Chairman and CEO of AeroVironment briefs Chief of Naval Operations Admiral Jonathan Greenert on capabilities and potential applications of Global Observer, a long-range, long-duration UAV, Simi Valley, California, November 2014 (U.S. Navy/Peter D. Lawlor)

Cheap Technology Will Challenge U.S. Tactical Dominance

By T.X. Hammes

The convergence of dramatic improvements in the fields of robotics, artificial intelligence, materials, additive manufacturing, and nanoenergetics is dramatically changing the character of conflict in all domains. This convergence is creating a massive increase in capabilities available to increasingly smaller political entities—extending even to the individual. This new diffusion of power has major implications for the conduct of warfare, not the least of which are the major hazards or opportunities that it presents to medium and even small powers. The outcome will depend on the paths they choose.

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Historical Case

Fortunately, this level of technological change and convergence is not unprecedented. From 1914 to 1939, there were technological breakthroughs in metallurgy, explosives, steam turbines, internal combustion engines, radio, radar, and weapons. In 1914, at the beginning of World War I, battleships were considered the decisive weapon for fleet engagements, and the size of the battleship fleet was seen as a reasonable proxy for a navy's strength. The war's single major fleet action, the Battle of Jutland, seemed to prove these ideas correct. Accordingly, during the interwar period, battleships received the lion's share of naval investments. Navies took advantage of rapid technological gains to dramatically improve the capabilities of the battleship. Displacement almost tripled, from the 27,000 tons of the pre–World War I U.S. *New York*-class to the 71,660 tons of Japan's *Yamato*-class. The largest main batteries grew from 14-inch to 18-inch guns with double the range. Secondary batteries were improved, radar was installed, speed increased from 21 to 33 knots for U.S. fast battleships, cruising range more than doubled, and armor improved. Yet none of these advances changed the fundamental capabilities of the battleship; they simply provided incremental improvement on existing strengths. This is typical of mature technology—even massive investment leads to only incremental improvement.

In contrast, naval aviation was in its infancy in 1914. Aircraft were slow, short-legged, lightly armed, and used primarily for reconnaissance. Air combat was primitive; one early attempt involved a grappling hook. Military aviation made great strides in tactics, technology, and operational concepts during the war. Yet after the war, aviation, particularly naval aviation, remained auxiliary and was funded accordingly. The American and British governments focused most of even this limited investment on heavy bombers. Despite this neglect, by 1941 carrier aviation in the form of fighters, dive bombers, and torpedo bombers dominated Pacific naval warfare. Most of the advances in aircraft design and production that applied to naval aviation were developed for civilian uses. Aircraft production was a wide-ranging and highly competitive business that led to these rapid technological advances. Relatively modest investment in these new technologies resulted in massive increases in aircraft capability. As a result, during World War II, aircraft—the small, swift, and plentiful weapons of naval forces—could swarm and destroy the less numerous but powerful battleships. By mid-1942, the battleships were reduced to expensive antiaircraft and naval gunfire platforms.

It is important to note, however, that the transition took nearly 20 years. Thus the early investment in battleships was correct. The failure lay in not understanding when the character of naval warfare changed and naval aviation capabilities exceeded those of the battle line. Interestingly, there was also relatively little investment in submarines, the other powerful newcomer to naval battle. Submarines progressed from a fragile but deadly weapon system in World War I to one that almost defeated Britain and did destroy Japanese industry in World War II. It is essential to remember that institutional biases can keep investment focused on the dominant technology even as multiple emergent technologies clearly challenge it.

Evolving Technologies

We are in an area of rapidly evolving technologies that, when combined, may well radically alter the way we fight. This article is much too short to even begin to explore the explosion of new technologies that are daily changing our lives. But it will take a look at a few that will have short-term effects on how wars are fought. This article also considers how they may come together to change conflict.

Additive Manufacturing. In the last few years, additive manufacturing (AM), also known as 3D printing, has gone from an interesting hobby to an industry producing a wide range of products from an ever-growing list of materials. The global explosion of AM means it is virtually impossible to provide an up-to-date list of materials that can be printed, but a recent Top 10 list includes metals such as stainless steel, bronze, gold, nickel steel, aluminum, and titanium; carbon fiber and nanotubes; stem cells; ceramics; and food.[1] In addition to this wide range of materials, AM is progressing from a niche capability that produces prototypes to a manufacturing industry capable of producing products in large quantities. The United Parcel Service (UPS) has created a factory with 100 printers.[2] The current plant requires one operator per 8-hour shift and works 24/7. It accepts orders, prices them, and then prints and ships them from an adjacent UPS shipping facility the same day. UPS has plans to increase the plant to 1,000 printers in order to support major production runs.

At the same time, AM is dramatically increasing the complexity of the objects it can produce while simultaneously improving speed and precision. Recent technological developments indicate industry will be able to increase 3D printing speeds up to 100 times, with a goal of 1,000 times—all while providing higher quality than current methods.[3] In January 2015, Voxel8 revealed a new printer—with a cost of $8,999—that printed a complete, operational unmanned aerial vehicle (UAV) with electronics and engine included.[4] In February 2015, Australian researchers printed a jet engine.[5] Furthermore, the very nature of AM reduces the price of parts because there is little or no waste. With subtractive (or traditional) machining, one starts with a block of metal and cuts it to the correct form, wasting a great deal of material. With AM, material wastage is near zero; thus it may be cheaper to make a part from titanium using AM than from steel using traditional machining. Only two decades old, AM is starting to encroach on a wide range of traditional manufacturing.

Nanotechnology. Another field that is advancing rapidly in many areas is nanotechnology. Two of these technologies are of particular interest. The first is nanoenergetics or nanoexplosives. As early as 2002, nanoexplosives generated twice the power of conventional explosives.[6] Since research in this field is "Close Hold," it is difficult to say what, if any, progress has been made since that point. However, even if 2 times is as good as it gets, a 100 percent increase in destructive power for the same size weapon is a massive increase. Much smaller platforms will carry greater destructive power. The second area is that of nanomaterials. This field has not advanced as far as nanoenergetics, but the potential for nanocarbon tubes to dramatically reduce the weight needed for structural strength will have significant implications for increasing the range of UAVs. In a related field, numerous firms are applying nanomaterials to batteries and increasing their storage capacity.[7] In fact, a recent accidental discovery may triple battery power storage and increase battery life by a factor of

Marines with Combat Logistics Battalion 5 return after learning about downward thrust of Kaman K1200 ("K-MAX") unmanned helicopter during initial testing in Helmand Province, Afghanistan (U.S. Marine Corps/Lisa Tourtelot)

four.[8] At the University of California, San Diego, researchers have found a cheap way to coat products with a super-thin, nonmetal material that manipulates light and radar waves.[9] These improvements in energy storage, materials, and explosives will lead to increases in range, payload, and stealth for a wide variety of vehicles, including inexpensive UAVs.

Space-Like Capabilities. The addition of cheap, persistent space-based and air-breathing surveillance will provide the information necessary to employ these new technologies. In space, several companies, including Skybox Imaging, which was recently purchased by Google, are deploying cube satellites. Their goal is to sell half-meter resolution imagery with a revisit rate of several times a day—including interpretation of what the buyer is seeing.[10] A buyer could literally track port, airfield, road, or rail system activity in near-real time. Initially, Skybox and other cube satellite companies achieved low-cost launch by serving as ballast on larger rockets. Today, New Zealand's Rocket Lab is proposing to conduct weekly launches specifically for cube satellites to allow rapid and inexpensive launch. Although Rocket Lab has not yet opened its space port, numerous firms have signed up for its services.[11]

Other firms are working on systems that can duplicate the communications and surveillance functions provided by satellites. Google's Project Loon is attempting to provide reliable, cost-effective Internet services for much of the southern hemisphere by deploying a constellation of balloons that will drift in the stratosphere.[12] High-Altitude, Long-Endurance (HALE) UAVs are another avenue to satellite capabilities without the satellite. The U.S. Air Force has successfully tested the Global Observer UAV to conduct surveillance and intelligence operations.[13] For very long endurance, several organizations are pursuing solar-powered UAVs.[14]

Artificial Intelligence. Two areas of artificial intelligence (AI) are of particular importance in the evolution of small, smart, and cheap weapons: navigation and target identification. The Global Positioning System (GPS) has proven satisfactory for basic autonomous UAV applications such as the unmanned K-MAX logistics helicopter used by the Marine Corps in Afghanistan.[15] However, GPS will be insufficient for operations in narrow outdoor or indoor environments, dense urban areas, and areas where GPS is jammed. Academic and commercial institutions are working hard to overcome the limitations of GPS to provide truly autonomous navigation for UAVs.[16] Inertial and visual navigation are advancing rapidly and are already inexpensive enough to use in small agricultural drones.[17] Clearly, the commercial applications for navigating in agricultural areas and inspecting buildings in urban areas could be adapted for military uses. While such a system would serve to get a UAV to the target area, it would not ensure it could hit a specific target. For that, optical or multispectral recognition is essential. There have in fact been major advances in surveillance and tracking software that are more than sufficient for an autonomous UAV to attack specific classes of targets—and perhaps specific targets.[18] Today, AI can identify a distinct object such as an aircraft or fuel truck using onboard multispectral imaging.[19] In short, the AI necessary for many types of autonomous UAV operations currently exists and is operating aboard small commercial UAVs.

AI is the development that makes the convergence of material, energetics, UAVs, and additive manufacturing such a dangerous threat. It is advancing at such a rapid rate that more than 1,000 distinguished researchers signed an open letter seeking to ban autonomous weapons. They stated that "the deployment of such systems is—practically if not legally—feasible within years, not decades."[20] It is exactly that autonomy that makes the technological convergence a threat today. Because such UAVs will require no external input other than the signatures of the designated target, they will not be vulnerable to jamming. Not requiring human intervention, they will be able to operate in very large numbers. They can be programmed to wait prior to launch or even proceed to the area of the target but hide until a specified time or a specified target is identified.

UAVs. Clearly, UAV capabilities have increased dramatically in the last 5 years and, perhaps most significantly, usage has spread widely. Still, small UAVs can carry only a limited payload. This limitation can be overcome via two separate approaches. First is the use of Explosively Formed Penetrators (EFPs).[21] The second (and less technically challenging) approach is to think in terms of "bringing the detonator."

For harder targets, EFPs will allow even small UAVs to damage or destroy armored targets. Weighing as little as a few pounds, these penetrators can destroy even well-armored vehicles. In Iraq, coalition forces found EFPs in a wide variety of sizes—some powerful enough to destroy an Abrams tank. Others were small enough to fit in a hand or on a small UAV.[22] And of course nanoexplosives at least double the destructive power of the weapons.

The primary limitation on production in Iraq was the need for high-quality shaped copper plates that form the projectile when the charge is detonated. Until recently, this was a significant challenge that required a skilled machinist with high-quality tools. However, in the last few years AM has advanced to the point that it can be used to print a wide variety of materials, to include copper.[23] The National Aeronautics and Space Administration has printed a copper combustion chamber liner for a rocket motor.[24] Thus, we can expect small- and medium-sized UAVs to pack a significant punch against protected targets.

The second approach—to bring the detonator—applies to aircraft, vehicles, fuel, and ammunition dump targets. In each case, the objective is simply to detonate the large supply of explosive material provided by the target. Against these targets even a few ounces of explosives delivered directly to the target can initiate the secondary explosion that will destroy the target.

The convergence of the new technologies discussed above may allow these small, smart, and cheap weapons based on land or sea or in the air to dominate combat. Anyone with a television or access to YouTube during the last decade has become familiar with America's use of UAVs both to hunt enemies and to protect U.S. and allied forces. Although numbering in the tens of thousands worldwide, these UAVs represent only the first wave. Like many technologies, early versions were expensive and difficult to operate, so only the wealthy employed them. But over time, technology becomes cheaper, more reliable, and more widely employed. We are seeing this with the explosive growth in commercial UAVs. AM will soon make them inexpensive enough for small companies or even individuals to own a large swarm of simple, autonomous UAVs.

The U.S. Air Force is in fact actively exploring the use of swarms, but is focusing on smart swarms that communicate and interact with each other and other platforms.[25] The U.S. Navy is also pursuing swarming technology with the Low-Cost Unmanned Aerial Vehicle Swarming Technology (LOCUST),[26] as well as small craft.[27] While these programs are vague about how many UAVs they envision being able to employ, recent dramatic cost reductions in each of the needed technologies will increase the number by an order of magnitude. Researchers in England have prototyped a simple UAV body that costs roughly $9 per copy.[28] Researchers at the University of Virginia are 3D printing much more complex UAVs in a single day, then adding an Android phone to produce a $2,500 autonomous UAV.[29] Thus a small factory with only 100 3D printers using the new printing technology noted above could produce 10,000 UAVs a day. The limitation is no longer the printing but rather the assembly and shipment of products. Both processes could be automated with industrial robots. The limitation then becomes preparing the UAVs for launching when they arrive in theater. Preparing and launching thousands of UAVs at a time would require refined organization, planning, and equipment.

Moreover, cheap UAVs will not be limited to the air. In 2010, Rutgers University launched an underwater "glider" UAV that crossed the Atlantic Ocean unrefueled.[30] Such UAVs are being used globally and cost about $100,000.[31] In 2015, the U.S. Navy launched its own underwater glider that harvests energy from the ocean thermocline and plans to operate it without refueling for 5 years.[32] Based on the commercially produced Slocum Glider, a 5-foot-long autonomous underwater research vehicle, it can patrol for weeks following initial instructions, then surface periodically to report and receive new instructions. In short, small sea platforms have demonstrated the capability of achieving intercontinental range while producing very little in the way of signatures.

Ashore, mobile landmines/autonomous antivehicle weapons are also under development.[33] The natural marriage of improvised explosive devices (IEDs) to inexpensive, autonomous unmanned ground vehicles (UGVs) is virtually inevitable. However, truly autonomous UGVs—those that actually move on the ground—will remain the most difficult challenge simply because land is the most complex combat environment. Thus AI and maneuvering for UGVs require an order of magnitude more capability than for air or sea. In the interim, cheap fixed- and rotary-wing UAVs will provide an inexpensive way to strike ground targets. State and nonstate actors alike can rapidly transition to UGVs that can hunt mobile targets.[34]

Implications for the Modern Battlefield

Irregular War. Unfortunately for nation-states, autonomous UAVs will initially favor less technologically advanced actors because their targeting problem is simpler. For instance, a nonstate actor may not own armored vehicles or aircraft, so its autonomous UAVs only have to find and attack *any* armored vehicle or parked aircraft. It does not have to discriminate but instead simply fly a preprogrammed route to a suspected target area. Target areas for many locations in the world—to include most airfield flight lines—can be determined using Google Maps or Google Earth. Inexpensive optical recognition hardware and software that provide effective target discrimination are also becoming widely available. Thus, once in the target area, the UAV can scan for an easily identifiable target—say, a large cargo aircraft—and then simply crash into it. Limited standoff is also currently available. If the software of a farmer's autonomous UAV can point and shoot a camera, it can point and shoot an explosively formed penetrator.

Skybox Imaging or similar firms will soon provide near-real-time imagery to anyone with a credit card and a laptop. Terrorists and insurgents will be able to conduct initial target studies without leaving their houses. Using Tor and the current version of the Silk Road Dark Web site, they will be able to purchase the systems, too.

Clearly, today's commercial products have demonstrated the ability of an autonomous UAV to reach a target area, but what weapon could it use? Against the thin skin of an aircraft, a simple 3-ounce warhead would be sufficient, so even very small commercial quadcopters could destroy an aircraft on the ground. Against armor, the UAV designer might choose the heavier and more complex explosively formed penetrator. This would require larger quadcopters/UAVs, but would also provide standoff distance. Like most commercial products, for more money, one could purchase more capability in terms of payload, range, and discrimination. Advances in additive manufacturing, composite materials, energy densities in gel fuels, and nanoexplosives indicate that we will be able to build longer range, more powerful, and stealthier UAVs in the immediate future. Unfortunately, almost all of our antiterror physical defenses are based on blocking observation and ground access to targets. UAVs will simply fly over existing defenses. Defending against this threat is feasible but expensive—particularly when the cost of defending against these weapons is compared to the cost of employing them.

In theater, top-down attack UAVs will negate the gains the West has made in survivability against ground IEDs. Even Mine Resistant Ambush Protected and light armored vehicles will no longer protect our people or supplies. Even more troubling, fuel and water trucks are distinctive and vulnerable. A smart enemy could ignore our combat forces and literally fly over them to attack our logistics forces. Operationally, how do we protect ports of debarkation and logistics nodes? How do we defend intermediate supply depots? Overhead cover will work, but that dramatically increases the time, resources, and effort that must be dedicated to logistics support. Of course, the supply vehicles would remain vulnerable while loading and transporting those supplies.

For the first time in history, insurgent groups may well be able to purchase weapons that can project force far outside the area of conflict. Very-long-range UAVs and submersibles give an insurgent the capability to strike air and sea ports of debarkation—and perhaps even embarkation. This will create major political problems in sustaining a U.S. effort. For instance, a great deal of our support into Iraq flows through Kuwait. Suppose the Islamic State of Iraq and the Levant (ISIL) demonstrates to Kuwait that it can deploy UAVs that can hit an airliner sitting at Kuwait International Airport. ISIL states that it will not do so as long as Kuwait withdraws landing rights for those nations supporting Iraq. Similar threats could be made against sea ports. Is the West prepared to provide the level of air defense required to protect key targets across those nations providing interim bases and facilities?

Conventional War. While these systems create a genuine threat to all nation-states, they and their descendants will provide a significant boost to the defense similar to that between 1863 and 1917, when any person or animal moving above the surface of the ground could be cheaply targeted and killed. Defense became the dominant form of ground warfare. UAV swarms may make defense the dominant form of warfare in ground, sea, air, and space domains. UAV swarms will also be able to attack the physical elements of the cyber domain. The advantage will lie with those who can exploit the domains while operating from a heavily defended and fortified position.

Ground Domain. The performance of American and British armored forces in Operation *Desert Storm* and Operation *Iraqi Freedom* showed how well-trained crews with advanced gunnery systems could make short work of poorly trained crews in less-capable tanks. It seemed the combined arms team in the offensive was dominant on the battlefield. Then the 2006 Israeli-Hizballah summer war indicated that well-trained, determined irregulars armed with advanced antitank weapons, particularly guided antitank missiles, could make the defense dominant again in ground warfare. Since then, conventional ground warfare has become both deadlier and cheaper. Direct-fire gunnery systems have improved and wire-guided and fire-and-forget missiles systems are proliferating, but both are very expensive. In contrast, artillery can now provide much cheaper precision fire. While each Excalibur 155 millimeter (mm) round costs about $100,000,[35] the Army let a contract in 2015 for a new 155mm fuze that makes any 155mm artillery round a precision weapon. Each fuze costs only about $10,000.[36]

The next great leap will be inexpensive UAVs. For much less than the price of a precision fuze, commercially available autonomous UAVs will provide greater range than artillery without artillery's large logistics and training tail. These UAVs, deployed in large numbers, will provide a particularly nasty challenge for ground forces. Autonomous UAVs, which have already demonstrated the ability to use multispectral imagery to identify specific objects, will hunt on their own.

Today, even relatively light forces are dependent on vehicles and helicopters for support. For more than a decade, Western forces have struggled with hunting IEDs to ensure the ability to move about the battlespace. Now IEDs will start actively hunting our forces in the field, vehicles, helicopters, and fuel and ammunition dumps.[37] When we combine simple UAVs with additive manufacturing, ground forces face the real possibility of thousands of UAVs (or UGVs) in wave attacks (see textbox).

Autonomous UAVS will be the most difficult to defeat, but remote control UAVs will most likely appear first. Remote control UAVs, however, no longer require the operator to have line of site to his target. Today even hobbyists are using immersion goggles to control high-speed maneuvering UAVs.[38]

As mentioned earlier, autonomous UGVs will be the most difficult to develop. But they will arrive—early versions may simply be self-deploying mines/IEDs. Later versions may be advances on the Fire Ant and be capable of actively hunting ground targets.[39] This has major implications for everything from force structure to equipment purchases to operational and tactical concepts. Tactically, how does a force protect itself against swarms of thousands of small, smart, inexpensive UGVs?

Sea Domain. Swarms of autonomous UAVs obviously provide a challenge to any naval force trying to project power ashore. The UAVs will not attempt to sink a ship but only to achieve a mission kill. For instance, a UAV detonating against an aircraft on the deck of a carrier or firing a fragmentation charge against an *Aegis*-class ship's phased array radar will degrade that platform's capabilities. Ships' self-defense systems and speed will make them difficult targets. But amphibious or cargo ships have to slow or stop to operate and thus will be easier targets. Moreover, with UAVs achieving transatlantic range already, home ports must now be defended.

Undersea weapons will provide a much greater challenge to navies. There is clearly a movement by middle powers in Asia to establish effective submarine forces. However, a submarine force is expensive, complex, and difficult to operate. Unmanned underwater vehicles (UUVs) may provide a much cheaper deterrent for a middle power. Similar UUVs are being purchased globally for about $100,000 each,[40] but commercial firms are striving to reduce the cost by 90 percent.[41] If developed as a weapons system, they could dramatically change naval combat. Offensively, they can become self-deploying torpedoes or mines with transoceanic range. Defensively, they can be used to establish smart minefields in maritime chokepoints. They can be launched from a variety of surface and subsurface platforms or even remain ashore in friendly territory until needed—then be launched from a port or even a beach. Imaginatively employed, they could be a relatively inexpensive substitute for a submarine force. Clearly such UUVs could be modified to be long-range autonomous torpedoes or even to position smart mines. For the cost of one *Virginia*-class submarine,[42] a nation could purchase 17,500 such UUVs at current prices. If additive manufacturing can reduce the cost of these systems roughly

Is It Possible to Launch Thousands of UAVs?

It is one thing to have access to thousands of unmanned aerial vehicles (UAVs); it is quite another to have the logistics and manpower available to effectively employ them. One method that demonstrates it can be done is a Chinese system that mounts 18 Harpy unmanned combat air vehicles on a single 5-ton truck using a system similar to a Multiple Launch Rocket System.[1] The Chinese can transport, erect, and fire these fairly large UAVs using a single 5-ton vehicle and one- or two-person crew. Initially developed in the 1990s by Israel as an anti-radar system, the Chinese version has a range of 500 kilometers and a warhead of 32 kilograms with multiple types of seeker heads. Both China and Israel have displayed these weapons at trade shows in an effort to sell them to other nations. The system is currently operational with the Turkish, Korean, Chinese, and Indian armies. The Israeli version, the Harop or Harpy 2, has an electro-optical sensor to attack non-emitting targets and an extended range of 1,000 kilometers.[2] One can assume China has made similar improvements to its systems. Thus, by using old technology the capability to launch swarms of UAVs already exists. Furthermore, the Harpy is not a small weapon system. A similarly sized vehicle could be configured to carry over 100 Switchblade-size UAVs or perhaps a thousand mini-UAVs.[3]

Notes

[1] "UAV/UCAV: Harpy/JWS01," Chinese Military Aviation, available at <http://chinese-military-aviation.blogspot.com/p/uav.html>.

[2] "Israel Special—IAI's Harop Ups the Stakes on SEAD Missions," *Flightglobal.com*, February 11, 2008, available at available at <www.flightglobal.com/news/articles/israel-special-iai39s-harop-ups-the-stakes-on-sead-221439>.

[3] "Switchblade," Aeroenvironment, *Avinc.com*, <www.avinc.com/downloads/Switchblade_Datasheet_032712.pdf>.

the same 40 percent predicted for satellites,[43] one could buy almost 30,000 such UUVs for the current cost of a *Virginia*-class submarine. Of greater importance, the skills and organization needed to build and employ a glider are orders of magnitude less than those needed for a nuclear submarine.

Sea mines should be a particular concern to trading nations. They have the distinction of being the only weapon that has denied the U.S. Navy freedom of the seas since World War II. Mines first defeated a U.S. amphibious assault—the U.S. landing at Wonson in 1950. While lanes were eventually cleared through the primitive minefields, forces attacking up the east coast of Korea had already seized the amphibious objectives before the first amphibious forces got ashore. After Wonson, the commander of U.S. naval forces noted that the most powerful navy in the world was stopped by weapons designed 100 years ago and delivered by ships designed 2,000 years ago. Not much has changed. In February 1991, the U.S. Navy lost command of the northern Arabian Gulf to more than 1,300 simple moored sea mines that had been sown by Iraqi forces.[44]

Since 1950, mines have become progressively smarter, more discriminating, and more difficult to find. They have sensors that can use acoustic, magnetic, and other signals to attack a specific kind of ship.[45] As early as 1979, the United States fielded CAPTOR mines, encapsulated torpedoes anchored to the ocean floor. When they detect the designated target, they launch the captured torpedo to destroy it out to a range of nearly 5 miles.[46] Today, China possesses "self-navigating mines" and even rocket-propelled mines.[47] We are seeing early efforts to use UUVs to deliver mines. Since commercially available UUVs are already crossing the ocean autonomously, pairing UUVs with mines will almost certainly make it possible to mine sea ports of debarkation and perhaps even sea ports of embarkation, as well as sea lines of communication.

These gliders can also be used against commerce. Launched from shore bases, these systems will allow any nation bordering the South China Sea and its critical straits to interdict trade. While they cannot stop trade, damaging a few ships would cause dramatic increases in maritime insurance rates. To date, no nation has developed a mine-hunting force capable of destroying clearly smart, self-deploying mines with a high degree of confidence.

Air Warfare. For airpower, the key problem will be protecting aircraft on the ground. An opponent does not have to fight modern fighters or bombers in the air. Instead, he can send hundreds or even thousands of small UAVs after each aircraft at its home station. Support aircraft, such as tankers, Airborne Warning and Control System planes, and transports, are even more difficult to protect on the ground. Even if aircraft are protected by shelters, radars, fuel systems, and ammunition dumps will still be highly vulnerable. Range is currently a problem for printed UAVs. However, an Aerovel commercial UAV first crossed the Atlantic in 1998, and the company now sells an extremely long-endurance UAV.[48] The exceptionally rapid increase in commercial UAV capabilities indicates range problems will be solved soon even for markedly smaller UAVs.

While manned aircraft will become more vulnerable due to basing issues, cruise missiles will become both more capable and less expensive. According to the Naval Air Systems Command, the older Tomahawk Land Attack Missile (TLAM) cost $607,000 in fiscal year (FY) 1999 dollars.[49] Today that cost is $785,000 in FY2013 dollars.[50] As noted earlier, Lockheed Martin expects to be able to cut the cost of two new satellites by 40 percent using AM. This has some interesting implications for reducing the cost of complex systems. If we assume that we can obtain production savings similar to those projected for the satellites, TLAMs will cost about $470,000 each. These missiles carry a 1,000-pound warhead for a distance of up to 1,500 miles (Block II).[51] While somewhat expensive, missiles such as these can provide long-range heavy strike—particularly if the warhead uses nanoexplosives. Because they can be fired from a variety of land and sea launchers, they can be either dispersed or hidden in underground facilities (including commercial parking garages) until minutes before launching, thus remaining both immune to most preemptive strikes and much less expensive than ballistic missiles.

The previously mentioned U.S. Air Force experiments using cargo aircraft to launch dozens of UAVs also has a number of interesting implications for the future of airpower. The combination of cheap UAVs and much more capable cruise missiles may offer small and medium-size states antiaccess/area-denial (A2/AD), precision strike, and long-range strike capabilities in the air domain.

Space Warfare. In space, the advent of micro- and cube satellites paired with commercial launch platforms will allow a middle power to develop an effective space program for surveillance, communications, navigation, and even attack of other space assets. In addition to Skybox Imaging and Rocket Lab, Japan's Axelspace Corporation is launching a cube satellite. In this case, the Japanese company launched a $1.9 million satellite to provide navigation assistance in the Arctic. Axelspace Corporation plans to launch a constellation of cube satellites similar to those of Skybox Imaging that will provide hourly satellite imagery of Tokyo's traffic.[52] Surveillance and navigation satellites are thus already within reach of a small or medium power; that power, however, could also choose to purchase the service from a commercial company.

In addition, HALE UAVs, capable of staying aloft for months at a time, and even balloons are being tested by a number of commercial firms as alternatives for providing Internet connectivity and surveillance. The British Ministry of Defence is studying the Zephyr 8, a solar-powered UAV that can fly at altitudes of up to 70,000 feet and provide surveillance and communications at a fraction of the cost of current satellites.[53]

Cyber Warfare. While one would not normally think of UAVs as part of a cyber conflict, it is important to remember that all networks have nodes in the real world. Furthermore, some of these nodes, such as key fiber optic network lines and

C-5 Galaxy cargo hold and intercontinental flight capabilities were major assets for deploying equipment during Operation *Desert Shield* (U.S. Air Force)

switches, are quite exposed. For instance, satellite downlinks and points where fiber optic networks come ashore are both exposed and vulnerable. Smart UAVs provide a way to attack these nodes from a distance.

Offering more potential for precision effects, Boeing successfully tested its Counter-electronics High-Powered Advanced Missile Project (CHAMP) in 2012. CHAMP is a UAV-mounted electromagnetic pulse system that successfully knocked out all electronic targets during its test.[54] Such a system could target specific nodes of an enemy's network, while not damaging friendly nodes.

Strategic Implications

Since *Desert Storm*, there has been a belief that information superiority tied to precision weapons will defeat mass. It certainly allowed numerically smaller allied forces to defeat Iraq's much larger army (twice) as well as to drive al Qaeda and the Taliban out of Afghanistan using a small ground force. However, the convergence of several new technologies seems to be pointing to the revival of mass (in terms of numbers) as a key combat multiplier. The small, smart, and cheap revolution will provide all nations—and some nonstate groups—with capabilities previously reserved for great powers simply because they cost so much.

Western forces have had the luxury of unopposed access to the theaters of operations outside Europe for decades. This monopoly is changing, however; U.S. access will be contested in several domains. We have to ask the question, "Does the strategic cost/benefit calculation change as a result?" When almost any enemy can cause severe damage throughout even a major power's supply, deployment, and employment chains—perhaps even to the ports and airfields of embarkation in its homeland—does the cost of intervention expand nearly exponentially? Just as troubling, the mechanics of moving forces from home bases to the combat zone will become much more difficult. Will other nations provide transit or port rights if it means their homeland is subject to significant attacks? Militarily powerful nations will find their options limited and will be required to rethink how they project power.

Conclusion

The world has entered an era of rapid and converging technological advances in many fields similar to that following World War I. This creates the potential for disruptive shifts by creative applications, especially by combinations of these advances. The key question is whether we will invest in the equivalent of battleships or aircraft. Will our invest-

3-D printed rocket part blazes to life during hot-fire test designed to explore how well large rocket engine components withstand temperatures up to 6,000 degrees Fahrenheit and extreme pressures (NASA/MSFC/Emmett Given)

ments prove exquisite and irrelevant or change the face of conflict? Today's Department of Defense unfortunately seems to be mirroring the navies between the wars. It is applying new technologies in an effort to squeeze another 5 percent of performance out of older weapons while underinvesting in the evolving technologies that are changing the character of contemporary and future conflict.

In contrast to the ever more expensive, extremely high-technology systems, small, smart, and relatively cheap UAVs are creating entirely new challenges across the battlefield. While current U.S. high-technology programs produce fewer and fewer custom-built weapons systems, the convergence of technological advances is resulting in a proliferation of tens of thousands of cheap smart systems. Western nations are struggling to find answers to this challenge—and none of them look like the few and customized programs currently consuming the bulk of major procurement programs.[55]

For small and medium nations, the idea of "small, smart, and many" represents a great opportunity for their investment programs. They can generate many of the capabilities of the most expensive current systems at a fraction of the cost. They may also be shifting the balance to the tactical defensive, which would allow a smaller power to employ effective, affordable A2/AD against a much larger power. They may simply raise the cost of conflict too high for any possible gain.

The critical military functions will remain, but how they will be accomplished will change. Rather than investing everything in a few, exquisite, and very expensive systems, it makes more sense to explore augmenting them and, in time, replacing them with systems that are small, smart, and inexpensive. **JFQ**

Notes

[1] Nancy S. Giges, "Top 10 Materials for 3D Printing," *ASME.org*, available at <www.asme.org/engineering-topics/articles/manufacturing-processing/top-10-materials-3d-printing>.

[2] Eddie Krassenstein, "CloudDDM—Factory with 100 (Eventually 1,000) 3D Printers & Just 3 Employees Opens at UPS's Worldwide Hub," *3D Printer and 3D Printing News*, May 4, 2015, available at <http://3dprint.com/62642/cloudddm-ups/>.

[3] Joseph DeSimone, "What If 3D Printing Was 100x Faster?" *TED Talks*, available at <www.ted.com/talks/joe_desimone_what_if_3d_printing_was_25x_faster?language=en>.

[4] Dario Borghino, "Voxel8 Paves the Way for 3D-printed Electronics," *Gizmag.com*, January 14, 2015, available at <www.gizmag.com/voxel8-3d-electronics-printer/35489>.

[5] Rose Troup Buchanan, "3D Printer Creates Jet Engine in World First," *The Independent* (London), February 26, 2015, available at <www.independent.co.uk/life-style/gadgets-and-tech/3d-printer-creates-jet-engine-in-world-first-10072740.html>.

[6] Andrzej W. Miziolek, "Nanonenergetics: An Emerging Technology Area of National Importance," *AMPTIAC Quarterly* 6, no. 1 (Spring 2002), 45, available at <http://ammtiac.alionscience.com/pdf/AMPQ6_1ART06.pdf>.

[7] Wendy Koch, "Tiny Batteries Could Revolutionize Green Energy," *National Geographic*, November 16, 2014, available at <http://news.nationalgeographic.com/news/energy/2014/11/141117-nanotechnology-for-better-batteries/>.

[8] "Tiny Balls of Fire," *The Economist*, August 15, 2015, available at <www.economist.com/news/science-and-technology/21660963-nanotechnological-accident-may-lengthen-battery-lives-tiny-balls-fire>.

[9] Li Yi Hsu, Thomas Lepetit, and Boubacar Kante, "Extremely Thin Dielectric Metasurface for Carpet Cloaking," *Progress in Electromagnetic Research*, vol. 152 (2015), 33–40, available at <www.jpier.org/PIER/pier152/03.15032005.pdf>.

[10] Tekla S. Perry, "Start-up Profile: Skybox Imaging," *IEEE Spectrum*, May 1, 2013, available at <http://spectrum.ieee.org/at-work/innovation/startup-profile-skybox-imaging>.

[11] "Book a Spot Online to Put Your Satellite into Space," *Popular Mechanics*, August 10, 2015, available at <www.popularmechanics.com/space/rockets/news/a16810/heres-the-worlds-first-online-rocket-launch-scheduler>.

[12] Tom Simonite, "Project Loon," *MIT Technology Review*, February 18, 2015, available at <www.technologyreview.com/featuredstory/534986/project-loon>.

[13] "Global Observer High Altitude Long Endurance UAV, United States of America," *Airforce-Technology.com*, n.d., available at <www.airforce-technology.com/projects/globalobserverunmann>.

[14] Jonathan Vanian, "Behind the Scenes with Facebook's New Solar-Powered Internet Drone and Laser Technology," *Fortune*, July, 30, 2015, available at <http://fortune.com/2015/07/30/facebooks-solar-power-drone-internet-earth>.

[15] James K. Sanborn, "Beacon Improves UAV's Cargo-Delivery Accuracy," *Marine Corps Times*, July 8, 2012, available at <http://archive.marinecorpstimes.com/article/20120708/NEWS/207080314/Beacon-improves-UAV-s-cargo-delivery-accuracy>.

[16] "Vision-based Control and Navigation of Small, Lightweight UAVs," Workshop Proceedings from the International Conference on Intelligent Robots and Systems 2015, Congress Center, Hamburg, Germany, October 2, 2015,

available at <www.seas.upenn.edu/~loiannog/workshopIROS2015uav>. Also, “Drones at CES 2015 Showcase UAV Technology’s Bright Future,” *Dronelife.com*, January 14, 2015, available at <http://dronelife.com/2015/01/14/drones-ces-2015-showcase-uav-technologys-bright-future>.

[17] “Crop Falcon—UAV for Autonomous Crop Monitoring and Operations,” *YouTube.com*, February 16, 2015, available at <www.youtube.com/watch?v=m1wyWNhvV8Y>.

[18] “Surveillance and Tracking of People,” *YouTube.com*, available at <www.youtube.com/watch?v=tgULkozh32U>.

[19] “Agricultural UAV Drones Photos—Multi-Spectral Camera,” Homeland Surveillance & Electronics, LLC, available at <www.agricultureuavs.com/photos_multispectral_camera.htm>.

[20] “Autonomous Weapons: An Open Letter from AI & Robotics Researchers,” Future of Life Institute, *FutureofLife.org*, July 28, 2015, available at <http://futureoflife.org/AI/open_letter_autonomous_weapons>.

[21] “Future Weapons: Explosively Formed Penetrator (EFP),” *YouTube.com*, June 24, 2011, available at <www.youtube.com/watch?v=Pbf7WEVzKcQ>.

[22] Bill Roggio, “Troops Find IED Factory in Sadr City,” *The Long War Journal*, October 30, 2008, available at <www.longwarjournal.org/archives/2008/10/iraqi_troops_find_ef.php>.

[23] Eddie Krassenstein, “Plus-MFg’s +1000k Multi Material Metal 3D Printer Shows Its Power,” *3DPrint.com*, August 6, 2015, available at <http://3dprint.com/87236/plus-mfg-3d-metal-printer>.

[24] Jamie Condliffe, “This Is NASA’s First 3D-Printed Full-Scale Copper Rocket Engine Part,” *Gizmodo.com*, April 22, 2015, <http://gizmodo.com/this-is-nasas-first-3d-printed-full-scale-copper-rocket-1699394241>.

[25] Kris Osborn, “Air Force Developing Swarms of Mini-Drones,” *Military.com*, May 27, 2015, available at <http://defensetech.org/2015/05/27/air-force-developing-swarms-of-mini-drones/>.

[26] David Smalley, “LOCUST: Autonomous Swarming UAVs Fly into the Future,” Office of Naval Research, April 14, 2015, available at <www.onr.navy.mil/Media-Center/Press-Releases/2015/LOCUST-low-cost-UAV-swarm-ONR.aspx>.

[27] David Smalley, “The Future Is Now: Navy’s Autonomous Swarmboats Can Overwhelm Adversaries,” Office of Naval Research, available at <www.onr.navy.mil/Media-Center/Press-Releases/2014/autonomous-swarm-boat-unmanned-caracas.aspx>.

[28] Victoria Woollostan, “Cheap Drones Are Coming! Researchers Successfully Build and Fly a Low-Cost 3D Printed DISPOSABLE Aircraft,” *Daily Mail* (London), March 28, 2014, available at <www.dailymail.co.uk/sciencetech/article-2591533/Cheap-3D-printed-drones-coming-Researchers-successfully-build-fly-low-cost-DISPOSABLE-aircraft.html>.

[29] Jordan Golson, “A Military-Grade Drone That Can Be Printed Anywhere,” *Wired.com*, September 16, 2014, available at <www.wired.com/2014/09/military-grade-drone-can-printed-anywhere>.

[30] Ari Danial Shapiro, “Remotely Piloted Underwater Glider Crosses the Atlantic,” *IEEE Spectrum*, February 26, 2010, available at <http://spectrum.ieee.org/robotics/industrial-robots/remotely-piloted-underwater-glider-crosses-the-atlantic>.

[31] Alix Willimex, “Autonomous Submarine Drones: Cheap, Endless Patrolling,” Center for International Maritime Security, *CIMSEC.org*, June 5, 2014, available at <http://cimsec.org/autonomous-subarine-drones-cheap-endless-patrolling/>.

[32] Mark Thompson, “The Navy’s Amazing Ocean-Powered Underwater Drone,” *Time*, December 22, 2013, available at <http://swampland.time.com/2013/12/22/navy-underwater-drone/>.

[33] “Fire Ant EFP Tank Killer,” *YouTube.com*, January 5, 2013, available at <www.youtube.com/watch?v=JNboWkzKGkg>.

[34] “XP2 Quadcopter Off Road Racing Demo Reel,” July 3, 2013, *YouTube.com*, available at <www.youtube.com/watch?feature=player_embedded&v=QRrSriR5b6s>.

[35] *Defense Acquisitions: Assessments of Major Weapon Programs*, GAO-15-342SP (Washington, DC: Government Accountability Office, March 2015), 79, available at <www.gao.gov/assets/670/668986.pdf#page=87>.

[36] Joe Gould, “U.S. Army ‘Dumb’ 155mm Rounds Get Smart,” *Defense News*, March 13, 2015, available at <www.defensenews.com/story/defense/land/weapons/2015/03/13/orbital-atk-wins-us-army-deal-for-pgk/70222932/>.

[37] “XP2 Quadcopter Off Road Racing Demo Reel—Aerial Video and Photography,” *YouTube.com*, July 3, 2013, available at <www.youtube.com/watch?feature=player_embedded&v=QRrSriR5b6s>.

[38] “FPV Racing Drone Racing Star Wars Style Pod Racing Are Back!” *YouTube.com*, September 30, 2014, available at <www.youtube.com/watch?v=ZwL0t5kPf6E>. YouTube has dozens of videos of unmanned vehicle races.

[39] “Fire Ant EFP Tank Killer.”

[40] “Autonomous Submarine Drones.”

[41] Will Connor, “Underwater Drones Are Multiplying Fast,” *Wall Street Journal*, June 24, 2013, available at <www.wsj.com/articles/SB10001424127887324183204578565460623922952>.

[42] Robert Farley, “U.S. Navy Orders 10 *Virginia*-class Submarines at a Record Cost of $17.6 Billion,” *The Diplomat*, May 3, 2014, available at <http://thediplomat.com/2014/05/us-navy-orders-10-virginia-class-submarines-at-a-record-cost-of-17-6-billion>.

[43] Andrea Shalal, “Lockheed Eyes Avatars, 3D Printing to Lower Satellite Costs,” Reuters, available at <www.reuters.com/article/2014/05/19/us-lockheed-satellites-military-idUSBREA4I00J20140519>.

[44] Scott C. Truver, “Taking Mines Seriously: Mine Warfare in China’s Near Seas,” *Naval War College Review* 65, no. 2 (Spring 2012), 30, available at <www.usnwc.edu/getattachment/19669a3b-6795-406c-8924-106d7a5adb93/Taking-Mines-Seriously—Mine-Warfare-in-China-s-Ne>.

[45] Andrew S. Erickson, Lyle J. Goldstein, and William S. Murray, *Chinese Mine Warfare: A PLA Navy’s ‘Assassin’s Mace’ Capability*, Naval War College China Maritime Studies Number 3 (Newport, RI: Naval War College Press, June 2009), 14, available at <www.usnwc.edu/Research—-Gaming/China-Maritime-Studies-Institute/Publications/documents/CMS3_Mine-Warfare.aspx>.

[46] “MK 60 Encapsulated Torpedo (CAPTOR),” available at <www.fas.org/man/dod-101/sys/dumb/mk60.htm>.

[47] Truver, 41.

[48] “U.S. Government Makes Aerovel’s Flexrotor ITAR-Free,” *Aerovelco.com*, November 24, 2014, available at <http://aerovelco.com/us-government-makes-aerovels-flexrotor-itar-free>.

[49] Naval Air Systems Command: Aircraft and Weapons, “Tomahawk,” *NavAir.Navy.mil*, available at <www.navair.navy.mil/index.cfm?fuseaction=home.display&key=F4E98B0F-33F5-413B-9FAE-8B8F7C5F0766>.

[50] Department of the Navy Fiscal Year 2013 Budget Estimates: Justification of Estimates, February 2012, Operation and Maintenance, Navy, 3.4, available at <www.secnav.navy.mil/fmc/fmb/Documents/13pres/OMN_Vol1_Book.pdf>.

[51] Naval Air Systems Command.

[52] Takashi Amano, “Japan’s Micro-Satellites Expand Space Race to Arctic Ice,” *Bloomberg.com*, January 16, 2014, available at <www.bloomberg.com/news/articles/2014-01-17/japan-s-micro-satellites-expand-space-race-to-arctic-ice-tech>.

[53] Mark Nicol, “MoD Tests Defences Against High-Street Drones as MI5 Braces Itself for Jihadi Chemical Attack on UK,” *Daily Mail*, September 12, 2015, available at <www.dailymail.co.uk/news/article-3232350/MoD-tests-defences-against-high-street-drones-MI5-braces-jihadi-chemical-attack-UK.html>.

[54] Nic Halverson, “Drone Missile Kills Electronics, Not People,” *Discovery.com*, October 26, 2015, available at <http://news.discovery.com/tech/champ-drone-emp-121026.htm>.

[55] Richard Whittle, “Uncle Sam Wants Your Ideas for Stopping Drones: Black Dart Tests,” *BreakingDefense.com*, June 26, 2015, available at <http://breakingdefense.com/2015/06/uncle-sam-wants-your-ideas-for-stopping-drones-black-dart-tests/>.