a payload of only 25 pounds.[46] For comparison, an armed Reaper with an endurance of 16 hours can sustain 12 hours on station at 460 miles and can carry 3,750 pounds.[47] A Blackjack equipped with satellite communications could operate at greater range, sustaining nine hours on station at 460 miles, but the payload would still be limited. Larger payload enables more advanced sensors as well as weapons. DARPA is pursuing an uninhabited aircraft called TERN that would be capable of flying from an Independence-class Littoral Combat Ship (LCS 2) with a combat radius of approximately 700 to 1,000 miles and a payload of 600 pounds.[48] While this would be a significant force-multiplier for Independence-class ships, it would still not match the payload of a Reaper. The overhead surveillance, close-air support and time-critical strike enabled by larger, Reaper-class aircraft have proved to be tremendous game-changers for ground forces, and the DOD should investigate the feasibility of launching and recovering such an aircraft from a helicopter carrier amphibious assault ship.[49]

MARITIME DOMAIN AWARENESS FOR EARLY DETECTION OF THREATS

Long-endurance uninhabited aircraft can improve maritime situational awareness, both for tracking enemy ships as well as for early identification of possible threats to U.S. vessels. The Navy's land-based MQ-4C Triton is designed to provide broad-area maritime surveillance and complements the land-based human-inhabited P-8 Poseidon surveillance aircraft.

The Navy can improve the situational awareness of its surface ships against potential threats with ship-launched persistent uninhabited aircraft. The Navy's program for doing so is the MQ-8 uninhabited helicopter, which has two variants: a smaller MQ-8B Fire Scout and a larger MQ-8C Fire-X. In its FY2015 budget submission, however, the Navy terminated additional MQ-8 procurement and will not be upgrading its existing MQ-8Bs to the more capable MQ-8C models.[50]

HIGH-ALTITUDE LONG-ENDURANCE PSEUDOLITES FOR AIRBORNE COMMUNICATIONS AND NAVIGATION RELAY

U.S. space assets are vulnerable to a range of kinetic and nonkinetic threats. Some, such as communications and GPS jamming, are reversible and could conceivably be undertaken by adversaries in peacetime. Others, such as employing cyberweapons or co-orbital microsatellites, might be difficult to detect and could allow an adversary a nonattributable means of disabling or destroying a U.S. satellite.[51] Satellites are inherently vulnerable because their orbits are predictable. Adjusting a satellite's course requires the expenditure of scarce fuel and must be limited.

These vulnerabilities pose a tremendous problem for the United States. The U.S. military relies on satellites for a range of critical functions, including communications, positioning, navigation, timing and reconnaissance. The precision timing enabled by GPS is required for synchronized encrypted communications. Without its satellites, the U.S. military would be crippled, unable to communicate or navigate. It is moving to diversify its space-based assets through the use of "hosted payloads," military payloads on commercial and partner military satellites. Diversification raises the political and military costs to an adversary for an attack and does so at relatively low cost for the United States, but it does not change the fundamental vulnerability of space-based assets. If an adversary were willing to launch a wholesale attack against military and civilian satellites, there is little that could be done to continue operating in space.[52]

Long-endurance uninhabited vehicles offer an alternative. Airborne pseudolites consisting of long-endurance aircraft or airships could provide a redundant backup layer to space-based assets. Nonstealthy aircraft could not operate within the threat ring posed by anti-aircraft capabilities and would be subject to jamming within line-of-sight of an enemy's territory, but they could provide a valuable airborne communications and navigation network farther from enemy territory. This would be an essential backup in the event of a widespread disruption of U.S. satellites, either due to a cyberattack or kinetic attack. Stealthy long-endurance aircraft, or communications and navigation relays mounted on penetrating attack aircraft, could extend this network into enemy territory. In either case, a backup communications and navigation network that does not depend on space assets is absolutely vital. The DOD has a plan to develop such a network but, like other innovative areas, it has struggled to find funding.[53]

The Joint Aerial Layer Network (JALN) is DOD's plan for building a redundant air-breathing network. It is not a "program of record," a formal designation within DOD that denotes dedicated funding, but is rather an umbrella suite of various smaller programs. However, many key components of JALN are unfunded. In the FY2015 defense budget, the Air Force funded tactical data links to network together existing aircraft and the Navy funded communications relays on its MQ-4C Triton aircraft, but a key component of JALN, the Battlefield Airborne Communications Node (BACN), was not funded. BACN is a payload that acts as a universal translator and communications relay to help network together DOD's various non-standard communications networks. BACN, along with the creation of a new, similar program to relay navigation and timing information, is an essential component of a backup airborne layer. Mounted on ultralong-endurance air vehicles with several days of endurance, these capabilities could offer the United States an essential resilient, redundant alternative to space.[54] In addition, the existence of such an airborne layer could reduce the attractiveness of attacking U.S. satellites in the first place, since such an attack would not cripple the U.S. military. But once again, these innovations are not funded.

The Air Force should establish BACN as a program of record and begin an analysis of platform options for high-altitude long-endurance air vehicles. The Navy, meanwhile, should install the universal BACN on its MQ-4Cs, not another bespoke communications package. In addition, the Air Force should fund research and development into ultralong-endurance air vehicles. While today's high-altitude uninhabited aircraft have endurances on the order of approximately 30 hours, numerous companies have concept aircraft for endurances of several days. Airships could stay aloft for months or years at a time. With funding and a signal from DOD that this is a worthwhile area for future investment, these ultralong-endurance air vehicles might get off the ground.

LONG-ENDURANCE AIRCRAFT FOR FORWARD MISSILE DEFENSE

Long-endurance uninhabited aircraft could have particular advantages in early detection of enemy missile launches and even boost-phase intercept. Long-endurance aircraft could loiter near or, in the case of stealthy aircraft, possibly even over enemy territory. Equipped with infrared and other sensors and robust data links to remote human controllers, they could provide early detection and tracking data for enemy ballistic missiles. If equipped with advanced missiles, they could even conceivably intercept enemy missiles in the boost phase as they are exiting the atmosphere, when they are most vulnerable to attack.[55]

LOITERING UNINHABITED AIRCRAFT FOR PERSISTENT DEFENSIVE COUNTER-AIR

Defensive counter-air, or maintaining combat fighter patrols to protect U.S. ships and bases, is another mission in which increased endurance could result in cost savings and improved operations. Long-endurance uninhabited air vehicles could maintain 24/7 air coverage over U.S. ships and bases at much lower cost than human-inhabited fighter aircraft. Moreover, since such vehicles are uninhabited, commanders could take additional risk with them. They could be built at low cost and made to be attritable – expected to take some losses or attrition in combat. Such an aircraft, a long-endurance "AMRAAM truck," would need enough stealth to get within missile range of enemy aircraft without being detected but would not need higher-end all-aspect stealth required to penetrate enemy air defenses.[56] The Navy has recently raised the idea of uninhabited aircraft in an air-to-air combat role, but the feasibility of these operations has not been explored in great detail.[57]

SEA SURFACE AND UNDERSEA VEHICLES ENABLE PERSISTENT UNDERSEA SURVEILLANCE

Long-endurance sea surface and undersea vehicles have tremendous potential for persistent surveillance of the world's oceans, undersea infrastructure and enemy ships and submarines. For example, DARPA is working to develop a long-endurance uninhabited surface vessel, the Anti-submarine warfare Continuous Trail Unmanned Vessel (ACTUV), to track enemy submarines.[58] While surface vessels such as ACTUV can use long-endurance air-breathing diesel electric engines, power is a significant limiting factor for the endurance of undersea vehicles.[59]

A number of potential novel power methods could dramatically expand endurance, however. Advanced fuel cells could enable undersea vehicle operations of 30 to 60 days. More novel methods could enable operations for years at a time. Undersea gliders with thermal engines, which draw energy from temperature differentials in the ocean, exist today and can operate at sea *for up to five years* without ceasing or refueling. When near the surface, thermal gliders communicate by satellite, passing along information and receiving new instructions.[60] Wave-powered surface drones and robotic jellyfish that draw power directly from the water could operate until mechanical failure and have already been demonstrated.[61] The Navy has been investing heavily in uninhabited undersea vehicles, seeing this as a potential game-changer if power limitations can be overcome. Communications with undersea vessels is also a significant challenge, forcing a greater reliance on autonomy.

One area the Navy has been reluctant to explore is radioisotope power, because of safety and environmental concerns regarding radioactive material. Radioisotope thermoelectric power draws heat energy from decaying radioactive material, which provides a reliable source of ultralong-endurance power.[62] Radioisotope thermoelectric power is not without risks, but it has been safely used in spacecraft since the late 1960s. Protective "casks" have prevented contamination, even when radioisotope-powered spacecraft have crashed into the ocean.[63] Because of the extreme longevity and game-changing potential, the Navy should launch an independent study of the policy and safety issues associated with radioisotope thermoelectric power to determine the conditions under which it could be used safely.

EXOSKELETONS: "WEARABLE ROBOTICS" TO STRENGTHEN AND PROTECT INFANTRY TROOPS

In World War II, being in the front-line infantry was the third-deadliest job in the U.S. military, behind being in a bomber crew or on a submarine. Today, technology has enabled stealth bombers and submarines, dramatically increasing their safety, but front-line ground combat jobs are as deadly as ever. Even though they make up less than 4 percent of the joint force, infantry and special operators account for more than 80 percent of all U.S. casualties since World War II.[64]

While technology has enabled tremendous leaps forward in air, maritime and tank warfare, its ability to do so for infantry troops is limited by the fact that they must carry everything they need. Improved weapons, body armor and night vision are all advantageous but add weight.[65] Today's foot soldier carries 60 to 100 pounds of gear, a figure that has not changed since ancient times. [66] Additional weight dramatically limits endurance and combat effectiveness, and infantry troops are constantly weighing the value of any newfangled technology against the additional weight it will bring.[67] Exoskeletons, or wearable robotics, could change that.

> *Robotic exoskeletons, or "Iron Man suits"... have been demonstrated successfully in laboratory settings and are available commercially for medical applications.*

Robotic exoskeletons, or "Iron Man suits," are no longer the stuff of science fiction. They have been demonstrated successfully in laboratory settings and are available commercially for medical applications.[68] U.S. Special Operations Command has even started a developmental program to build a functional combat exoskeleton, with the aim of reducing casualties.[69]

The practical utility of exoskeletons for military applications is limited by power, however. Battery technology does not currently enable powered operations beyond a few hours, although companies are working on alternative power solutions such as fuel cells to extend suit endurance to several days.[70] As in many cases, whether a given new technology will translate into a useful capability depends on key supporting technologies, such as power.

V. THE OPERATIONAL ADVANTAGES OF ROBOTICS ON THE BATTLEFIELD: DARING

> *"Who dares, wins."*
>
> BRITISH SPECIAL AIR SERVICE

War is a deadly and hazardous endeavor. Throughout history, the willingness to take risks with bold, daring actions has often proved decisive. From Pointe du Hoc to Inchon, Entebbe and Abbottabad, those who have dared to undertake risky, seemingly impossible missions have caught their enemies off-guard, often with spectacular results.

Uninhabited systems can not only save human lives by undertaking dangerous missions in their place, they can enable new concepts of operation that would not be possible were human lives at risk. Just a few of the possibilities are explored below.

COUNTERMINE OPERATIONS

Just as ground robots have proved tremendously useful in countering improvised explosive devices on land, the Navy is investing in uninhabited surface and underwater vehicles for countering sea mines.[71] One promising avenue for further exploration is the use of robotics for countermine amphibious operations. Deployed from large-diameter uninhabited underwater vehicles, submarines or surface boats, amphibious robots could find and clear beach obstacles and mines prior to the arrival of amphibious assault troops.[72] Once ashore, robots could establish a perimeter and act as scouts and sentries for the amphibious assault itself.

EXPENDABLE SCOUTS

Because of their ability to take risk, robotic systems can be used as expendable scouts for a wide range of missions. Air and ground robots can scout ahead for ground troops, amphibious and undersea robots can provide pre-assault mapping and scouting of beaches, and small expendable uninhabited air vehicles can provide immediate battle damage assessment of strikes. If communications links are assured, uninhabited systems can be sent on one-way suicide missions into enemy strongholds to draw out enemy defenses and send back valuable information as they perish, like NASA probes plunging into the depths of Jupiter.

One example of this approach is the Army's manned-unmanned teaming model for its aviation assets, where uninhabited MQ-1C Gray Eagle and RQ-7 Shadow aircraft will perform forward reconnaissance for human-inhabited Apache attack helicopters. The Army's primary motivation is cost savings, as the Gray Eagles and Shadows will replace the Army's retiring Kiowa helicopter fleet, but this approach will also allow new concepts of operation. Commanders will be able to take more risk with the uninhabited Gray Eagles and Shadows than would have been possible with the human-occupied Kiowas, opening up novel tactics.

DECOYS, DECEPTION AND DEFENSE

The miniature air-launched decoy (MALD) is an example of what is possible with expendable uninhabited systems. Not quite an aircraft and not quite a munition, the MALD is a small loitering air vehicle that is launched from a fighter aircraft. It flies ahead of human-occupied fighters, emitting signals in the electromagnetic spectrum to deceive enemy radars into thinking it is a fighter. When enemy radars give away their position by attacking the decoy aircraft, the real fighters pounce.[73] Expendable decoys can draw out enemy defenders and redirect the enemy against decoy targets, which increases the survivability of human-occupied vehicles and encourages the enemy to waste munitions.

Amphibious robot emerges from the water onto the beach.
(Photo courtesy of QinetiQ North America)

Uninhabited vehicles can serve as valuable decoys in a variety of settings. Uninhabited ground vehicles can undertake feint maneuvers to confuse enemy forces. Ship-based uninhabited air vehicles can carry electromagnetic and infrared decoys to lure away anti-ship ballistic and cruise missiles.[74] Long-endurance uninhabited surface vessels can emit false signatures, confusing enemy sensors. And uninhabited underwater vehicles can emit false acoustic and other signatures to act as decoy submarines, drawing out enemy submarines and wasting enemy torpedoes.[75]

STAND-IN JAMMING AND ELECTRONIC ATTACK

In addition to serving as scouts and decoys, uninhabited air vehicles can perform electronic attack missions, such as radio-frequency jamming and delivering high-powered microwaves. The MALD-Jammer is a variant of the MALD that conducts stand-in jamming.[76] Electronic attack has been demonstrated with Reaper aircraft.[77] Because the disruptive effect on a target from electronic attack is a function of both power and distance, uninhabited vehicles are particularly attractive for this mission; their reduced size and greater ability to take risk means they can get close to a target, where lower power is needed.

SUPPRESSION AND DESTRUCTION OF ENEMY AIR DEFENSES

Uninhabited aircraft can be used not only to jam and suppress enemy air defenses, but also to destroy them. DOD's now-defunct Joint Unmanned Combat Air Systems (J-UCAS) program built a functional prototype of an uninhabited aircraft to perform precisely these missions. Envisioned at only $10 million to $15 million apiece, the J-UCAS would have been extremely low-cost for a penetrating stealthy aircraft, which would have allowed large numbers to be purchased for commanders to employ them in daring, innovative ways. Even more revolutionary, J-UCAS was envisioned as an "aircraft in a box" that could sit on the shelf for years before being employed in combat, potentially saving billions of dollars in operations costs. J-UCAS is now a museum piece, however, and the Air Force has no funded plans for future uninhabited combat aircraft.[78]

SMALL-BOAT INTERDICTION

The U.S. Navy today faces a significant threat from swarming enemy "small boats," fast attack craft that could overwhelm a ship's defenses and, packed with explosives, deliver a crippling suicidal blow. Uninhabited surface vessels have the potential to intercept such threats from a safe distance away, protecting U.S. ships.

The Navy has already tested such a vessel. In 2012, the Navy launched small guided missiles from an armed, uninhabited surface vessel as a demonstration of their utility to intercept swarming small boats.[79] Uninhabited surface vessels would give the Navy a tremendous advantage in countering the small-boat threat, and the Navy should move to operationalize this capability immediately.

CASUALTY EVACUATION

Casualty evacuation is a mission area ripe for uninhabited vehicles. Almost by definition, casualties are likely to occur in dangerous areas, and human-inhabited evacuation missions run the risk of additional casualties. Uninhabited vehicles could be used to extract wounded from dangerous areas and evacuate them to safety without risking additional lives.

While the value in such a capability seems obvious, cultural barriers to using uninhabited aircraft for this mission have hampered development. The U.S. Army Medical Department Center and School issued not one but three memoranda, in 2006, 2009 and 2013, prohibiting the use of uninhabited aircraft for casualty evacuation, stating "… the use of unattended robotic platforms for casualty evacuation [is] unacceptable."[80] A comprehensive three-year NATO study on casualty evacuation found no merit in such a prohibition, noting that some uninhabited vehicles might not be appropriate or safe for casualty evacuation but that others might be and there was no justification for prohibiting them entirely.[81]

The Army's stance against casualty evacuation via uninhabited vehicles is akin to early 20th-century fears about the perils of casualty evacuation by "motor car."

The Army's stance against casualty evacuation via uninhabited vehicles is akin to early 20th-century fears about the perils of casualty evacuation by "motor car."[82] Unfortunately, DOD's recently released *Unmanned Systems Integrated Roadmap, FY2013-2038* reinforces this policy, stating:

> Although currently prohibited by policy, future capabilities by unmanned systems could include casualty evacuation and care, human remains evacuation, and urban rescue.[83]

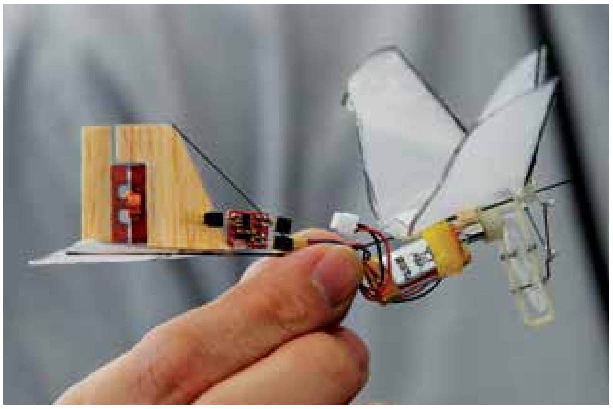
While the Army's policy is probably unenforceable, it may be contributing to the lack of viable casualty evacuation options using uninhabited vehicles.[84] Meanwhile, other nations are developing dedicated casualty evacuation uninhabited aircraft to save their wounded.[85] The Army should rescind its policy and fund development of "pods" or other modifications needed for uninhabited aircraft like the K-MAX helicopter so they could be used for casualty evacuation.[86]

CLANDESTINE RECONNAISSANCE AND SABOTAGE

Because of their ability to take more risk, robots could be sent deep behind enemy lines, not just as scouts but also for intrusive intelligence-gathering and sabotage. Stealthy uninhabited aircraft can be used for clandestine reconnaissance without risking a "Gary Powers" incident. While, in the event of a shoot-down or crash, a highly sophisticated aircraft would not be plausibly deniable, small cheap robots could be if they were made from commercial off-the-shelf components and without identifying markings.

Birdlike drones could "perch and stare" at possible targets. Long-endurance surface vessels could patrol an enemy's coastline, gathering valuable intelligence. Robotic snakes could swim up enemy rivers, across beaches onto land and even into enemy facilities. Using visual-aided navigation independent from GPS, air-mobile robots could fly down the air shafts of hardened and deeply buried facilities to map out targets.[87] Novel, transforming robots could alternatingly swim, fly and crawl as needed.[88] Persistent robotic systems could "forage" off of enemy infrastructure, tapping into host nation wireless networks and power lines to send encrypted messages and draw power.

Robotic systems could be used to tag, track and locate enemy targets. Unattended ground sensors, deployed from other clandestine air and ground robots, could watch key roads and facilities. Small, hummingbird-size air-mobile drones could embed themselves into mobile missile launchers. "Hull crawling" robots could attach themselves to enemy ships and submarines. These tiny robots could periodically send short transmissions of the enemy vehicle's location or could wait passively for a signal from other U.S. assets before responding.



The Hummingbird bionic robot at the International Workshop on Bio-Inspired Robots in Nantes, Japan.

(STEPHANE MAHE/Reuters)

Such systems could also be used to seed the battlefield before an attack. On order, they could spring into action, delivering kinetic or nonkinetic electronic warfare or cyber payloads to sabotage enemy systems. DARPA's Upward Falling Payloads program aims to exploit just such a concept undersea, seeding the ocean floor with clandestine payloads that, on order, would release from the ocean floor and "fall upward," rising to the sea surface.[89]

VI. ENABLERS AND OBSTACLES

Technological innovation does not occur in a vacuum. Transforming new technologies into useful military capabilities often requires key enablers. Uninhabited and autonomous systems have tremendous potential to enable greater range, persistence and daring, but require enablers such as communications and power. Technology also cannot be divorced from the institutions and culture that support its adoption. The best weapon in the world is of no use if militaries resist adopting it. This section explores the enablers required for uninhabited and autonomous systems to realize their full potential, as well as obstacles to achieving these advantages.

> *"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."*
>
> GENERAL MIKE HOSTAGE, U.S. AIR FORCE

Robotics Depends on Key Enabling Technologies

RESILIENT COMMUNICATIONS LINKS ARE NEEDED

The central weakness in uninhabited systems is the loss in cognition that comes from not having a person on board. Uninhabited systems must rely on some combination of onboard autonomy and communications with human controllers to perform their tasks. When the tasks are simple, such as flying a pre-programmed route, or when communications links are robust and assured, this is relatively straightforward. When communications links are disrupted or degraded or when the environment or tasks being performed are complicated, this becomes much more difficult.

Uninhabited aircraft today are enormously reliant on assured communications to human controllers, in many cases over satellite links. These communication links are extremely vulnerable to disruption. Most of the bandwidth required for contemporary uninhabited aircraft operations, however, is used in transmitting the data collected from the aircraft's sensors, not for actual control of the aircraft itself. The bandwidth needed for vehicle control of uninhabited aircraft is actually one or more orders of magnitude less than the bandwidth needed for data transfer. Command links for controlling uninhabited aircraft require on the order of approximately 0.1 megabits per second (mbps). By contrast, sensor data can range anywhere from 1 mbps for radar and electro-optical sensors, to 10 mbps for full-motion video, to nearly 100 mbps for sensors that use more advanced data such as hyperspectral imagery.[90]

If uninhabited systems are to be used in future conflicts where adversaries might jam or attack communications, then more resilient communications architectures are required. Massive amounts of assured bandwidth are not necessarily required, however. Onboard automation of data processing could significantly reduce the bandwidth burden, and increased vehicle autonomy can allow extended operations without communications. Uninhabited undersea gliders operate today for extended periods without communications links to human controllers, instead surfacing periodically to transmit data and receive additional instructions.

A resilient communications architecture for uninhabited systems would have several components:

- When available, satellite communications or nonstealthy communications could be used.
- An airborne communications layer, such as JALN, would be required as a backup in case of satellite disruption. Outside of anti-access areas, this could consist of high-altitude, long-endurance nonstealthy uninhabited aircraft or airships to act as communications relays. Inside anti-access areas, these platforms would need stealth to be survivable. Design features for stealth would reduce endurance somewhat, but uninhabited aircraft would still be preferable for this role because of the increased range and persistence enabled by their longer refueled endurance compared with human-inhabited aircraft.
- Low probability of intercept (LPI) and low probability of detection (LPD) communication is needed for operations in contested areas. Examples of LPI/LPD communication include spread-spectrum and optical communications. Spread spectrum techniques emit a low power signal across a wide swath of the electromagnetic spectrum, thus reducing the energy in any one part of the spectrum to avoid detection.[91] Optical communications are lasers that send directed, narrow beams of energy directly at their target and thus cannot be detected unless one is directly within their path. Each method has challenges. Spread spectrum techniques have relatively limited bandwidth, while optical communications can have very high bandwidth but are limited in range and subject to environmental conditions.[92] These techniques can be used both in the air and undersea, although the means of communication depends on the medium. Underwater, acoustic signals (sound waves) are a viable option. Optical communications are possible in water, but these use different wavelengths of light than in air in order to optimize transmission. In general, communication underwater is extremely challenging and much more limited in range and bandwidth than in air.[93] In any environment, a mix of multiple LPI/LPD communications techniques will likely be needed.[94]
- Mission-level autonomy is needed for uninhabited vehicles, both to reduce the communications burden and to ensure continued operation of the vehicle in the face of communications disruptions. This type of autonomy is used in many underwater vehicles today because of communications challenges, and a similar approach could be taken to air and ground vehicles. Humans would direct which tasks the vehicle should perform but would not control the actual movement of the vehicle, which would be autonomous.
- Onboard data processing is needed to reduce bandwidth burdens. Rather than send all data back to human controllers, onboard computers could sift through the data and send back key items of interest to humans. For example, an uninhabited aircraft flying down a road searching for a mobile missile launcher does not need to send back high-resolution full motion video of the entire road, but rather can use onboard automation to look for objects that look like mobile missiles, and then send back a photo and location data to humans when the sensor detects one. This could be done at much lower bandwidth than what is used for uninhabited aircraft operations today.
- Self-healing networks can be used to cover the loss of a communications node or compensate for jamming by adjusting the topology of the network. For example, a network of airborne uninhabited vehicles could adjust positions so they communicate out of the direct line of an enemy jammer, improving communications.

- Doctrine, training and procedures will need to be developed in order to adjust rapidly between peacetime operations, where large amounts of bandwidth may be available, and wartime operations, where communications may be severely degraded. Training and exercises under degraded communications conditions will be required.

Many components of this architecture are not unique to uninhabited platforms but are needed for human-inhabited platforms to fight as a network in anti-access areas. Even if human-inhabited platforms, such as long-range bombers, have the range to penetrate anti-access areas, if not networked together with resilient LPI/LPD communications, they will be forced to fight alone and with significantly degraded effectiveness. Moreover, outside of contested areas the United States could still find its communications links severely degraded in a conflict if an adversary attacked U.S. communications satellites kinetically or with cyberattacks. In that case, many of these same approaches, such as an airborne backup layer and doctrine and training to continue to operate with degraded communications, are essential.

Other novel means of communication may be useful in some situations and should also be considered:

- Mobile "messenger" uninhabited vehicles could connect a network of uninhabited systems by shuttling among them and between them and human controllers. Such a messenger vehicle would not enable continuous communications but could allow periodic short-range high-bandwidth communication syncs with each element of a network and with human controllers.
- Clandestine robots performing intrusive reconnaissance and surveillance could "forage" off of the host nation infrastructure by tapping into Wi-Fi and cellular networks and sending clandestine communications back to human controllers.
- In the undersea domain, masking acoustic signatures in animal sounds, such as whale noises, has been suggested as a means of LPI/LPD communications.[95]

AUTONOMY AND AUTOMATION VS. HUMAN COGNITION

Improved autonomy is essential to realizing the potential for uninhabited systems. Automation can help reduce the bandwidth needed for communications links and allow uninhabited vehicles to operate for extended periods without links to human controllers. Autonomous vehicle navigation in controlled settings or simple environments is possible today. A major area for development in more advanced autonomy is the ability for machines to better perceive and understand their environment. In some areas, such as for ground vehicles, DOD may be able to directly leverage civilian innovation. Other areas may require investment for specific military missions. Human-level cognition is not necessarily required, however, for uninhabited systems to be militarily useful. Uninhabited aircraft operating inside enemy airspace in a conflict environment do not need the same level of airspace perception that is required, for example, in commercial airspace where there are civilian airlines in the sky. "Sense and avoid" is a major hurdle today for uninhabited aircraft, but loitering munitions, decoys and jammers, such as cruise missiles and MALDs, do not have "sense and avoid" yet are useful in conflict environments.

More automated features will increase the capabilities of uninhabited systems, but some decisions will need to be made by humans. Human and machine cognition excel in different areas. Machines outperform humans in performing repetitive tasks, in structured environments or in situations where speed is essential. However, machine intelligence is "brittle." That is, machines can often outperform humans in narrow tasks, such as chess or driving, but if pushed outside their programmed parameters they fail, and often badly. Human intelligence, on the other hand, is very robust to changes in the environment and is capable of adapting and handling ambiguity. The most capable military systems will be those that are optimized to take advantage of the best of both machine and human cognition. Just as the best chess opponents today are teams of humans and machines that work together in "freestyle chess," so too will the optimal cognitive systems of the future be those that engage in "freestyle combat," using machines for some tasks and humans for others.[96]

Which tasks should be done by machines and which by people will be important to balance moving forward. This will be made increasingly challenging as machines continue to advance in cognitive abilities.[97] Fundamental differences between human and machine cognition will remain, however. Barring major advances in novel computing methods that aim to develop computers that work like human brains, such as neural networks or neuromorphic computing, machines will remain "brittle" when pushed outside their set of programmed tasks. Human-machine interfaces and training for human operators to understand when automation will yield superior results and when it will fail will be just as important as the autonomy itself. Cognitive human performance enhancement may help and in fact may be essential to managing the data overload and increased operations tempo of future warfare.

Use-of-force decisions are particularly significant and must remain under human control. Even though advanced sensors and algorithms will likely increase the capabilities of machine target detection and identification, use-of-force decisions also depend on context and the broader environment. What level of human control is appropriate will depend on the target, environment and type of force used. For example, decoys and jammers like MALD-J are already used in a more autonomous context today than lethal weapons. DOD policy for autonomy in weapons, DOD Directive 3000.09, lays out sensible guidelines for the use of autonomy and human control in decisions regarding the use of force and provides a flexible and responsible framework for assessing new capabilities as they emerge.[98]

The most capable military systems will be those that are optimized to take advantage of the best of both machine and human cognition.

EXTREME ENDURANCE REQUIRES ADVANCED POWER

Advanced power will be needed to take advantage of the extended endurance that is possible with uninhabited systems. Power is a limiting factor today for a number of uninhabited vehicle concepts, including ultralong-endurance aircraft, ground vehicles and undersea vehicles. Wearable robotics, or exoskeletons, are quite capable today but are held back by power limitations. Intelligent power management systems can improve efficiency by turning off sensors or other power-draining systems when they are not needed, but these methods alone will not lead to orders-of-magnitude leaps forward in endurance.

Advances in power generation and density through more capable batteries, fuel cells or renewable energy, such as solar power, could pay tremendous dividends. Uninhabited vehicles that can draw energy from the environment, such as wave-powered surface vessels or undersea thermal gliders, can operate for years at a time. Similarly, small clandestine robots that could forage off of existing energy infrastructure inside a country, such as drawing energy from power lines, could theoretically operate until mechanical failure.[99] At latitudes where sunlight is more available, solar-powered aircraft could stay aloft for years. Radioisotope thermoelectric power is a potential game-changer for ultralong-endurance undersea vehicles and should be explored to better understand how it could be safely used.

Culture and Bureaucracy Can be Obstacles to Innovation

Wars are fought by Soldiers, Sailors, Airmen and Marines, but the weapons they fight with are procured by bureaucracies. Cultural and bureaucratic factors within DOD will be major determinants of whether those weapons are the best ones for future conflicts.

Wave-powered uninhabited surface vessel.

(Photo courtesy of Liquid Robotics)

CULTURE CAN ENABLE OR HINDER INNOVATION

Culture can be a powerful driver or inhibitor of innovation. Organizations like DARPA that have a culture of accepting and encouraging risk-taking are routinely engines of positive, disruptive change. At the same time, the military services often not only ignore game-changing opportunities but sometimes even resist them. Contemporary examples such as multiaircraft control, remote operations, carrier-based uninhabited aircraft and uninhabited casualty evacuation are not aberrations. Historical examples abound, from the Navy's resistance to steam-powered ships to the Army's resistance to air power and, in some parts of the Army, trading horses for tanks.[100]

Warfighters are often skeptical of new technology, and for good reasons. Frequently, new technology doesn't work well at first – consider early versions of mobile devices – and may require several iterations of development to reach a truly usable capability. Many warfighters, quite sensibly, prefer a less-capable but more reliable tool on the battlefield over an exquisite solution that might fail at a crucial moment.[101]

This sentiment is understandable, but many of the examples of bureaucratic resistance to new technology outlined in this report go beyond healthy skepticism. Like early versions of steamships, aircraft and tanks, uninhabited and autonomous systems often threaten the core identity of key constituencies within the services. Arguments against a culturally threatening technology range from the perception that it is high-risk to the excuse that there is a lack of current doctrine and concepts for use. The sensible approach to these obstacles is a plan of deliberate experimentation and iterative technology development to address these concerns. New doctrine and tactics cannot be created in a vacuum. Warfighters often need to learn the specific capabilities and limitations of a new technology in order to understand how it might be employed, and experimentation may uncover new, serendipitous uses. Similarly, technologies perceived as high-risk can't be made more reliable without experimentation and improvement.

Unfortunately, too often the services do not respond with incremental approaches to build trust and overcome concerns, but instead new technologies that challenge existing cultural paradigms are shunted to the side and not developed. If these technologies were merely nice-to-have baubles, then assigning them lower priority would make sense, but in many cases the technologies are essential to U.S. power projection against anti-access threats. Overcoming these obstacles will require leadership at high levels within DOD to give direction and hold the services, and specific communities within them, accountable.

In other cases, it is not autonomy or uninhabited vehicles, per se, but an aspect of their use that runs into cultural obstacles. Many of the concepts suggested for uninhabited systems involve taking greater risk with them, but willingness for a commander to take that risk depends on the asset being relatively low-cost and replaceable for the mission being performed. Commanders may be unwilling to risk an expensive and hard-to-replace asset, whether there is a person on board or not. Treating military systems as low-cost and expendable is a new paradigm for DOD, which tends to view platforms as multimission, costly and in need of expensive features that make them survivable. If low-cost expendable uninhabited systems are to be built, it will take conscious effort on the part of those drafting requirements within DOD to maintain downward pressure on cost in order to retain the ability to take risk.

DOD BUREAUCRACY CAN STIFLE INNOVATION

Even when a service's culture embraces innovations, they often fall victim to the "valley of death" between research and development and adoption into a program of record. Research labs like DARPA and the Office of Naval Research (ONR) often fund game-changing innovative technologies, but transitioning promising projects into formal service programs can be challenging at best. Establishing a program of record can take years, and this can be particularly lethal to innovation from small companies that may not be able to wait two to five years while requirements are drafted and adjudicated by the department. Furthermore, government contracts can come with extensive and byzantine paperwork requirements, which can impose costly burdens. The net effect can be that companies may decide that dealing with the DOD is more headache than it is worth and not even pursue military applications.[102]

> *"The key to successful innovation … is having an effective bureaucracy."*
>
> MAX BOOT, *WAR MADE NEW*

These challenges are not unique to uninhabited systems and plague the DOD's ability to pursue innovative technologies across the board. The 2014 QDR highlights innovation as a major theme, but institutional changes will be required within the department to realize this vision. DOD's current acquisition process is optimized for programs with long development timelines, in some cases taking 20 to 30 years to bring a platform from concept to production. This system is wholly inadequate to keep pace with rapid changes in information technology and with the broader security environment. U.S. systems are, from a computer processing and networking point of view, obsolete long before they even begin production. In other cases, the security environment may change such that by the time systems are produced, the threat they were optimized against no longer exists. Fifth-gen fighter aircraft such as the F-22 and F-35 were originally envisioned to counter Soviet forces in Europe, where ranges are much shorter than in the Pacific. As a result, they are highly capable aircraft but have woefully inadequate range for current threats.

Lengthy program cycles also invite a deadly disease of "next-gen-itis." In an attempt to ensure that systems with 30-year development timelines are not obsolete by the time they reach production, DOD tries to engineer into a program future, not-yet-invented technologies, like airborne lasers or ultralight nano-armor. This fundamentally misses the nature of technology development, however, which is inherently serendipitous and unpredictable. DOD is, in many ways, a victim of its own success in that there is often a belief that any future technology can be built with simply sufficient time and resources. If the evolution of technology worked that way, our world would be populated with flying cars and devoid of smartphones, wearable computers and the Internet.[103] DOD must continue to pursue advanced technology development, but it should be separate from acquisition programs, which should be based on mature technology. Within the field of technology development, however, the cultures of risk-taking that allow organizations like DARPA and ONR to thrive need to be expanded into other areas of the department, to allow the exploration of new, innovative ideas. No one can pick the direction of future technology, but DOD can hedge against surprise by making small bets in a large number of technology areas.

DOD also needs better tools to import commercial sector innovations. This is especially critical for robotics and information technology, where much of the fundamental advances are occurring outside of traditional defense industries. Regular experimentation, such as the Army's "robotics rodeo" or various DARPA challenges, that invite industry to demonstrate capabilities against specific tasks are essential to iterative development of technology.[104] These events allow mutual sharing of information between DOD and industry on the current state of the art and on user needs, which helps industry make better products and helps DOD write requirements grounded in a realistic understanding of technological feasibility and cost.

If the U.S. military is to maintain its technological edge, it needs shorter requirements and acquisition time cycles, with the ability to move a program from concept to production in just a few years, not decades. Competitive prototyping and experimentation are vital tools to ensure DOD understands the tradeoffs in capability and cost before embarking on acquisition programs. Such an approach can help DOD stay on top of new technological advances, including leveraging commercial sector innovations, much better than attempting to predict what technologies might be available in 20 or 30 years.

VII. RECOMMENDATIONS

Most of the concepts outlined in this report are not new. In fact, many are specifically captured in various DOD "vision" or "roadmap" documents. Some are achievable with existing technology, while others require investment in technology development.

What is missing is direction from senior leaders that pursuing these capabilities and concepts is a priority and that they should be funded. In some cases, cultural prejudices against certain concepts are inhibiting development. In other cases, funding for new, innovative ideas is crowded out by an attachment to existing programs and concepts of operation.

Austerity ought to be a driver, not an inhibitor, of innovation. The Army's recent plan for manned-unmanned teaming for aviation is precisely the kind of cost-effective and operationally innovative approach that is needed. Rather than pursue a costly next-generation armed reconnaissance helicopter, the Army found a low-cost and sensible way to meet the need for an armed aerial reconnaissance capability with a mix of uninhabited aircraft and human-inhabited Apache helicopters. Moreover, the Army will employ cutting-edge automation to allow novel concepts of operation, such as an Apache helicopter pilot directly controlling an MQ-1C Gray Eagle uninhabited aircraft.[105] This approach will allow not only lower costs but also more daring operations as commanders will be able to push uninhabited aircraft forward into the battle space, taking more risk than would be possible with human-inhabited helicopters.

DOD is facing a deadly combination of evolving operational threats from both state and non-state actors as well as a sharp fiscal downturn. Now is precisely the time to invest in new technologies and experiment with innovative approaches to meeting these challenges.

The Air Force should:

- Develop, fund and implement a plan for developing multiaircraft control. This should include research to improve understanding of human task loading and experimentation and iterative development to improve human-machine interfaces.
- Conduct an analysis of alternatives for long-endurance uninhabited air vehicles to act as pseudolites for communications and navigation relay as part of a Joint Aerial Layer Network, with the eventual aim of establishing a program of record. Fund development of ultralong-endurance concept air vehicles. Establish the Battlefield Airborne Communications Node as a program of record and install it on existing and future high-altitude long-endurance platforms. Ensure that all JALN platforms have GPS-independent means of navigation so they are not dependent on space assets, and invest in a BACN-like navigation and timing relay system.[106]
- Begin prototyping and experimentation with small uninhabited aircraft made from commercial off-the-shelf robotics that could be used for clandestine or covert reconnaissance.
- Begin an analysis of design concepts for low-cost long-range attritable uninhabited aircraft for hazardous missions such as suppression and destruction of enemy air defenses with electronic warfare, reconnaissance and strike. Requirements should be balanced against cost, to ensure aircraft are cheap enough that commanders can use the aircraft for dangerous missions where some losses are anticipated.

The Navy should:

- Clarify the requirements for the UCLASS program to include broadband all-aspect stealth in order to survive in denied airspace. Where necessary, trade other requirements such as unrefueled endurance in order to optimize stealth sufficient to operate in anti-access environments.

- Fund an automated aerial refueling demonstration with an uninhabited aircraft to overcome current concerns about risk and feasibility.
- With the Air Force, fund JALN to build a network of high-altitude long-endurance air vehicles to act as communications and navigation relays. Establish BACN as a program of record and install BACN on MQ-4 Triton aircraft. Additionally, install GPS-independent navigation on MQ-4 Triton and any other future JALN platforms so they are not dependent on space assets.
- Commission an independent study on the potential performance advantages and safety concerns associated with radioisotope thermoelectric power in order to chart a course for how, if at all, it could be used safely in uninhabited undersea vehicles.
- Fund competitive prototyping and experimentation with uninhabited surface vessels to act as picket line defenses for ships against swarming small boats, with the aim of clarifying requirements for a program of record.

The Marine Corps should:

- Conduct competitive prototyping of a medium-altitude uninhabited aircraft that is capable of launch and recovery from an amphibious assault ship (LHA/LHD), with the aim of clarifying requirements for a new program of record. The aircraft should have sufficient payload and endurance to support expeditionary close air support, surveillance and reconnaissance, and communications relay for ground forces.
- Sponsor an amphibious robotics "rodeo" to better understand current industry capabilities in amphibious robotics for clearing obstacles and mines and performing beach reconnaissance, with the aim of informing requirements for a new program of record.

The Army should:

- Adopt a hybrid remote operations concept for MQ-1C Gray Eagle aircraft, so that aircraft operators stateside are able to fly MQ-1Cs remotely to support real-world operations, even when not forward deployed. Invest in sufficient satellite data links, ground control stations and other infrastructure to enable remote operations.
- Rescind the policy prohibiting casualty evacuation using uninhabited systems. Develop CASEVAC options for warfighters with uninhabited vehicles, including a dedicated CASEVAC platform, like Israel's AirMule, as well as "pods" or other modifications for existing uninhabited vehicles.
- Fund research into advanced power methods, such as fuel cells or regenerative braking, to expand the usable endurance of robotic exoskeletons.
- Install commercial off-the-shelf automation on existing vehicles, such as intelligent cruise control, to minimize accidents and improve convoy operations. As commercially available vehicle automation increases, import these automated tools into Army vehicles to improve safety and operational efficiency.
- Institute a series of experiments exploring the possibility of uninhabited robotic ground vehicles as expendable forward scouts and decoys for ground maneuver operations.

All the services should:

- Develop, fund and implement experimentation plans for new robotic systems to allow industry, including nontraditional defense industry companies, to demonstrate and test robotic vehicles against service-established tasks.
- Launch servicewide reviews of potential new concepts of operation enabled by uninhabited systems and, using these, generate a service-specific vision for uninhabited and autonomous systems along with sufficient resources for achieving that vision.

The Office of the Secretary of Defense should:

- Establish a senior innovation group, led by the deputy secretary of defense, to ensure DOD continues to invest in future capabilities and concepts of operation, even in austere budget environments and even when technologies threaten existing cultures and bureaucracies.
- Hold services accountable for developing, funding and executing plans for advancing uninhabited and autonomous systems, particularly when cultural obstacles hold back investment.
- Fund demonstrations for key innovative technologies perceived as high-risk, such as automated aerial refueling or multiaircraft control.
- Develop target goals for future operational energy needs where power is a limiting factor for game-changing technologies, along with an investment plan that outlines where DOD should invest in specific energy technologies and where DOD should rely on commercial sector investments.
- Separate advanced technology development from procurement, which should be based on mature technologies. Use bureaucratic tools like joint emergent operational needs (JEONs) to shorten requirements and acquisition cycles for new programs.
- Protect the Army's independent command-and-control structure for Army MQ-1C Gray Eagle aircraft so they are allocated directly to Army ground commanders. Ensure that remotely operated MQ-1C Gray Eagle aircraft are allocated to theater-level surveillance missions only when they are not required for direct support to ground commanders.

Innovation Must Be a Priority

Implementing many of these recommendations will cost money. Meanwhile, the Department of Defense's budget is getting smaller, not larger. Funding these innovations will require prioritizing innovative solutions over "wasting assets" that will have reduced utility in future conflicts.[107] This may require the courage to delay or even terminate cherished programs. While there are significant internal and external pressures on Defense Department leaders to not terminate existing programs, it is not impossible. Former Secretary of Defense Bob Gates showed a particular zeal for curtailing or canceling bloated, underperforming or misguided defense programs.[108]

Funding these innovations will require prioritizing innovative solutions over "wasting assets" that will have reduced utility in future conflicts

Congress is also a key player in this debate. Congress has a vital role to play in defense oversight and funding and can help shape military investments in these areas. When intransigent culture or bureaucracy stands in the way of necessary innovation, congressional leadership can and should hold DOD accountable. At the same time, Congress needs to help DOD make necessary reforms to control rising personnel costs, reduce unnecessary force structure and close excess bases in order to free up resources for these and other vital investments in the future. Presently, Congress has blocked many of these painful but necessary reforms. If Congress continues to not allow DOD to take reasonable measures to trim bloated and unnecessary spending, congressional leaders are not only contributing to government waste but effectively robbing dollars from readiness and modernization, putting U.S. forces at a disadvantage during future conflicts. Without active congressional leadership and support, the investments needed to sustain American military superiority in the future will be impossible.

Conclusion: The Coming Swarm

This report outlines the advantages gained from robotics on the battlefield and how they enable new concepts of operation with greater range, persistence and daring. This report has largely focused on the advantages of individual systems, however, not on the advantages gained from large numbers of robots operating as swarms. Low-cost uninhabited and autonomous systems produced in large numbers could once again make mass a significant factor in military operations. Networked robotics have the potential to conduct operations with greater coordination and intelligence than individual systems operating independently. And autonomy and automation can compress the decision cycle, yielding operations with greater speed. These additional features of the reconnaissance-strike swarm – greater mass, coordination and intelligence, and speed – will be covered in a subsequent report, "Robotics on the Battlefield, Part II: The Coming Swarm."

ENDNOTES

1. For example, the 3DR Iris autonomous multicopter can perform autonomous takeoff, landing and flight via GPS waypoints and retails for $749.99. See http://www.adafruit.com/products/1546?gclid=CNrO0Or18r0CFaN9OgodT20AGQ.

2. Robert O. Work and Shawn Brimley, "20YY: Preparing for War in the Robotic Age" (Center for a New American Security, January 2014), 10-19, http://www.cnas.org/20YY-Preparing-War-in-Robotic-Age; Barry Watts, "The Evolution of Precision Strike" (Center for Strategic and Budgetary Assessments, August 2013), http://www.csbaonline.org/publications/2013/08/the-evolution-of-precision-strike/; Barry Watts, "Six Decades of Guided Munitions and Battle Networks: Progress and Prospects" (Center for Strategic and Budgetary Assessments, March 2007), http://www.csbaonline.org/publications/2007/03/six-decades-of-guided-munitions-and-battle-networks-progress-and-prospects/; and Wayne P. Hughes Jr., *Fleet Tactics and Coastal Combat* (Annapolis, MD: Naval Institute Press, 2000), 285.

3. Department of Defense, *Unmanned Systems Integrated Roadmap, FY2013-2038* (December 2013), 20, http://www.defense.gov/pubs/DOD-USRM-2013.pdf.

4. U.S. Army.

5. "… the Navy needs [an unmanned combat aerial vehicle (UCAV)] for the superior 'all-aspect' stealth that only a tailless, cockpit-less design can provide." See Chris Pocock, "Navy sets stiff test for UCAV carrier ops," AINonline.com, June 9, 2009, http://www.ainonline.com/aviation-news/paris-air-show/2009-06-09/navy-sets-stiff-test-ucav-carrier-ops. While one could, in principle, retain a person inside an aircraft but without a glass cockpit, it is hard to imagine most pilots being willing to fly in a fully enclosed metal can. There is a great scene in the movie *The Right Stuff* where the Mercury astronauts insist on a window in the capsule, even though engineers point out they are merely along for the ride and the capsule will fly fully autonomously. Needless to say, that argument did not resonate with the astronauts. Mercury capsules were modified to include a window. See http://www.youtube.com/watch?v=hAyJiNobfY8.

6. For example, see Bluefin Robotics, http://www.bluefinrobotics.com/technology/autonomy-and-behaviors/.

7. For example, see Hod Lipson, "Building 'self-aware' robots," TED.com, 2007, http://www.ted.com/talks/hod_lipson_builds_self_aware_robots#.

8. Some forward-deployed personnel are required to launch and recover the aircraft and perform maintenance. The Department of Defense uses the term "remote split operations" to refer to the concept of flying uninhabited aircraft from the States. "Split" refers to the fact that some personnel are required forward for aircraft launch and recovery.

9. This is approximate. In practice, stateside personnel could not sustain indefinitely the same tempo of operations as they would while deployed. Some additional personnel would be required to allow rotations for soldiers to attend other vital Army training and education, as well as take leave. Still, the total number of soldiers required if using remote operations would be significantly less than under the Army's current model, even accounting for these other factors. If the Army were to switch to a 1:3 rotational model, where soldiers spend three months at home for every month abroad, then the inefficiencies under the current approach would be even more severe.

10. Army MQ-1C aircraft will have data links to enable satellite communications, so the additional costs of adopting hybrid remote operations would be satellite bandwidth as well as any additional ground control stations that would need to be purchased. By leveraging already existing people and aircraft, however, the cost of these additional surveillance "orbits" would be exceptionally low relative to already-purchased orbits.

11. Army objections to remote operations are twofold. The first is a cultural attitude that soldiers must "deploy to war." This explains the rationale for continuing to forward deploy MQ-1C operators, but it does not explain the resistance to a hybrid approach in which soldiers augment deployed forces with additional MQ-1Cs flown remotely while the soldiers are stateside between rotations. The second objection is more bureaucratic. Army MQ-1C Gray Eagle aircraft and Air Force Predators and Reapers operate under different command models, even though they are both medium-altitude long-endurance aircraft. Air Force aircraft are centrally managed by the theater air commander and allocated to specific missions as needed. Army aircraft are assigned to ground commanders and are under their direct control. Both models have advantages and drawbacks. The Air Force's centrally managed model allows more flexible allocation of aircraft across a theater to meet urgent needs as they arise. The Army model allows commanders to have assured, dedicated assets, which both improves their ability to plan operations since they can count on those assets and ensures that they cannot be reallocated elsewhere without notice. Needless to say, these differing models are bitterly contested between the Army and Air Force. (For example, see Lt Gen Dave Deptula, "Air Force Unmanned Aerial System (UAS) Flight Plan 2009-2047," slides 28-29, http://www.defense.gov/dodcmsshare/briefingslide/339/090723-D-6570C-001.pdf.) The Army objection to even a hybrid remote operations concept stems from a fear that if Army aircraft could be controlled from the States, then the Office of the Secretary of Defense would push for those aircraft to be centrally managed as well, rather than directly assigned to ground commanders. This need not be the case. Remote operations and centrally managed tasking are not necessarily linked. However, given the severe shortfalls in DOD's ability to meet global demand for airborne surveillance and reductions in Air Force Predator and Reaper fleets, the Army's fears are not entirely unjustified.

12. Deptula, "Air Force Unmanned Aerial System (UAS) Flight Plan 2009-2047," slide 11.

13. The Air Force term for this concept is "monitored transit operations."

14. Author correspondence.

15. See Keith Button, "The MAC attack," *Defense News,* October 1, 2009, http://www.defensenews.com/article/20091001/C4ISR02/910010314/The-MAC-attack.

16. This direction was issued as part of the Fiscal Year (FY) 2012 Defense Budget, with $46 million allocated over the future years' defense plan from FY12-FY15.

17. The Air Force's recently released RPA Vector report discusses multiaircraft control, but the Air Force has no funded plan for developing multiaircraft control technology to achieve this vision. U.S. Air Force, *United States Air Force RPA Vector: Vision and Enabling Concepts 2013-2038* (February 17, 2014), http://www.af.mil/Portals/1/documents/news/USAFRPAVectorVisionandEnablingConcepts2013-2038.pdf.

18. According to the U.S. Army, the Universal Ground Control Station, tentatively slated for fielding in summer 2015, will be capable of allowing one operator to control two aircraft at the same time.

19. Mike Hoffman, "Marines Work to Extend K-MAX in Afghanistan Through 2014," Defense Tech blog on Military.com, September 25, 2013, http://defensetech.org/2013/09/25/marines-work-to-extend-k-max-through-2014/.

20. Allen McDuffee, "Driverless Trucks Will Keep Army Safe from IEDs," *Wired* (January 31, 2014), http://www.wired.com/2014/01/driverless/.

21. Mark Odell, "Rolls-Royce looks to plot a course to the future with drone ships," *Financial Times*, December 26, 2013, http://www.ft.com/cms/s/0/b299c77c-6c00-11e3-85b1-00144feabdc0.html#axzz2xeISX83V.

22. Author correspondence.

23. Required number of hours varies by pilot experience and where the squadron is in the training cycle.

24. Actual numbers vary by the type of sensor used on an aircraft, but total number of people dedicated to data processing, exploitation and dissemination, or "PED," is between 79 and 95 people per 24/7 orbit. Source: U.S. Air Force.

25. ARGUS-IS stands for Autonomous Real-Time Ground Ubiquitous Surveillance Imaging System.

26. Of the approximately 80 people doing data processing, exploitation and dissemination per 24/7 orbit today, only about 30 are doing imagery analysis. If one assumes that the 64 additional video streams from a wide-area sensor only require image processing and no additional personnel are required in overhead, maintenance or signals intelligence, then $80 + 64*30 = 2,000$ personnel per wide-area sensor. This is probably a conservative estimate.

27. Author correspondence.

28. DARPA, author correspondence.

29. Decisions regarding the use of force are particularly sensitive. DOD Directive 3000.09, *Autonomy in Weapon Systems*, provides a framework for understanding which decisions relating to the use of force are particularly important for human control and governs current DOD policy on autonomy in the use of force. U.S. Department of Defense, *Autonomy in Weapon Systems,* DOD Directive 3000.09 (November 21, 2012), http://www.dtic.mil/whs/directives/corres/pdf/300009p.pdf.

30. The Air Force's recently released RPA Vector report includes the clearest DOD statement to date on whether uninhabited aircraft could or should be used for nuclear strike missions, but still leaves open the potential of a future uninhabited aircraft nuclear strike role. Given the size and endurance capabilities of long-range nuclear bombers, it is not clear what, if any, advantages might be gained from removing a person from a nuclear bomber. The weight of the two-person crew plus cockpit is less than 1 percent of the empty weight of the B-2 bomber, and because a two-person crew allows for crew rest, the B-2 bomber has carried out 40-hour missions. The risks, on the other hand, from removing a person are significant. Given the ongoing proliferation of uninhabited aircraft, including to nuclear-capable states, the United States could benefit strongly from a clearer statement on the appropriateness, or lack thereof, of uninhabited aircraft for nuclear missions. U.S. Air Force, *United States Air Force RPA Vector: Vision and Enabling Concepts 2013-2038*, 54.

31. Work and Brimley, "20YY: Preparing for War in the Robotic Age."

32. For a comprehensive overview of anti-access challenges, see Roger Cliff et al., "Entering the Dragon's Lair: Chinese Antiaccess Strategies and Their Implications for the United States" (The RAND Corporation, 2007), http://www.rand.org/content/dam/rand/pubs/monographs/2007/RAND_MG524.pdf. While Cliff's report focuses on Chinese anti-access capabilities, these technologies and approaches will proliferate to a wider array of actors over time, making them critical challenges for future U.S. forces independent of the likelihood of any U.S.-China conflict. DOD's Air-Sea Battle Concept provides a useful overview of the conceptual thinking behind anti-access challenges and, at an unclassified level, DOD's response. U.S. Department of Defense, *Air-Sea Battle* (May 2013), http://www.defense.gov/pubs/ASB-ConceptImplementation-Summary-May-2013.pdf.

33. Office of the Secretary of Defense, *Annual Report to Congress: Military and Security Developments Involving the People's Republic of China 2013* (2013), 5, http://www.defense.gov/pubs/2013_china_report_final.pdf.

34. Andrew S. Erickson and David D. Yang, "On the Verge of a Game-Changer," *Proceedings,* 135 no. 5 (May 2009), http://www.usni.org/magazines/proceedings/2009-05/verge-game-changer.

35. Jeremy Binnie, "Iran tests anti-ship ballistic missile," *Jane's Navy International,* July 19, 2012; and "N. Korea Developing Anti-Ship Missile," *The Chosunilbo,* October 14, 2013, http://english.chosun.com/site/data/html_dir/2013/10/14/2013101400683.html.

36. Pocock, "Navy sets stiff test for UCAV carrier ops."

37. "EA-6B Prowler specifications," GlobalSecurity.org, http://www.globalsecurity.org/military/systems/aircraft/ea-6-specs.htm.

38. For comparison, the wingspan of an E-2D Hawkeye, which is on the larger end of carrier-based aircraft, is 81 feet, while the B-2 bomber's wingspan is 172 feet.

39. A stealthy aircraft capable of penetrating advanced enemy air defenses would not only cost more than a nonstealthy aircraft, it would also have different design parameters. An aircraft optimized for surveillance missions in permissive or lightly contested airspace would have a long unrefueled

endurance, like the Predator or Reaper. Design choices made to optimize an aircraft for extended unrefueled endurance, on the order of 14 hours or more, would force compromises in stealth, however. These design choices would limit how much the aircraft could reasonably be modified to add stealth at a later date, without resorting to an entirely new aircraft design. Thus, a fundamental choice is required regarding the intended mission of the aircraft.

40. For a good overview of the history of the UCLASS requirements debate, see Sam LaGrone, "Pentagon Altered UCLASS Requirements for Counterterrorism Mission," *USNI News,* August 29, 2013, http://news.usni.org/2013/08/29/pentagon-altered-uclass-requirements-for-counterterrorism-mission; and Dave Majumdar and Sam LaGrone, "Navy Delays UCLASS Request for Proposal Amidst Requirement Evaluation," *USNI News,* January 22, 2014, http://news.usni.org/2014/01/22/navy-delays-uclass-request-proposal-amidst-requirement-evaluation.

41. See Noel McKeegan, "Autonomous aerial refueling of UAVs demonstrated," Gizmag.com, December 4, 2007, http://www.gizmag.com/uav-autonomous-aerial-refueling/8460/. The title is misleading. Test flights in 2007 demonstrated the theoretical *ability* for uninhabited aircraft to conduct autonomous aerial refueling operations, but the actual tests were performed with a human-inhabited Learjet using autonomous software.

42. The X-47B's 2013 landing on an aircraft carrier was a watershed moment for uninhabited aircraft carrier aviation, even though fully automated aircraft carrier landings are actually routinely performed with human-inhabited aircraft such as the F-18. Brandon Vinson, "X-47B Makes First Arrested Landing at Sea," U.S. Navy, July 10, 2013, http://www.navy.mil/submit/display.asp?story_id=75298.

43. The distance from the Strait of Hormuz to the desert of northern Mali is approximately 3,700 miles, beyond the range of even an unarmed "slick" Reaper.

44. Department of the Navy, *Highlights of the Department of the Navy FY2015 Budget* (March 2014), 4-11, http://www.finance.hq.navy.mil/FMB/15pres/Highlights_book.pdf.

45. LHA stands for Landing Helicopter Assault and LHD stands for Landing Helicopter Dock. Both types of ships are amphibious assault ships that function as "small aircraft carriers" for helicopters and vertical takeoff and landing aircraft. U.S. Navy, "Amphibious Assault Ships – LHA/LHD/LHA(R)," http://www.navy.mil/navydata/fact_print.asp?cid=4200&tid=400&ct=4&page=2.

46. Naval Air Systems Command, "RQ-21A Blackjack," http://www.navair.navy.mil/index.cfm?fuseaction=home.displayPlatform&key=5909B969-2077-41C2-9474-C78E9F60798C. Fifty nautical miles is listed as a "minimal operating radius," so greater distances may be possible, but are not specified by the Navy. According to the manufacturer, the aircraft has a range of approximately 630 miles if equipped with a beyond line of sight (aka satellite) communications link. There are no indications that the Navy intends to equip the RQ-21A with beyond line of sight communications, but even if it did the range and payload would not match a Reaper because of the RQ-21A's smaller size. Traveling at a cruising speed of 63 miles per hour and with an endurance of 24 hours, the RQ-21A could sustain nine hours on station at 460 miles to the Reaper's 12 hours on station. The payload difference, and therefore the capabilities the aircraft would have when on station, would still be enormous. See Boeing, "Insitu Integrator," http://www.boeing.com/farnborough2012/pdf/Integrator_Backgrounder_March2012.pdf.

47. Assumes two hours of transit time each way at 230 miles per hour cruising speed.

48. TERN stands for "tactically exploited reconnaissance node." For more information, see DARPA, "DARPA's new TERN program aims for eyes in the sky from the sea," March 1, 2013, http://www.darpa.mil/NewsEvents/Releases/2013/03/01.aspx.

49. Another potential alternative would be to explore an unmanned version of a V-22 Osprey, which is already used on amphibious assault ships. The V-22 is not optimized for endurance but can carry up to 20,000 pounds of cargo, some of which could be traded for additional fuel.

50. Department of the Navy, *Department of the Navy FY2015 President's Budget* (March 2014), slide 11, http://www.finance.hq.navy.mil/FMB/15pres/DON_PB15_Press_Brief.pdf.

51. Obviously, there are limits to how much an attack of this type could be scaled up and still remain plausibly deniable. One satellite going offline might be due to a malfunction. Several occurring simultaneously would indicate an attack. For more on co-orbital microsatellites, see Brian Weeden, "China's BX-1 microsatellite: a litmus test for space weaponization," TheSpaceReview.com, October 20, 2008, http://www.thespacereview.com/article/1235/1.

52. For an excellent overview of the challenges in space resiliency, see Todd Harrison, "The Future of MILSATCOM" (Center for Strategic and Budgetary Assessments, July 24, 2013), http://www.csbaonline.org/publications/2013/07/the-future-of-milsatcom/.

53. Documentation of these capability needs dates back to at least 2006. U.S. Air Force, *United States Air Force RPA Vector: Vision and Enabling Concepts 2013-2038*, 38 and 69-71.

54. The Air Force has BACN installed on three Global Hawk Block 20 aircraft, but these are grossly insufficient in quantity to form a functional aerial layer. Together, the three aircraft could be expected to sustain a single 24/7 "orbit" over one area, or basically function as one node in a network.

55. U.S. Air Force, *United States Air Force RPA Vector: Vision and Enabling Concepts 2013-2038*, 50; and Thomas P. Ehrhard and Robert O. Work, "Range, Persistence, Stealth, and Networking: The Case for a Carrier-Based Unmanned Combat Air System" (Center for Strategic and Budgetary Assessments, 2008), 132, http://www.csbaonline.org/publications/2008/06/range-persistence-stealth-and-networking-the-case-for-a-carr-ier-based-unmanned-combat-air-system/.

56. The AIM-120 AMRAAM, or Advanced Medium-Range Air-to-Air Missile, has a range in excess of 20 miles. U.S. Air Force, *AIM-120 AMRAAM* (April 1, 2003), http://www.af.mil/AboutUs/FactSheets/Display/tabid/224/Article/104576/aim-120-amraam.aspx.

57. Dave Majumdar, "Navy's UCLASS Could Be Air to Air Fighter," *USNI News,* February 13, 2014, http://news.usni.org/2014/02/13/navys-uclass-air-air-fighter.

58. DARPA, "Anti-submarine warfare (ASW) continuous trail unmanned vessel (ACTUV)," http://www.darpa.mil/Our_Work/TTO/Programs/Anti-Submarine_Warfare_(ASW)_Continuous_Trail_Unmanned_Vessel_(ACTUV).aspx; and David Antanitus, "Sailor-Less Ships Soon Could Be a Reality in U.S. Navy," *National Defense Magazine* (April 2014), http://www.nationaldefensemagazine.org/archive/2014/April/Pages/Sailor-LessShipsSoonCouldBeaRealityinUSNavy.aspx.

59. Spencer Ackerman, "Navy Chief: Robotic Subs Might Span Oceans. (Someday.)," *Wired* (March 19, 2012), http://www.wired.com/dangerroom/2012/03/ocean-drones/.

60. Autonomous Undersea Vehicle Applications Center, "Slocum Thermal Glider configuration," http://auvac.org/configurations/view/51.

61. Liquid Robotics, "How it works," http://www.liquidr.com/technology/waveglider/how-it-works.html and Peter Murray, "RoboJelly, the unmanned underwater vehicle that uses water for fuel," June 11, 2012, http://singularityhub.com/2012/06/11/ready-robojelly-the-unmanned-underwater-vehicle-that-uses-water-for-fuel/.

62. Spencer Ackerman, "Navy Chief Presses Nerds to Power Up Undersea Drones," *Wired* (November 8, 2010), http://www.wired.com/dangerroom/2010/11/navy-chief-presses-nerds-to-power-up-undersea-drones/.

63. After an accident in 1964 in which a launch failure led to a burn-up of the radioisotope generator on re-entry, radioisotope thermoelectric generators were redesigned with protective casks to survival orbital re-entry. U.S. radioisotope generators have since crashed into the ocean in 1968 and 1970, and environmental monitoring has indicated no radioactive leakage into the environment. Richard R. Furlong and Earl J. Wahlquist, "U.S. space missions using radioisotope power systems," *Nuclear News,* 42 (1999), 26-35, http://www3.ans.org/pubs/magazines/nn/pdfs/1999-4-2.pdf.

64. Robert H. Scales and Paul van Riper, "Sgt. Giunta's fair fight," *The Washington Post,* November 19, 2010, http://www.washingtonpost.com/wp-dyn/content/article/2010/11/18/AR2010111805015.html.

65. A recent example is the debate over the XM25 Punisher, which has been described as a game-changer for ground combat but has also been criticized for its weight. Matthew Cox, "XM25 'Punisher' Finds Home in Infantry Squads," Military.com, September 21, 2012, http://www.military.com/daily-news/2012/09/21/xm25-punisher-finds-home-in-infantry-squads.html.

66. John Keegan, *A History of Warfare* (New York: Alfred A. Knopf, 1993), 301-302.

67. This tradeoff between weight and mobility is hardly a new problem. For example, see S.L.A. Marshall, *The Soldier's Load and the Mobility of a Nation* (Quantico, VA: The Marine Corps Association, 1950).

68. For example, see Ekso Bionics, http://eksobionics.com/ekso. See also Dan Nosowitz, "Paralyzed Woman Completes London Marathon in Bionic Suit After 16 days," *Popular Science* (May 8, 2012), http://www.popsci.com/technology/article/2012-05/paralyzed-woman-completes-london-marathon-bionic-suit-after-16-days.

69. Sydney Freedberg, "SOCOM Wants YOU To Help Build High-Tech 'Iron Man' Armor," BreakingDefense.com, October 21, 2013, http://breakingdefense.com/2013/10/socom-wants-you-to-help-build-high-tech-iron-man-armor/.

70. "Human Universal Load Carrier (HULC), United States of America," army-technology.com, http://www.army-technology.com/projects/human-universal-load-carrier-hulc/.

71. Joey Cheng, "Navy gets minehunting sonar for unmanned underwater vehicles, *Defense Systems* (March 4, 2014), http://defensesystems.com/articles/2014/03/04/navy-lcs-unmanned-minehunter-raytheon.aspx.

72. For example, see QinetiQ, "C-Talon Submersible Crawling Robot," https://www.qinetiq-na.com/products/pscs/c-talon/.

73. Raytheon, "Miniature Air Launched Decoy (MALD)," http://www.raytheon.com/capabilities/products/mald/.

74. Decoys of this type already exist and are widely in use by many countries using expendable tube-launched aerial decoys. Airborne Systems, "Naval Decoy IDS300," http://www.airborne-sys.com/pages/view/naval-decoy-ids300; and "Siren Active RF Naval Decoy," *Defense Update* (2004), http://defense-update.com/products/s/siren.htm.

75. Antoine Martin, "U.S. Expands Use of Underwater Unmanned Vehicles," *National Defense Magazine* (April 2012), http://www.nationaldefensemagazine.org/archive/2012/April/Pages/USExpandsUseOfUnderwaterUnmannedVehicles.aspx.

76. Raytheon, "Miniature Air Launched Decoy (MALD)."

77. General Atomics, "GA-ASI and Northrop Grumman Showcase Additional Unmanned Electronic Attack Capabilities in Second USMC Exercise," January 22, 2014, http://www.ga-asi.com/news_events/index.php?read=1&id=432.

78. National Museum of the US Air Force, "Boeing X-45A J-UCAS," http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=4657. The Air Force's recently released RPA Vector charts out an ambitious but unfunded course for next-generation uninhabited combat aircraft. U.S. Air Force, *United States Air Force RPA Vector: Vision and Enabling Concepts 2013-2038*.

79. Tamir Eshel, "US Navy Tests Rafael Spike Missiles on Unmanned vessels," *Defense Update* (October 31, 2012), http://defense-update.com/20121031_us-navy-tests-rafael-spike-missiles-on-unmanned-vessels.html.

80. As cited in "Safe Ride Standards for Casualty Evacuation Using Unmanned Aerial Vehicles," STO Technical Report TR-HFM-184 (NATO's Science and Technology Organization, December 2012), 3-4, http://ftp.rta.nato.int/public//PubFullText/RTO/TR/RTO-TR-HFM-184///$$TR-HFM-184-ALL.pdf. The most recent memorandum from the Army Medical Department states, "The [Army Medical Department] does not support the use of unmanned systems in accomplishing direct medical care tasks or medical evacuation without human accompaniment. … Medical doctrine with regard to patient evacuation is governed by factors that preclude the use of [unmanned systems] in conducting autonomous medical evacuation/casualty evacuation (CASEVAC)." Army policy does allow the use of unmanned systems for casualty extraction: "The [unmanned system] can potentially conduct extraction and/or retrieval of combat casualties on behalf of the first responder and deliver the wounded

Soldier (within a short distance) to a safer location." Major General Philip Volpe, "Position Paper: Army Medical Department Employment of Robotic Systems in an Operational/Tactical Environment," March 27, 2013.

81. "Safe Ride Standards for Casualty Evacuation Using Unmanned Aerial Vehicles."

82. "Safe Ride Standards for Casualty Evacuation Using Unmanned Aerial Vehicles," 2-2.

83. Department of Defense, *Unmanned Systems Integrated Roadmap, FY2013-2038,* 25.

84. Setting aside the wisdom of the Army's policy, it is not clear that such a prohibition is enforceable. The Army Medical Command is responsible for medical evacuation missions – the use of dedicated medical assets for evacuating wounded. Under Army terminology, casualty evacuation is the use of nonmedical assets, such as troop-carrying helicopters or ground vehicles, to evacuate wounded. Casualty evacuation, therefore, falls outside of the purview of the Army Medical Command and is the responsibility of the ground force commander. It is hard to imagine a ground commander who had an opportunity to save one of his or her soldiers' lives being deterred by a letter from the Army Medical Department, assuming the commander was even aware of this policy. This policy may be contributing to a lack of viable uninhabited vehicle casualty evacuation options for ground commanders, however.

85. "Global Interest in Israeli Casualty Evacuation UAV," i-hls.com, January 24, 2014, http://i-hls.com/2014/01/global-interest-israeli-casualty-evacuation-uav/.

86. K-MAX is an uninhabited helicopter that has been used for cargo resupply in Afghanistan.

87. Richard W. Madison et al., "Vision-Aided Navigation for Small UAVs in GPS-Challenged Environments," *The Draper Technology Digest*, Vol. 12 (2008), Charles Stark Draper Laboratory, 4-13, http://www.draper.com/Documents/tech_digest_08.pdf.

88. For example, see Sandia National Laboratories, "Volant," http://www.sandia.gov/research/robotics/unique_mobility/volant.html.

89. DARPA, "Upward Falling Payloads," http://www.darpa.mil/Our_Work/STO/Programs/Upward_Falling_Payloads_(UFP).aspx.

90. Hyperspectral imagery uses spectroscopy to measure the chemical composition of materials at a distance and has many uses. For example, see U.S. Geological Survey, "USGS projects in Afghanistan: Hyperspectral Data," http://afghanistan.cr.usgs.gov/hyperspectral-data. Source for data rates: Brien Alkire, "A Primer on Military Applications of Unmanned Aircraft Systems (UASs)" (The RAND Corporation, October 2009).

91. John M. Shea, "Military Wireless Communications," University of Florida, http://wireless.ece.ufl.edu/eel6509/lectures/MilitaryComm6509.pdf.

92. U.S. Air Force, *United States Air Force RPA Vector: Vision and Enabling Concepts 2013-2038*, 32 and 69; Office of Naval Research, "High-Bandwidth, Free-Space Optical Communications," http://www.onr.navy.mil/en/Media-Center/Fact-Sheets/High-Bandwidth-Communications.aspx; Stew Magnuson, "Game-Changing Laser Communications Ready for Fielding, Vendors Say," *National Defense Magazine* (January 2013), http://www.nationaldefensemagazine.org/archive/2013/January/Pages/Game-ChangingLaserCommunicationsReadyForFielding,VendorsSay.aspx; Exelis, "The Tactical Line-of-Sight Optical Network," http://www.exelisinc.com/news/pressreleases/Pages/Exelis-completes-US-Naval-Research-Laboratory-evaluation-of-high-speed-laser-based-communications-technology.aspx; and Cubic, "Free-Space Optical Communications," http://www.cubic.com/Defense-Applications/Applied-Innovations/Free-Space-Optical-Communications.

93. Ambalux, "1013C1 High-Bandwidth Underwater Transceiver," http://www.ambalux.com/gdresources/media/AMB_1013_Brochure.pdf; Vikrant, Anjesh Kumar and Dr. R.S. Jha, "Comparison of Underwater Laser Communication System With Underwater Acoustic Sensor Network," *International Journal of Scientific & Engineering Research,* 3 no. 10 (October 2012), http://www.ijser.org/researchpaper/Comparison-of-Underwater-Laser-Communication-System-with-Underwater-Acoustic-Sensor-Network.pdf; T.C. Yang and Wen-Bin Yang, "Low probability of detection underwater acoustic communications using direct-sequence spread spectrum," *The Journal of the Acoustical Society of America,* 124 no. 6 (December 2008), http://w3.antd.nist.gov/pubs/JASA_LPD.pdf; and Milica Stojanovic and Lee Freitag, "Multichannel Detection for Wideband Underwater Acoustic CDMA Communications," *IEEE Journal of Oceanic Engineering,* 31 no. 3 (July 2006), http://darchive.mblwhoilibrary.org:8080/bitstream/handle/1912/1534/whoiaofnc.pdf?sequence=1.

94. The recent DARPA Spectrum Challenge, which pitted teams competing to "dominate the spectrum," hints at how difficult this problem will be. See DARPA, "DARPA Spectrum Challenge," http://dtsn.darpa.mil/spectrumchallenge/Default.aspx; and Brendan Koerner, "Inside the New Arms Race to Control Bandwidth on the Battlefield," *Wired* (February 18, 2014), http://www.wired.com/2014/02/spectrum-warfare/.

95. Ahmad ElMoslimany et al., "An Underwater Acoustic Communication Scheme Exploiting Biological Sounds," December 20, 2013, http://www.academia.edu/5489905/An_Underwater_Acoustic_Communication_Scheme_Exploiting_Biological_Sounds.

96. Humans can still add value to a combined human-computer chess team, although this may not be the case forever. Checkers is an entirely "solved" game, so computers can play checkers perfectly and humans add no value. Chess is a much more complicated game than checkers, but machine abilities at chess continue to grow. For an interesting explanation of the advantages of human and machine cognition in chess today, see Tyler Cowen, "What are humans still good for? The turning point in Freestyle chess may be approaching," MarginalRevolution blog on MarginalRevolution.com, November 5, 2013, http://marginalrevolution.com/marginalrevolution/2013/11/what-are-humans-still-good-for-the-turning-point-in-freestyle-chess-may-be-approaching.html.

97. Humans are also increasing in intelligence, although not at the same rate. Even though the underlying genetic hardware of the brain has not changed significantly, human cognition has measurably increased, on the order of 30 IQ points, over the past 100 years. Whether this increase can be extrapolated into the future is unclear.

See James Flynn, "Why our IQ levels are higher than our grandparents'" (TED conference, Long Beach, CA, 2013), http://www.ted.com/talks/james_flynn_why_our_iq_levels_are_higher_than_our_grandparents.

98. Department of Defense, *Directive 3000.09, Autonomy in Weapon Systems* (November 21, 2012), http://www.dtic.mil/whs/directives/corres/pdf/300009p.pdf. In full disclosure, this author was a major contributor to DOD Directive 3000.09.

99. Department of Defense, *Unmanned Systems Integrated Roadmap, FY2013-2038,* 25.

100. William M. McBride, *Technological Change and the United States Navy, 1865–1945* (Baltimore: Johns Hopkins University Press, 2000), 11; Johnny R. Jones, *William "Billy" Mitchell's Air Power* (Airpower Research Institute, 1997), xiii; and George Hofmann, *Through Mobility We Conquer* (Lexington, KY: University Press of Kentucky, 2006).

101. Infantry soldiers have often, for example, envied the reliability of the AK-47 over the more accurate but jam-prone M4 carbine.

102. For example, Google recently acquired Boston Dynamics, a leading robotics company and maker of the "BigDog" legged ground robot. Google has said that it will honor existing DOD contracts, but it seems unlikely that Google will pursue future defense-related work. See Mike Hoffman, "Google Buys Pentagon's Robotics Lab," Defense Tech blog on Military.com, December 16, 2013, http://defensetech.org/2013/12/16/google-buys-pentagons-robotics-lab/; and Grant Turnbull, "'Don't be evil': inside Google's acquisition of Boston Dynamics," army-technology.com, January 29, 2014, http://www.army-technology.com/features/featuredont-be-evil-inside-googles-acquisition-of-boston-dynamics-4167064/.

103. For an outstanding and readable exploration of the nature of technology and its evolution, see Kevin Kelly, *What Technology Wants* (New York: Viking, 2010).

104. The Army's "robotics rodeo" has been eclipsed by a series of experiments under the Army Expeditionary Warrior campaign. See "Army Expeditionary Warrior Experiment," http://www.benning.army.mil/mcoe/cdid/aewe/. Likewise, DARPA has funded "challenges" on unmanned and autonomous vehicles, robotics and electromagnetic spectrum management.

105. This is possible without causing task overload because of a high degree of automation in the MQ-1C Gray Eagle aircraft. Apache pilots will not be "flying" the Gray Eagle, but rather directing it where to go, employing mission-level command and control.

106. Global Hawk aircraft today are capable of navigating for a short time without GPS using inertial navigation systems but rely on GPS for regular position updates. Without external navigation aids, inertial navigation systems will "drift" over time as position accuracy decreases.

107. Andrew Krepinevich, "The Pentagon's Wasting Assets," *Foreign Affairs* (July/August 2009), http://www.foreignaffairs.com/articles/65150/andrew-f-krepinevich-jr/the-pentagons-wasting-assets?nocache=1.

108. For example, see Robert M. Gates, "Statement on Department Budget and Efficiencies" (Pentagon, Washington, January 6, 2011), http://www.defense.gov/speeches/speech.aspx?speechid=1527.

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