Small Power: The Role of Micro and Small UAVs in the Future

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CHAPTER 6
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James M. Abatti

I. Introduction

Every military faces decisions that ultimately impact its success in future operations. In 1851, Austrian military leaders made a decision to reject a revolutionary new breech-loading rifle (the Dreyse needle gun) that could be fired three times faster than its muzzle-loaders.[1] Their decision was based purely on budgetary issues rather than military necessity. "The Austrian manufacturing plant for the old rifles had just finished retooling for more efficient production. Adopting a new rifle would have been a financial calamity."[2] Facing an equally sized Prussian army in July 1866, the Austrian army suffered a crushing defeat on the battlefield.[3] "It is generally accepted that this victory was largely due to a novel breech-loading rifle…with which the Prussian infantry was equipped."[4] Austria's failure to acquire the Dreyse needle gun resulted in its defeat on the battlefield and the ultimate decline of the Austrian empire.

Although this event occurred in the 19th century, the lessons learned apply today. Faced with declining budgets and the rapid advancement of new technologies, Air Force leaders face the same dilemma as their Austrian predecessors. In the near future, procuring the correct unmanned aerial vehicle (UAV)[5] force structure will be a major challenge for the U.S. Air Force (USAF). Given that today's force structure decisions sculpt tomorrow's battlefield success or failure, this paper will identify the potential roles of micro[6] and small[7] UAVs in future conflicts. Based on research, this paper purports that these small low cost UAVs will be a significant force multiplier in the future. Budget and vehicle cost constraints will significantly impact the acquisition of large high-tech UAVs, forcing the USAF to operate with fewer high-tech UAVs. Moreover, the exponential growth in technology coupled with the proliferation of double-digit surface to air missiles (SAMs) will increase the threat environment in which these low-density-high-demand (LDHD) UAVs operate. Using LDHD UAVs such as the Predator[8] and Global Hawk[9] in a high-threat environment will significantly limit a combatant commander's flexibility and capability unless other UAV options are explored.

Advances in commercial and military technologies are rapidly increasing the capabilities of low cost micro and small UAVs, enabling them to carry out missions comparable to the larger UAVs at considerably less cost and risk. In addition, new concepts of operation, such as cooperative behavior protocols or "swarming,"[10] will open the door to numerous missions once thought impossible for small low-cost, low-tech UAVs. In the future micro and small UAVs will be able to conduct missions across the full spectrum of conflict, from intelligence, surveillance, and reconnaissance (ISR), suppression of enemy air defenses (SEAD), and electronic warfare (EW) to attack/strike operations. Given their inherent low cost, flexibility, and expendability, micro and small UAVs will play a major role in the success of tomorrow's Air Force.

To determine the utility of these smaller UAVs, this paper will analyze three main areas: the drivers, the enablers, and the missions. The drivers are the forces that sculpt the future requirement for smaller UAVs. The enablers, on the other hand, are the technologies and concepts of operation that give these smaller UAVs the capability to fulfill the future needs of the USAF. Finally, given the need and capability, the last section of this paper will discuss the missions that micro and small UAVs will fulfill in future conflicts.

II. The Drivers

The force structure of tomorrow's UAV fleet will be driven by two primary variables: the procurement process (budget, timelines, and costs) and the threat environment. Declining military budgets and increasing vehicle procurement costs will significantly influence the shape and capabilities of tomorrow's UAV force. In addition, the rapid growth of dual-use technologies and the worldwide proliferation of advanced integrated air defense (IAD) systems will significantly impact the threat environment in which these systems must operate. Operating an LDHD UAV force structure in an increasingly high-threat environment poses a potential capability gap for combatant commanders. However, micro and small UAVs can mitigate this vulnerability by providing low cost flexible and expendable UAV assets to future commanders.

Procurement

Since the end of the Cold War, the U.S. military has seen a marked decline in its ability to purchase new and revolutionary aerial vehicles. Declining budgets coupled with high vehicle costs are causing reductions in the acquisition of large quantities of high-tech vehicles. In addition to lower numbers of new aerial vehicles, senior leadership officials are beginning to predict significant changes to the USAF's force structure over the next 20 years. As Lieutenant General Duncan McNabb, Deputy Chief of Staff for plans and procurement, stated, "Our nation is heading into a period of tremendous fiscal pressures. Between 2010 and 2030, we're going to see close to 30 million baby boomers retiring and coming onto the books for Medicare and Social Security, but only 10 million new wage earners joining the work force."[11] Both General McNabb and General Hornburg predict a significantly smaller force in the future.[12]

Several U.S. budgetary documents support the senior leadership's perspective of a smaller USAF force structure in the near future. The Fiscal Year (FY) 2005 Air Force President's budget overview outlines a decrease in the overall USAF budget from $125.8 billion in FY03 to $120.5 billion in FY05.[13] Although part of this decrease is due to a reduction in contingency funding, recent announcements by the Secretary of Defense indicate deeper cuts in military budgets. In December 2004 he directed military services to trim an additional $30 billion dollars from their budget over the next six years.[14] Additionally, the current U.S. budget projects national defense spending will return from its 10-year high in FY04 of 19.8 % of the national outlays to 17% in FY09.[15] The USAF and other services are poised to face significant budgetary pressures as they continue to transform their forces under declining budgets. These budget cuts will significantly impact the USAF's ability to acquire and maintain large quantities of its fifth-generation fighters, new tankers, and high-value UAVs. This places the USAF in a precarious situation of owning low numbers of high-tech, high demand aerial vehicles.

In addition to lower budgets, increased cost overruns and extended procurement timelines are plaguing major manned and unmanned acquisition programs, resulting in reduced acquisition numbers. The F-22 Raptor[16] acquisition program highlights some of the recent issues associated with high-value programs. The F-22 program began in 1981 as part of the Advanced Tactical Fighter program. At that time, the Air Force intended to purchase 648 aircraft at an estimated total program cost of $86.6 billion.[17] Twenty-four years later the program is still not fully operational and is fraught with cost overruns. Today, due to budget constraints and cost overruns, future F-22 production numbers could go as low as 180 aircraft.[18]

UAV procurement has followed in the footsteps of manned aerial vehicles. By 2002 the Pentagon had invested over $6 billion in UAVs, but it had fewer than 100 flying.[19] High-tech UAV programs are very complex and involve the use of immature technologies, which often results in program cost overruns and delays. For example, the Global Hawk program conceptually began in January 1990 as part of the "Long-Endurance Reconnaissance, Surveillance, and Target Acquisition (RSTA) Capability mission need statement (MNS)."[20] The original unit flyaway cost of $10 million was unattainable and ultimately abandoned by USAF.[21]

The Government Accounting Office (GAO) reports, "DOD's desire to add additional Global Hawk capabilities tripled development costs. The program acquisition unit cost increased 44 percent since program start, yet fewer vehicles are to be produced than originally planned [from 63 vehicles to 51]."[22] With total program cost estimated at $6.3 billion, Global Hawk is DOD's most expensive UAV.[23] A single Global Hawk costs $57.9 million, making it five times as expensive as originally planned and twice as costly as an F-16.[24] The high cost, coupled with greater budgetary pressures, is forcing USAF to readjust its procurement numbers. According to a Pentagon source, the USAF is expected to cut funding for three new Global Hawks to pay for the system's rising military construction and operations and maintenance costs.[25] The result is fewer large high-tech UAVs to cover ever increasing combatant commander demands.

Even the smaller and less expensive MQ-1 Predator is seeing a moderate upward creep in vehicle costs. The unit cost for an MQ-1 Predator A UAV is $4.5 million;[26] however, the larger MQ-9 Predator B will be considerably more expensive. As General Hornburg said, "You'll find the price of the sensors exceed the price of the airplane. They're not going to be expendable."[27] As the cost of these systems continues to rise, pressure is increasing to place defensive systems on these vehicles, which will further increase vehicle costs without reducing the LDHD problem. The original vision for UAVs was to replace manned aircraft in the dull, dangerous, and dirty[28] combat roles. However, these high-tech vehicles are becoming economically infeasible for use in the dangerous and dirty roles, creating a significant gap in USAF UAV capabilities and fostering the need for less expensive, expendable UAV platforms.

Threat Environment

During Operation Enduring Freedom and Operation Iraqi Freedom, the U.S. dominated the adversary through the use of focused firepower and technological superiority. However, gaining and maintaining air and ground superiority with LDHD platforms will increasingly become more difficult in the future. The rapid pace of technological growth and the proliferation of advanced IAD systems pose significant threats to high value UAV assets in future conflicts. In addition, since most U.S. adversaries are unable to match the U.S. force on force, they will seek to exploit the weakness created by a LDHD force structure. Future USAF superiority will require high-tech vehicles and low-tech expendable UAVs to cover the full spectrum of conflict.

The proliferation of military and dual-use technologies continues to expand at an exponential rate. From lasers to cruise missiles, future adversaries will have access to technologies once held only by major military powers such as the United States and Russia. As Dennis Gormely of the International Institute for Strategic Studies observed,

> Military breakthroughs are increasingly resulting from commercial, rather than secret military, research…Chief among these new commercial technologies are cheap guidance and navigation systems based on the US Global Positioning System (GPS)…Combined with commercially available geographic-information systems and one-metre-resolution satellite imagery to target fixed objects, new guidance and navigation technology for cruise missiles offers substantially more accurate delivery (by at least a factor of ten) and costs notably less (half or less). [29]

The proliferation of dual-use technologies for cruise missile defenses will place USAF LDHD assets at risk in future wars. According to a RAND study, it would take less than six cruise missiles to destroy a fighter wing parked on a ramp.[30] The loss of several LDHD assets at a forward operating location could wreak havoc on USAF operations. To minimize this vulnerability, USAF LDHD platforms will need to be based further from the battlefield and protected by robust air defenses. The overall effect will be longer reaction times, less time on station, and larger logistical support for LDHD platforms. On the other hand, since the loss of a few low cost UAV platforms (produced in large quantities) would have relatively little impact on overall USAF combat capability, these systems could operate closer to the forward line of troops. Moreover, forward basing would reduce their reaction times and increase their time on station.

Cruise missiles are not the only threat to LDHD platforms on the ground. The same technologies that make small UAVs a viable part of the USAF inventory also make them a potential threat to USAF assets. A

RAND study on airbase attack highlights the emerging threat from small, slow flying, low cost UAVs used in a one-way kamikaze mission role. As its author noted, "Nothing says it has to be jet-powered or rocket-powered…it can just as easily be a small, cheap, piston-engined propeller aircraft using commercially available GPS and computer technology for guidance and control."[31]

In addition to the increased threat of destruction while on the ground, USAF assets in the air will face advanced defensive and offensive systems capable of harming our most formidable platforms. Directed energy weapons capable of inflicting damage to high-tech electronic systems are just over the horizon. Today, radio frequency weapons can be produced from parts bought from local hardware and automotive suppliers.[32] These weapons could be used to target UAVs on the ground and during launch and recovery. Furthermore, the proliferation of modern surface to air missile systems will continue to plague non-stealthy UAVs. Currently, more than 500,000 MANPADS [33] are stockpiled around the world. Low flying UAVs like the Predator are subject to these air defense systems when operating over mountains or underneath the weather. According to *Air Force Magazine*, "The Pentagon hasn't released exact details of all Predator crashes, but it does acknowledge that it has lost about 20 of the aircraft since the program began. 'The bulk of those,' says an Air Force official, 'were lost over enemy territory.'"[34]

The end of the Cold War has led to a surplus of both old and new integrated air defense systems. Currently, Russian arms manufacturers are offering their prize surface to air missile (SAM) systems to many foreign countries. According to senior intelligence officials, Moscow has pulled out the stops in the sale of their very best air defense systems.[35] Currently, several smaller countries are actively pursuing advanced IAD systems. For example, *Middle East News* reports Syria is negotiating with Russia for the advanced S-400 system, which is similar to the U.S.' Patriot system.[36] On the other hand, China currently operates the Russian SA-10 SAM system and is expected to acquire the SA-20 variant by 2020.[37] In addition, China is now indigenously producing its own surface to air missiles for export. The common characteristic among all these advanced systems is their inherent mobility and lethality to large non-stealthy UAV platforms. As a RAND report contends, "virtually all current and planned U.S. airborne ISR platforms, including Global Hawk, are extremely vulnerable to SA-10 and SA-20–class SAMs and to modern fighters."[38] Therefore, these UAVs would need to operate outside the lethal envelope of the threat, which will significantly impact their operational capabilities.

On the ground and in the air, USAF assets will operate in an increasingly more dangerous tactical environment. Long procurement timelines, high vehicle costs, and declining budgets will continue to limit the USAF's ability to procure large quantities of high-cost UAVs. Whether targeted by a directed energy weapon on the ground or an SA-10 in the air, the loss of a few of these LDHD systems would have a significant impact on the USAF and combatant commander's combat capabilities. It is simply not economically feasible to use these assets in dangerous (high threat) and dirty missions. Even with its full allotment of Global Hawks and Predators, the USAF cannot afford to wage attritional warfare with an adversary by pitting its LDHD UAVs against numerous hidden advanced mobile air defense systems or directed energy systems.

Though stealth offers a potential solution, it will increase vehicle procurement and maintenance costs, which will further reduce procurement numbers in an era of declining budgets. Stealthy UAVs will play a major role in future conflicts, but their limited numbers could hinder a commander's ability to maintain air superiority in large-scale conflicts. The USAF faced a similar problem when it replaced large numbers of C-141s with fewer but more capable C-17 aircraft. As General Charles Robertson said, "Even though tonnage capabilities remain close to the same, we lose tremendous flexibility with so many fewer tails. [The 135 C-17s] can only be in half as many places as 270 C-141s."[39] In a large-scale conflict, commanders might not be able to cover all required missions with a limited number of stealthy UAVs, and these aircraft are equally vulnerable on the ground when targeted by conventional munitions.

These problems could be solved by balancing the USAF's UAV fleet with a large number of small and low-cost but highly capable UAVs. Capitalizing on advances in technology and new operational concepts, the USAF could acquire large numbers of low-cost micro and small UAV platforms to perform the missions currently undertaken by the higher cost LDHD UAVs. Performing roles of decoy, searcher, and hunter, the low cost small UAVs could, if necessary, wage a war of economic attrition against expensive enemy missiles. It doesn't take long to win a war when one is trading a $2,000-$20,000 UAV for a $100,000 missile. Moreover, should the adversary refuse to engage the small UAVs, they would be able to complete their primary mission of finding, fixing, targeting, tracking, and/or killing the enemy.

III. Enablers

In the past the use of small low-cost UAVs was severely restricted due to vehicle performance and capability limitations. However, advances in technology and new concepts of operational use are rapidly closing the performance and capabilities gap between small and large UAVs. Current advances in miniaturization are giving small UAVs capabilities comparable to their larger cousins at significantly lower costs. In addition, future advances in computers and nanotechnology are projected to give these vehicles capabilities one once only read about in science fiction magazines. Furthermore, new concepts of operation, such as cooperative behavior protocols and swarming, are opening new missions for these small, low cost expendable UAVs.

Current Technology

Current advancements in miniaturization and micro-fabrication are eliminating the gaps in capability between small and large UAVs. The largest advances have occurred in the areas of miniaturization of sensors and navigation systems. Miniaturization and common off-the-shelf (COTS) technologies are providing low cost ISR products for even the smallest UAVs on the market. Currently, the Army's small Shadow UAV is capable of carrying a 55-pound color charge-coupled TV device and forward-looking infrared payload,[40] which gives the UAV day and night ISR capability. The Army is also expanding Shadow's capabilities by developing a new electro-optical/infrared (EO/IR) sensor with a laser designator and a laser range finder. [41] This system will give Shadow similar capabilities to USAF's Predator. However, the Army's Shadow UAV costs less than one-tenth that of the Predator.[42] In the area of micro UAVs (MAVs), Israel Aircraft Industries recently announced it would test an autonomous MAV with a system weight of less than 500g, including an enhanced video camera and improved avionics. [43] This MAV has a maximum endurance of an hour and will perform ISR for soldiers in the field.[44]

ISR is not the only area in which micro and small UAV capabilities are growing. The recent advance in the miniaturization of synthetic aperture radar (SAR) systems highlights just how far current technology advancements have impacted small UAV capabilities. Originally, the excessive weight of SAR systems limited their use to large UAVs. Sandia's original prototype SAR radar weighed in at a whopping 220kg (484 lbs). General Atomics' APY-8 Lynx SAR for the Predator is a derivative of the Sandia prototype, weighing in at 52kg (114lbs). To augment small UAVs and precision munitions, Sandia developed a "miniSAR that will weigh less than 14kg (31 lbs), yet match the 100mm ground resolution of Lynx, with a range of about 15km" (9.4 nm)."[45] This miniSAR will be one-fourth the weight and one-tenth the size of current generation SAR radars.[46] "Future versions of miniSAR are planned that will shrink the total weight to less than 10 pounds," [47] which will open the door for even smaller UAVs such as the Aerosonde UAV. The Aerosonde UAV, a $35,000 small UAV[48] that was the first UAV to cross the Atlantic Ocean, "has flown for over thirty-two hours in one stretch and it has undertaken continuous operations with relay aircraft extending over several days."[49]

On the other hand, ultra wideband (UWB) is set to revolutionize the role of micro and small UAVs. UWB radar has emerged as a leading technology candidate for MAV applications due to its small size, low power consumption, precision, and low weight.[50] The system weighs less than 50 grams, draws less than one watt of power, and has a resolution accuracy of better than one foot (vertical and horizontal).[51] This system provides MAV platforms with a collision avoidance system that can detect low radar cross-section targets such as wires and poles. [52] This capability will give MAVs the ability to operate in urban environments, forested areas, or the interior of buildings. Given its small size, low power requirements, and excellent accuracy, UWB will open up a whole new spectrum of operations for both micro and small UAVs.

Sensors are not the only area where current technology is breaking ground for micro and small UAVs. As discussed in the threat section, navigation systems are also benefiting from the miniaturization or components. MicroPilot, the world's leading manufacturer of miniature autopilots, currently produces the world's smallest autopilot, the MP2028^{g}.[53] Weighing a modest 28g (1 ounce), the $5,000 MP2028^{g} (single unit price) includes GPS waypoint navigation (up to 1000 points), altitude and airspeed hold, autonomous take-off and landing, integrated 3-axis gyros accelerometers, GPS and pressure sensors, and the HORIZON^{mp} ground control software, which "allows the operator to monitor the MP2028g, change waypoints, upload new flight plans, initiate holding patterns and adjust feedback loop gains, all while the UAV is flying."[54] The reduced size and weight of these micro navigation systems will significantly enhance micro and small UAV performance and capabilities while minimizing system costs.

Future Technology

Although current technology breakthroughs are truly amazing, the future of technology promises to rapidly expand the current capabilities of micro and small UAVs to the levels that were once considered science fiction. Advances in computer technology, miniaturization, and nanotechnology will revolutionize the capabilities of micro and small UAVs for military operations. The growth of computer processor power is forecast to continue at an exponential pace for the next decade. "The integrated circuit industry is predicting ~128× improvements in transistor density, based on current state of the technology, over the next 15 years or so." [55] Like the speed of modern day computers, UAV processing power will continue to grow exponentially. Increases in processing power will give micro and small UAVs the capability to process sensor data onboard the vehicle and the ability to perform autonomous operations (AO).[56] These advances will significantly reduce bandwidth requirements and increase vehicle capabilities.

According to the USAF Scientific Advisory Board (SAB), the bulk of UAV bandwidth is used to send raw data back to a ground station for processing.[57] Increased onboard processing power will allow even the smallest UAVs to process data in real time without the need to relay raw data to the ground station for processing, enabling many small UAVs to provide real-time targeting information to airborne controllers or ground troops without saturating bandwidth requirements. In addition, new capabilities, such as foliage penetrating radars that require extensive processing (100s of Gflops/sec),[58] will become a reality for these smaller vehicles. Moreover, increased processing power "will allow the Air Force to pack more and more intelligence into smaller and smaller, lighter and lighter, less-power-consuming (per function) packages that have increasing local intelligence and increasing autonomy."[59] Autonomous operations by lots of small cooperative UAVs will greatly increase individual UAV capability.

In addition, increased processing power will reduce small UAV payload weight and cost.

> The growth in computing power, plus advances in signal and data processing algorithms, means that enhancements to a sensor system may be derived more from the processing, than from the sensor, end of the system. Thus there is a trading of 'mass for MIPS' [million of instructions per second] whereby improved processing power compensates for inadequacies in sensing hardware. An example is the adoption of a 'relaxed-optical-tolerance-imaging' approach to overcome problems associated with space based large aperture optical sensors.[60]

By reducing sensor tolerance and platform stability requirements, increased processing power will enable smaller UAVs to carry lighter, cheaper sensors. Advancements in computer power, information transmission, and storage will continue to grow at tremendous pace, giving micro and small UAVs capabilities once relegated solely to larger UAVs but at a fraction of the cost.

"The significance of this miniaturization goes well beyond just the smaller size and reduced weight."[61] Miniaturization reduces cost, increases reliability, and enables increased functionality and capability in smaller packages. "These trends are extending to include micro-electro-mechanical systems (MEMS) and other technologies for sensors and actuators, thus allowing the possibility of miniaturizing entire systems and platforms. The combination of reduced size, weight, and cost per unit function has significant implications for Air Force missions, from global reach to situational awareness." [62] Advances in miniaturization and nanotechnology[63] will give micro and small UAVs incredible power at a much lower unit cost. Examples of the scope of predicted future miniaturization of sensors and systems gives light to revolutionary change to micro and small UAVs capabilities over the next 10-20 years.

"Miniaturisation techniques are expected to reduce the mass and volume of SAR systems by a factor of 100 by 2020."[64] In addition, the USAF Science and Technology Board predicts an extraordinary increase in capability and reduction in size for UAVs. According to its 2002 report, "Given micro- or nano-enabled or -enhanced sensors and subsystem technologies, MAVs can grow dramatically in capability, achieving autonomy and the functionality of systems that are currently many times larger, or can shrink in size to insect like dimensions. Current MAVs fly at 10 meters per second for 5 kilometers, but future systems could fly transonically for 1,000 kilometers or endure for tens of hours."[65] This Board is also predicting the same effects on the miniaturization of missiles and bombs. High-energy-density materials developed with nanotechnology are revolutionizing explosive performance and handling safety.[66] Future developments could lead to micro and nano-sized missiles capable of destroying soft targets. [67] As the size of the weapons decreases, so will the size of the platforms that carry them.

Moreover, miniaturization of systems and sensors in the future would allow development of large numbers of small low cost sensor UAVs, which could provide critical data to the U.S. military's network and air and ground systems. These small vehicles would literally become the military's eyes, ears, and nose. In addition, small low cost systems have an inherent advantage over high cost low density UAVs. "System survivability is enhanced by large numbers offering 'multiple-redundancies' and the low signatures offered by the micro systems."[68]

Cooperative Behavior/Multi-Agent Systems

The future concept of operations for UAVs will be significantly different from today's centralized control and execution concept of operations. "The advances in information density, miniaturization, and materials functionality will enable an advanced degree of autonomous systems operation and a paradigm shift from reliance on a few large systems to many small things that work together."[69] Using cooperative behavior protocols, single UAVs less capable than conventional UAVs, but able to communicate with each other, will exhibit behaviors and capabilities exceeding those of conventional UAVs that do not communicate.[70] This concept of operations will greatly increase micro and small UAV capabilities while minimizing costs.

Over the last millennium, some of the world's strongest creatures have become extinct while some of the smallest have flourished. One reason these small creatures have survived is their ability to cooperate as a group to accomplish seemingly impossible tasks. Scientists today are working with the same behavioral concepts for tomorrow's UAVs. The principle behind cooperative behavior is that individual entities with limited capabilities can use communication and cooperation to accomplish complex tasks. In the cooperative behavior concept of operations each UAV is an agent in a multi-agent system. Given the low-tech requirement of the individual agent, small UAVs could be mass produced and therefore expendable. In addition, "redundancy would occur at the level of UAV agents, not at the traditional level of UAV subsystems,"[71] which reduces the agent cost while increasing the system's survivability.

There are two primary ways to utilize cooperating UAVs in a multi-agent system. The first involves using multiple different types of specialized UAVs, which communicate with each other to accomplish a complex task. A University of Texas at Arlington research paper describes an application of this approach in the SEAD role. The MAS would be composed of a master, worker, and supervisor UAVs. "Master robots are responsible for distinguishing between friendly and enemy AA radars. They are equipped with sensors for long-range communication, but are ill-equipped to pinpoint the location of enemy AA radars. On the other hand, worker agents are equipped with low range, high accuracy sensors and jammers. The supervisor relays communications from masters to workers." [72] The master is the team's quarterback. When the master finds targets, it coordinates through the supervisor to move the workers towards the targets. "If the targets are separated by large distances or there are more targets than masters, the flock splits into groups (one group per target)." [73] Each group then prosecutes the target.

In the future this same approach could be used to neutralize next generation IADs. Small low cost and inherently stealthy UAVs carrying micro sensors could survey the battlefield looking for mobile SAMs. Through cooperative behavior these UAVs could scour a large battlefield for targets, and if necessary adapt to when an individual agent is shot down. When a mobile SAM system is found, the small UAV could fix, target, and track the system while relaying coordinates and video to a human controller who would then release a UCAV or a large stealth platform for target destruction. The capabilities of this type of system are enormous. It provides a robust low cost solution to a very complex problem without the risk of losing a scarce resource such as a Global Hawk or Predator. As a force enhancer, these low cost UAVs give combatant commanders increased flexibility and capability in all threat environments.

The second concept of cooperative behavior involves the use of identical platforms capable of performing the same roles but utilizing less sophisticated sensors to reduce costs. Spurred by the increased vulnerability and high cost of larger UAVs, an Australian scientific research program investigated the benefits of using multiple low cost UAVs to detect enemy radars.[74] Australian researcher have shown that multiple small inexpensive UAVs, carrying low cost direction finding (DF) sensors, can achieve better results than a large UAV carrying a high cost precise DF sensor. For instance, the time required to geo-locate the system is significantly reduced with multiple platforms correlating their data.[75] Based on the results of their research,

> The more accurate sensors are nominally placed on board high-value assets and must therefore standoff at a range of 100km, whereas the less capable sensors, which are significantly smaller and cheaper, are placed on more expendable platforms and may therefore stand-in (their cost means that we are also able to afford more of them). Analysis of the figures [results] shows that the system using the less accurate sensors has errors around 50% less than those of the more expensive system.[76]

The U. S. Navy's Smart Warfighting Array of Reconfigurable Modules (SWARM) operates on the same basic premise. According to the SWARM UAV project manager,

> These vehicles operate as a group, functioning together as a 'swarm' of aircraft. This operational model requires the vehicles to function as individual units while being a part of a larger functioning organization operating to achieve a common mission goal. The UAVs communicate relevant information and can reconfigure themselves, autonomously changing direction in response to sensor input to achieve the mission at hand. For example, if you have 100 aircraft collecting sensor input over a field of operation and five of them have engine failure or are shot out of the sky, the rest can reconfigure themselves to collect the required data and complete the mission.[77]

These vehicles can perform complex missions while adapting to changes in their environment, and because they cost under $2000, they are considered expendable, expanding their viability in future conflicts. As the program director said, "To be sure, many of these missions could also be carried out by existing UAVs, which are high-dollar assets and in high demand. But with an individual price goal of a fraction of current UAVs, these small, easy-to-use aircraft could be ideal for situations in which commanders did not want to risk scarce resources."[78]

Recent tests by the U.S. Office of Naval Research's (ONR's) autonomous intelligent networks and systems (AINS) project have shown that autonomous UAVs, unmanned ground sensors, and unmanned ground vehicles can perform a complex mission autonomously. Using the Navy's low cost Silver Fox UAV, which resembles a model airplane with an 8-foot wingspan, the Navy conducted a completely autonomous intercept of a car traveling down a road.[79] The car triggered "ground sensors that formed part of a prototype AINS network. The ground sensors, detecting the car, called two Silver Foxes over to have a look, recalls Tony Mulligan, ACR's chief executive officer. The sensors provided an approximate GPS location, and an onboard UAV visual system identified the object as a car. Silver Fox then called in ground robots, which surrounded the car—all without human intervention."[80]

What cooperative behavior and swarming of UAVs brings to the war fighter is a new means of conducting war. These new concepts of operation will enable low cost micro and small UAVs to achieve complex tasks unattainable as individual UAVs. Moreover, the ability to place a robust, adaptive, and expendable UAVs system into high threat environment will greatly increase the combatant commander's options and flexibility. As the USAF SAB stated,

> Initially, this autonomy will be seen simply as an evolutionary extension of the capabilities of current systems such as cruise missiles or UCAVs, providing increased accuracy and range or other performance advantages. Over the longer term, however, the dramatic increases in local information awareness and computational power will enable independent decision making and will have a dramatic impact on the conduct of warfare. Systems may also be able to power, self-repair, and reconfigure themselves to extend the scope of their missions. The lowered cost and increased functionality will lead to swarms of intelligent agents with emergent behavior that differs from that of any single entity.[81]

In the future micro and small low cost UAVs cooperating in swarms will be able to accomplish extremely complex tasks considered unimaginable today. In addition, these low cost systems will provide future commanders with greater flexibility than high cost LDHD UAV platforms.

IV. The Missions

The role of micro and small UAVs in future wars will be considerably different than today. Advances in computer technology, miniaturization, and nanotechnology coupled with new operational concepts such as cooperative behavior or swarming will give these mighty dynamos unbelievable capabilities in the near future. Micro and small UAVs will see a greatly expanded role in the ISR mission and will acquire additional roles in the dangerous SEAD, electronic warfare, and strike missions. These small dynamos have the capability to be force multipliers across the full spectrum of missions in the near future.

Intelligence, Surveillance, and Reconnaissance (ISR)

The predominant mission of today's small UAVs is the basic ISR mission. Primarily used by the Army and Marines, these systems provide brigade-level ISR data to the soldier on the ground. However, technology will gradually improve their capabilities and combat utility. In the future, these small UAVs will operate across a wider spectrum of ISR roles, including traditional ISR, nuclear, biological, and chemical (NBC) detection, battle damage assessment, and urban/covert operations.

The expansion of micro and small UAVs roles is beginning to take form. One concept of operations being tested by the USAF is to use MAVs as expendable ISR assets for fighter and AC-130 aircraft. In 2004, Raytheon demonstrated its SilentEyes micro UAV by ejecting it from a Predator pylon.[82] After falling free from the Predator, the vehicle unfolded its wings and began to glide towards a target transmitting images back to the controller. The controller had the capability to navigate the UAV through a data link in order to cover different targets within a search area. According to *Jane's International Defense Review*, the UAV's range is 40-50 km (25-31nm) from 25,000 feet.[83] The MAV will "provide confirmatory identification when no manned assets have access to denied areas and will complement sensors on tactical manned and unmanned platforms with autonomous, air-launched sensors."[84]

Today, commercially marketed small UAVs are capable of 30 hours of endurance with relatively small payloads. However, as technology reduces payload weight and increases propulsion efficiency, these vehicles will become capable low cost, long endurance platforms. Using miniSAR, UHF/VHF radar, and EO/IR sensors, these small vehicles will be able to perform roles comparable to larger UAVs and perhaps better than larger UAVs when employed in large numbers using cooperative behavior. In large operations, such as Operation Iraqi Freedom, these vehicles would be able to provide persistent coverage of large tracts of land, which would release LDHD UAVs for more demanding missions. In addition, low cost systems will give commanders access to high threat areas without the risk of losing a high value resource.

In addition to the basic ISR role, micro and small low cost UAV will be used extensively as airborne NBC detectors accomplishing the "dirty" missions for U.S. military and homeland defense forces. Recent advances in miniaturization and nanotechnology have significantly reduced the size of NBC detectors. For example, "Argonne [under DoD contract] has developed a miniature 'microelectronic nose' that detects chemical poisons such as cyanogen chloride and hydrogen cyanide gases at nonlethal concentrations. It is being trained to detect VX, sarin, and mustard gases as well. The prototype instrument fits in the palm of a hand."[85] Laboratories-on-a-chip are the just the latest inventions that will soon find their way into micro and small UAVs for use in military applications. Integrated within a MAV, such as the Army's Black

Widow,[86] these sensors will provide soldiers or air base defenders with a fast and economical means of identifying hazards. "MAVs will be able to map the size and shape of hazardous clouds and provide real time tracking of their location."[87]

Battle damage assessment (BDA) is another area in which micro and small UAVs will be used in the future. The Air Force Research Laboratory Munitions Directorate plans to demonstrate the use of a MAV for "instant BDA."[88] The MAV "constructed by AFRL of 'pretty indestructible' carbon fiber material, would be released at a selected altitude from a guided bomb. As the bomb impacts, the MAV, powered by an electric motor, would orbit around pre-selected coordinates, transmitting images to a command facility."[89] This capability will give pilots and commanders instant feedback on mission success or failure. As technology evolves, future MAVs could mimic the capabilities of large flying insects. In the same scenario, the MAV may be able to land and descend (crawl) into the crater or building to identify interior damage and then return to the surface and transmit images of the damage. Or the vehicle could do both optical and chemical analysis of the sites to determine if NBC contaminates were released into the air. The power of using these tiny vehicles for ISR will completely change the way commanders assess damage in future conflicts.

Micro and small UAVs will play an increasing role during urban warfare and peacekeeping operations. The Army is already pursuing MAV systems that soldiers can carry into battle. From a USAF perspective, miniaturization of weapons will enable small UAVs to accomplish missions similar to the Predator UAV today. In addition, lower system costs would enable the USAF to put more vehicles over an urban area for better coverage. A truly integrated system would allow a soldier on the ground to digitally target the small UAV's micro weapons onto ground targets such as snipers or automobiles. In addition, MAVs will have the capability to accomplish a "perch and stare" missions in all environments. Like their mammal counterparts, birds, these systems could land on a roof or a tree (perch) and watch (stare at) suspects or areas. According to Sam Wilson at DARPA, "'Private Jones' [the MAV] will operate under the canopy or inside buildings or caves for one-hour missions. This is a great capability for special operations forces. It will significantly reduce their exposure to hostile fire and/or booby traps. The 'perch and stare' capability of the MAV will provide tactical reconnaissance and surveillance for extended periods of time with low risk to the user."[90] The ISR role of micro and small UAVs will continue to expand in the future. These vehicles will become a vital force enhancement to all military services.

Suppression of Enemy Air Defenses (SEAD) and Electronic Warfare (EW)

SEAD/EW missions will perhaps be the first mission area where micro and small UAVs are widely used in a traditional combat role. Small UAVs and MAVs have an inherently small radar, infrared, and acoustic signature, which, when coupled with their low cost and expendability, makes them the optimum candidate for this very dangerous mission. In the area of air defense, technology is greatly improving the lethality and range of new IAD systems. To counter these threats, one must either spend lots of money buying large stealthy platforms or look for alternate low cost means of defeating/killing the systems. The first generation of low cost UAV jammers is well underway. Raytheon's miniature air-launched decoy jammer is an expendable UAV designed to fly a predetermined pattern and jam at a pre-determined time.[91]

Newer concepts include the use of small UAVs carrying new lightweight jammers, which will jam enemy radar sites. The Australian military has done extensive research in utilizing low cost small UAVs as 'stand-in' jammers against modern radar sites.[92] The premise behind their study is that small UAVs are inherently stealthy, which means they can fly closer to the target radar without detection. In addition, they are a low tech, low cost, expendable asset, which allows their purchase in large quantities (i.e., 100 Aerosonde UAVs for 1 Predator UAV).[93] Having a large number of these small UAVs would give commanders more flexibility to use the system without fear of losing a precious resource to defensive countermeasures such as home-on-jam missiles. The Australian report describes the utility of small UAVs as follows:

> A jamming platform must stand off at a considerable range from a target to allow for its own protection. Because it must stand off, it requires a large amount of power. By reducing the size of the platform and the need to protect it, we are able to stand in, which means that we need significantly less power to jam a given target. …because the stand in jammer is closer to its target its transmissions cover a smaller area …potential for electromagnetic fratricide is significantly reduced.[94]

In addition, the object being jammed does not have to be an enemy radar site. It can be a communications antenna located within a city or any other type of radio frequency (RF) transmission device, which cannot or should not be destroyed. Another means of handling fixed RF sites in precarious locations, which precludes their destruction (i.e., radar on top of a hospital), includes the use of small UAVs to precisely drop miniature jammers around the site.[95] Timothy Coffey and John A. Montgomery cite a recently developed jammer, "which produces a 50-milliwatt (mW) jamming signal with a 250-megahertz (MHz) bandwidth for 4 hours operating in S band and with a total weight of 20 grams,"[96] as a potential candidate for the mission. The small UAV under the cover of darkness would covertly proceed to the site and precisely place (with GPS) the jammers around the site. "If the mini UAV could place this jammer within 500 feet of a nominal 1 megawatt S-band radar, with an antenna gain of 1,000 and an instantaneous bandwidth of 1 MHz, then a 1-square-meter radar cross section aircraft could be screened to within a range of 10 kilometers (km) from the radar (this assumes a jammer antenna gain of one)."[97] Options like this could open up new avenues for handling adversaries who use civilians as shields for their military systems.

EW is not the only area in which future micro and small UAVs will be used. Small UAVs will be used as anti-radiation missiles, or they will carry and release micro UAVs with explosives to disable the radar. Current U.S. anti-radiation systems are very expensive and relatively inflexible once launched. The high-speed anti-radiation missile (AGM-88, HARM) costs $200,000 per missile and has zero loiter time should the radar shutdown.[98] Lockheed Martin's low-cost autonomous attack system (LOCAAS) provides a baseline for future UAV SEAD/strike systems. LOCASS is a miniature munition for theater missile defense, suppression of enemy air defenses, interdiction missions, and armed reconnaissance.[99] Powered by a miniature turbojet, LOCAAS is capable of loitering for 30 minutes and covering 25 square miles of land.[100] However, LOCAAS is a relatively expensive vehicle (~$100,000).[101] In the future, low cost, long duration small UAV platforms could provide the same coverage and capability, but for greater periods of time and at a much lower cost. One concept envisions the use of a small UAV to carry micro UAV sub-munitions. The long endurance UAVs would launch miniature vehicles at intervals over a period of days, to destroy sites as they come on air.[102]

Additional Missions

The future of micro and small UAVs will not be limited to ISR, SEAD, and EW missions. These small platforms will be capable of carrying out missions across the full spectrum of operations, including strike and airborne communication nodes. After watching the USAF's successful integration of offensive weapons on a Predator UAV, the Army has begun to actively pursue offensive capabilities for its small UAVs. The Army modified its Hunter UAV to carry Northrop Grumman's brilliant anti-armor (BAT) sub-munitions.[103] In addition, the Army is pursuing an upgrade to the BAT sub-munition in order to give it both moving target and stationary capability.[104] This is but the beginning of many new approaches for utilizing small UAVs as offensive weapons. Advances in miniaturization, computer technology, nano-technology, and explosive technology will greatly broaden the offensive capabilities of micro and small UAVs. Whether it is micro bombs or just good old-fashioned plastic explosives, these small vehicles will give future commanders flexible control over the destruction of enemy forces.

In addition to the strike mission, small UAVs in the future will perform critical force support roles as airborne communication nodes (ACNs). Boeing and the Insitu Group recently demonstrated this concept utilizing their small ScanEagle UAV. The fully autonomous vehicle carried "Harris Corporation's National Security Agency-approved Type 1 classified SecNet-11 ® Plus technology…streaming video and voice-over IP communication was sent from a ground control station over a secure high-bandwidth network to ScanEagle 18 miles away. The data was then instantaneously relayed to ground personnel six miles from the UAV."[105] The flight demonstrated the feasibility of providing secure communication to frontline troops using a small low cost platform. The ACN concept will give future commanders enhanced communication with frontline troops. In addition, "it avoids the necessity of bringing in heavy communications gear, such as MSE [mobile subscriber equipment] trucks and SATCOM terminals, at times when transport to the theater is in short supply."[106]

Forecast for the Future

The future of micro and mini UAVs is not a "Buck Rogers" fantasy. The United States and other governments are beginning to realize the potential force enhancement capabilities of these low-cost small UAVs. By 2010 several of the systems listed in the previous sections will be available for operational use by the U.S. military. In this short timeframe, micro and small UAVs will proliferate, performing several basic ISR missions for soldiers in the field. In addition, programs currently in development and test, such as Silent Eyes and AFRL's "instant BDA" MAV could be available for combat within five years. In fact, by 2010 the UAV roadmap projects a proliferation of multi-spectral imaging and miniaturized systems, which will enable small UAVs to perform all missions within the ISR spectrum of missions.[107]

Moreover, the SEAD/EW role will also see a burgeoning growth in micro and small UAV use in the next five to ten years. Small UAV jamming and detection platforms have already been tested by the U.S., Australian, and several other governments. In addition to basic SEAD/EW, the UAV roadmap predicts an exponential growth in autonomous capability from 2005 onwards [108] and projects that by 2015 UAVs will be capable of fully autonomous swarms, giving them unprecedented capabilities throughout the full spectrum of conflict.[109]

By 2025, the capabilities of intelligent nano, micro, and small UAVs will be beyond comprehension. According to Dr. Bushnell, NASA's Chief Scientist, by 2025 the world will be full of "wondrous/ubiquitous land/sea/air/space multiphysics/hyperspectral sensor swarms."[110] In addition to sensors, Bushnell suggests the future will be full of "miniaturized/brilliant/ lightweight/low-power/inexpensive swarms of everything" (UAVs, UUVs, satellites, weapons, robots, sensors, mines, etc.).[111] If Dr. Bushnell's predictions hold true, nano, micro, and small UAVs will become increasingly more capable and widespread throughout the world. The question is not whether technology will give these small UAVs the capability to accomplish future combat missions, but whether the USAF will be able to adapt fast enough culturally to keep pace with the changes in technology.

V. Conclusions and Recommendations

"The Air Force has significantly reduced the size of its combat air forces in response to changing national military objectives and declining budgets. Because of its smaller force structure, the Air Force now has fewer combat airplanes to replace on a steady-state basis, but the modernization funding burden remains high because of increasing development and procurement costs for these platforms."[112] Air Force leaders are stuck between the proverbial "rock and a hard spot." Budgetary pressures and increased UAV costs are forcing the Air Force to acquire fewer expensive large and low observable UAVs. However, the demand for these LDHD vehicles continues to increase as the U.S. prosecutes the war on terrorism.

In addition to acquiring fewer LDHD UAV assets, the Air Force will face new and more lethal threats from both state and non-state actors in the future. The rapid pace of technological advancements and the proliferation of advanced IAD systems will pose a significant threat to the USAF's LDHD assets. In the future, adversaries waging asymmetric warfare will exploit readily available technologies and new weapon systems in order to target these critical resources. The loss of a few of these critical LDHD UAVs could significantly impact a commander's combat capabilities. However, the USAF can break from the current paradigm and create "depth and density" within its UAV fleet by acquiring a large number of smaller low cost UAVs.

No longer are micro and small UAVs of limited utility for military operations. Technological advances and new operational concepts are eliminating the barriers that restricted their use on the battlefield. Advances in miniaturization, computer technology, and nanotechnology are broadening the capabilities of micro and small UAVs, making them an economically feasible means of augmenting the USAF's manned and unmanned fleet. Current advances in miniaturization and micro-fabrication have succeeded in reducing some UAV payloads by a factor of fifteen[113] and will continue to do so at an accelerating rate in the future. In addition, the exponential growth of computing power is expanding small UAV capabilities by providing more capable and intelligent systems in smaller and smaller packages. Scientists predict that lower costs and technology advances will enhance the degree of autonomous capability and create a paradigm shift from reliance on a few LDHD platforms to a robust network of small UAVs working together. [114] The synergistic capabilities of these agents working together in a MAS will enable the USAF to employ less capable low cost UAVs to perform complex missions. Moreover, a robust network of smaller UAVs provides commanders innate flexibility to accomplish a wide spectrum of missions regardless of the level of threat.

From ISR to strike missions, micro and small UAVs will be critical force enhancers in future conflicts. The traditional small UAV role of basic ISR will expand to include NBC detection and monitoring, battle damage assessment, urban ISR, and large area ISR coverage utilizing numerous cooperative UAVs. Due to their inherently low signatures and low cost, these small vehicles will play a major role defeating future adversaries. Whether they are deployable UAV jammers or UAV anti-radiation missiles, micro and small UAVs will be an integral part of the

USAF's arsenal.

UAVs are poised to change the nature of war in the future. However, the rising cost of large UAV platforms, coupled with a declining U.S. budget, will significantly impact the Air Force's ability to procure large numbers of high cost UAVs. In addition, these LDHD UAVs will face an increasingly threatening and lethal environment, which could limit their usefulness in the future. As with the Austrian empire in 1851, USAF leaders will face several decisions in the future that will affect the outcome of future battles. In the case of UAV procurement, the USAF should break from its current paradigm of purchasing high cost large UAVs and begin to develop and procure low cost micro and small UAVs. Thanks to technology advances and new operational concepts, these "small powers" are capable of being significant force enhancers in future conflicts.

Glossary

AA	Anti-aircraft Artillery
ACN	Airborne Communication Node
ACSC	Air Command and Staff College
AFIT	Air Force Institute of Technology
AGM	Air-to-Ground Munitions
AINS	Autonomous Intelligent Networks and Systems
AO	Autonomous Operations
AU	Air University
AWC	Air War College
BAT	Brilliant Anti-armor sub munitions
BDA	Battle Damage Assessment
COTS	Common Off the Shelf (Technology)
CADRE	College of Aerospace Doctrine, Research and Education
DARPA	Defense Advanced Research and Projects Agency
DF	Direction Finder
DoD	Department of Defense
EO/IR	Electo-Optical/Infrared
EW	Electronic Warfare
GAO	Government Accounting Office
GPS	Global Positioning System
HARM	High speed Anti Radiation Missile
IAD	Integrated Air Defense
IADS	Integrated Air Defense System
ISR	Intelligence, Surveillance, and Reconnaissance (ISR)
Km	Kilometer
LDHD	Low Density High Demand
LOCAAS	Low Cost Autonomous Attack System
MANPADS	Man Portable Air Defense System
MAS	Multi-Agent System
MAV	Micro Air Vehicle
MHz	Mega-Hertz
MSE	Mobile Subscriber Equipment
mW	Milli-watt
nm	Nautical Mile
O&M	Operations and Maintenance
ONR	Office of Naval Research
SAB	Scientific Advisory Board
SAM	Surface to Air Missile
SAR	Synthetic Aperture Radar
SEAD	Suppression of Enemy Air Defense
SWARM	Smart Warfighting Array of Reconfigurable Modules
TV	Television
U.S.	United States
UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Aerial Vehicle

UGS	Unmanned Ground Sensor
UGV	Unmanned Ground Vehicle
UHF	Ultra High Frequency
USAF	United States Air Force
UWB	Ultra Wide Band
VHF	Very High Frequency

Notes

[1] Azriel Lorber, *Misguided Weapons: Technological Failure and Surprise on the Battlefield* (Washington D.C.: Brassey's Inc., 2002), 11.

[2] Ibid.

[3] Ibid.

[4] Ibid., 10.

[5] UAV: "A powered, aerial vehicle that does not carry a human operator, uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a lethal or non-lethal payload. Ballistic or semi ballistic vehicles, cruise missiles, and artillery projectiles are not considered unmanned aerial vehicles." Definition obtained from Department of Defense, *Unmanned Aerial Vehicles Roadmap 2002-2027* (Washington D.C.: Office of the Secretary of Defense, December 2002).

[6] Micro UAV (MAV) is an unmanned aerial vehicle with a wingspan of 6 inches (15 cm) or less.

[7] Small UAV in this paper refers to smaller UAVs commonly called "mini-UAVs." These UAVs are smaller and less sophisticated than their large cousins the MQ-1 Predator (medium altitude long endurance UAV-MALE) or the RQ-4 Global Hawk (high altitude long endurance UAV- HALE). Examples of small UAVs include but are not limited to the U.S./Israeli Hunter, U.S. Army Shadow systems and the Australian Aerosonde UAV.

[8] "Air Force MQ-1 Predator was one of the initial ACTDs in 1994 and transitioned to an Air Force program in 1997. It takes off and lands conventionally on a runway and can carry a maximum 450 lb payload for 24+ hours. Operationally, it is flown with a gimbaled electro-optical/infrared (EO/IR) sensor and a SAR, giving it a day/night, all-weather (within aircraft limits) reconnaissance capability. It uses either a line-of-sight (C-band) or a beyond-line-of-sight (Ku-band Satellite Communications (SATCOM)) data link to relay color video in real time to commanders." Obtained from Department of Defense, *Unmanned Aerial Vehicles Roadmap 2002-2027* (Washington D.C.: Office of the Secretary of Defense, December 2002), 6.

[9] "The Air Force RQ-4 Global Hawk is a high altitude, long endurance UAV designed to provide wide area coverage of up to 40,000 nm^2 per day. It successfully completed its Military Utility Assessment, the final phase of its ACTD, in June 2000, and transitioned into Engineering and Manufacturing Development (EMD) in March 2001. It takes off and lands conventionally on a runway and currently carries a 1950 lb payload for up to 32 hours. Global Hawk carries both an EO/IR sensor and a SAR with moving target indicator (MTI) capability, allowing day/night, all-weather reconnaissance. Sensor data is relayed over Common Data Link (CDL) line-of-sight (LOS) (X-band) and/or beyond-line-of-sight (BLOS) (Ku-band SATCOM) data links to its Mission Control Element (MCE), which distributes imagery to up to seven theater exploitation systems." Obtained from Department of Defense, *Unmanned Aerial Vehicles Roadmap 2002-2027* (Washington D.C.: Office of the Secretary of Defense, December 2002), 8.

[10] "Swarming—defined as small, maneuverable fire units able to converge quickly from different directions on a common target", Harrison Donnelly, "Swarming UAVs," on-line, internet, 22 February 2005, available from http://www.military-aerospace-technology.com/article.cfm?DocID=686 .

[11] Laura M. Colarusso, "Air Force of the Future: Betting on Expensive, High-tech Promises," *Armed Forces Journal*, September 2004, 26.

[12] Ibid.

[13] Department of the Air Force, *USAF FY 2005 Budget* (Washington D.C.: Assistant Secretary of the Air Force [Financial Management and Comptroller], n.d.), on-line, Internet, 20 February 2005, available from http://www.saffm.hq.af.mil/, 13.

[14] Department of Defense, *Program Budget Decision: PBD #753,* (Washington D.C.: Office of the Secretary of Defense, 23 December 2004), on-line, Internet, 20 February 2005, available from http://www.navytimes.com/content/editorial/pdf/dn.pbd753.pdf, 1

[15] United States Government, *Budget of the United States Government: Historical tables FY 200,* (Washington D.C.: Executive Office of the President of the United States, 2004), 52.

[16] F-22 Raptor is a fourth generation US fighter manufactured by Lockheed Martin.

[17] F-22 History, *F-22 Raptor History*, on-line, Internet, 20 February 2005, available from http://www.globalsecurity.org/military/systems/aircraft/f-22-history.htm

[18] David Fulghum and Robert Wall, "Budget Bloodbath," *Aviation Week & Space Technology*, 10 January 10 2005, 20-22.

[19] Gail Kuafman and Gopal Ratnam, "The Search for an Affordable UAV," Air Force Times, 16 September 2002, 16.

[20] Robert S. Leonard and Jeffrey A. Drezner, *Innovative Development: Global Hawk and DarkStar—HAE UAV ACTD Program Description and Comparative Analysis*, RAND Report, MR-1474 (Santa Monica CA: RAND, 2002), 7.

[21] Ibid.

[22] House of Representatives, *UNMANNED AERIAL VEHICLES - Changes in Global Hawk's Acquisition Strategy Are Needed to Reduce Program Risks*, report to the Subcommittee on Tactical Air and Land Forces, Committee on Armed Services, House of Representatives, prepared by United States General Accounting Office November 2004, www.gao.gov/new.items/d056.pdf, Overview: What GAO Found.

[23] House, *UNMANNED AERIAL VEHICLES - Changes in Global Hawk's Acquisition Strategy Are Needed to Reduce Program Risks*, report to the Subcommittee on Tactical Air and Land Forces, Committee on Armed Services, House of Representatives, prepared by United States General Accounting Office November 2004, www.gao.gov/new.items/d056.pdf. Current GAO estimate is $6.3 billion for 51 vehicles and 14 ground stations.

[24] Department of the Air Force, *USAF FY 2005 Budget* (Washington D.C.: Assistant Secretary of the Air Force [Financial Management and Comptroller], n.d.), on-line, Internet, 20 February 2005, available from http://www.saffm.hq.af.mil/, Exhibit P-5, Weapon System Cost Analysis.

[25] Amy Butler, "Air Force Mortgages Global Hawk Buys to Pay For MILCON, O&M," *Defense Daily*, 10 September 2003.

[26] Adam Hebert, "New Horizons for Combat UAVs," *Air Force Magazine* 86, no. 12 (December 2003), 72.

[27] Ibid.

[28] Dull mission equate to long endurance missions. Dangerous missions are those where loss of system or life is high. Dirty include the missions involving CBRNE where the vehicle could be contaminated in the process of accomplishing a mission.

[29] Dennis M. Gormley, "Survival: Hedging Against the Cruise-Missile Threat," *International Institute for Strategic Studies*, Spring 1998, 92-111.

[30] David T. Orletsky and John Stillion, *Airbase Vulnerability to Conventional Cruise-Missile and Ballistic-Missile Attacks*, RAND Report, MR-1028-AF (Santa Monica CA: RAND, 1999), 13.

[31] Ibid., 15.

[32] David Shriner, *The Design and Fabrication of a Damage Inflicting RF Weapon by "Back Yard Methods,"* Joint Economic Committee Hearing on Radio Frequency Weapons and Proliferation, 25 February 25 1998.

[33] MANPADS is an abbreviation for Man Portable Air Defense System (MANPADS).

[34] Richard J. Newman, "The Little Predator the Could," *Air Force Magazine*, March 2004, 50.

[35] John A. Tirpak, "The Double-Digit SAMs," *Air Force Magazine* 84, no. 6 (June 2001), 49.

[36] "Syria Seeks S-400 Anti-Missile System from Russia," Middle East News, 9 February 2005, on-line, Internet, 21 February 2005, available from http://www.missilethreat.com/threat/syria.html

[37] Alan Vick, Richard M. Moore, Bruce R. Pirnie, and John Stillion, *Aerospace Operations Against Elusive Ground Targets*, RAND Report, MR-1398-AF (Santa Monica CA: RAND, 2001), 62.

[38] Ibid., 64-65.

[39] John A. Tirpak, "A Clamor For Airlift," *Air Force Magazine* 83, no. 12 (December 2000), 30.

[40] Douglas Richardson and Linda Deer, "Creatures Great and Small," *Jane's Defense Weekly*, 21 July 2004, 45.

[41] Ibid.

[42] Elizabeth Bone and Christopher Bolkcom, *Unmanned Aerial Vehicles: Background and Issues for Congress*, Report for Congress, RL31872, 25 April 2003, on-line, Internet, 12 January 2005, available from http://www.fas.org/irp/crs/RL31872.pdf, CRS-6. Estimated cost for a Predator is $4.5 million while Shadow's estimated to cost is $350,000.

[43] Arie Egozi, "IAI Reveals Details of Micro UAV," *Flight International* 165, no. 4927 (March 30-April 5, 2004), 15.

[44] Ibid.

[45] Douglas Richardson and Linda Deer, "Creatures Great and Small," *Jane's Defense Weekly*, 21 July 2004, 46.

[46] "Sandia's miniSAR offers great promise for reconnaissance and precision-guided weapons," Sandia Laboratory News Release, February 18, 2004, on-line, Internet, available from http://www.sandia.gov/news-center/nes-releases/2004/def-nonprolif-sec/minisar.html.

[47] Ibid.

[48] Galaxy Remotely Piloted Vehicles, 23 February 2005, on-line, Internet, available from http://www.galaxyrpv.com/about_rpvs.html, n.p. Cost estimate provided by the website.

[49] Ian McFarlane, "Victorian Company to supply NASA with Space Vehicles," *Aerosonde: News and Events*, 23 February 2005, on-line, Internet, available from http://www.aerosonde.com/drawarticle/82.

[50] Robert J. Fontana, et al., *An Ultra Wideband Radar For Micro Air Vehicle Applications*, Published in Proceedings IEEE Conference on Ultra Wideband Systems and Technologies, May 2002, on-line, Internet, 2 January 2005, available from http://www.multispectral.com/pdf/Advances_Radar.pdf, 2.

[51] Ibid.

[52] Ibid.

[53] "MicroPilot to Unveil the World's Smallest UAV Autopilot Introducing the MP2028g," on-line, Internet, 10 January 2005, available from http://www.micropilot.com/news/Releases /MP2028g.html, n.p.

[54] Ibid.

[55] Department of the Air Force, *Implications of Emerging Micro- and Nanotechnologies*, (Washington D.C.: Air Force Science and Technology Board [Committee on Implications of Emerging Micro-and Nanotechnologies], 2002), on-line, Internet, available from http://books.nap.edu/books/030908623X/html/183.html#pagetop, 182.

[56] Department of Defense, *Unmanned Aerial Vehicles Roadmap 2002-2027* (Washington D.C.: Office of the Secretary of Defense, December 2002), 41.

[57] United States Air Force, *Unmanned Aerial Vehicles in Perspective: Effects, Capabilities, and Technologies,* prepared by the United States Air Force Scientific Advisory Board [SAB-TR-03-01], July 2003.

[58] Jimmy Ennett, *The Impact of Emerging Technologies on Future Air Capabilities* [DSTO-GD-0186], Australian Department of Defence: Defence Science and Technology Organisation, Science Policy Division, on-line, Internet, 6 January 2005, available from http://www.dsto.defence.gov.au/, 19. A "Gflop" is the ability of the system to produce 1 billion floating-point calculations per second.

[59] Department of the Air Force, *Implications of Emerging Micro- and Nanotechnologies*, (Washington D.C.: Air Force Science and Technology Board [Committee on Implications of Emerging Micro-and Nanotechnologies], 2002), on-line, Internet, available from http://books.nap.edu/books/030908623X/html/183.html#pagetop, 182.

[60] Jimmy Ennett, *The Impact of Emerging Technologies on Future Air Capabilities* [DSTO-GD-0186], Australian Department of Defence: Defence Science and Technology Organisation, Science Policy Division, on-line, Internet, 6 January 2005, available from http://www.dsto.defence.gov.au/, 17.

[61] Department of the Air Force, *Implications of Emerging Micro- and Nanotechnologies*, (Washington D.C.: Air Force Science and Technology Board [Committee on Implications of Emerging Micro-and Nanotechnologies], 2002), on-line, Internet, available from http://books.nap.edu/books/030908623X/html/183.html#pagetop, 201.

[62] Ibid., 202.

[63] Nanotechnology is the "application of nanoscience in order to control processes on the nanometer scale, i.e. between 0.1 nm and 100 nm." Available from http://www.nanoword.net/library/def/Nanotechnology.htm.

[64] Jimmy Ennett, *The Impact of Emerging Technologies on Future Air Capabilities* [DSTO-GD-0186], Australian Department of Defence: Defence Science and Technology Organisation, Science Policy Division, on-line, Internet, 6 January 2005, available from http://www.dsto.defence.gov.au/, 28.

[65] Department of the Air Force, *Implications of Emerging Micro- and Nanotechnologies*, (Washington D.C.: Air Force Science and Technology Board [Committee on Implications of Emerging Micro-and Nanotechnologies], 2002), on-line, Internet, available from http://books.nap.edu/books/030908623X/html/183.html#pagetop, 212.

[66] Dr. Michael Kramer, "Nanotechnology Aids the Advanced Energetics Program," Air Force Research Laboratory, on-line, Internet, 12 January 2005, available from http://www.afrlhorizons.com/Briefs/Mar03/MN0210.html.

[67] Department of the Air Force, *Implications of Emerging Micro- and Nanotechnologies*, (Washington D.C.: Air Force Science and Technology Board [Committee on Implications of Emerging Micro-and Nanotechnologies], 2002), on-line, Internet, available from http://books.nap.edu/books/030908623X/html/183.html#pagetop, 208, 211.

[68] Dr. Michael Kramer, "Nanotechnology Aids the Advanced Energetics Program," Air Force Research Laboratory, on-line, Internet, 12 January 2005, available from http://www.afrlhorizons.com/Briefs/Mar03/MN0210.html, 10.

[69] Department of the Air Force, *Implications of Emerging Micro- and Nanotechnologies*, (Washington D.C.: Air Force Science and Technology Board [Committee on Implications of Emerging Micro-and Nanotechnologies], 2002), on-line, Internet, available from http://books.nap.edu/books/030908623X/html/183.html#pagetop, 183.

[70] David Frelinger, Joel Kvitky, and William Stanley, *Proliferated Autonomous Weapons: An Example of Cooperative Behavior*, RAND Report, DB-239-AF (Santa Monica CA: RAND, 1998), xi-xii.

[71] Arthur Reyes et al., "Overview of the University of Texas at Arlington's Autonomous Vehicles Laboratory," 15 February 2005, on-line, Internet, available from http://www3.uta.edu/faculty/reyes/AVL/Default.htm, 5.

[72] Ibid., 7.

[73] Ibid.

[74] Dr Anthony Finn, Dr Kim Brown, and Dr Tony Lindsay, *Miniature UAV's & Future Electronic Warfare*, Australian Department of Defence: Defence Science and Technology Organisation, EW and Radar Division, on-line, Internet, 6 January 2005, http://www.aerosonde.com/downloads/Aerosonde_DSTO_EW.pdf, 2.

[75] Ibid.

[76] Ibid., 5-6.

[77] Harrison Donnelly, "Swarming UAVs", on-line, Internet, 22 February 2005, available from http://www.military-aerospace-technology.com/article.cfm?DocID=686, 1.

[78] Ibid.

[79] Charlotte Adams, "UAVs That Swarm," *Aviation Today*, 2005, on-line, Internet, available from http://www.aviationtoday.com/cgi/av/show_mag.cgi?pub=av&mon=1003&file=1003uav.htm, n.p.

[80] Ibid.

[81] Department of the Air Force, *Implications of Emerging Micro- and Nanotechnologies*, (Washington D.C.: Air Force Science and Technology Board [Committee on Implications of Emerging Micro-and Nanotechnologies], 2002), on-line, Internet, available from http://books.nap.edu/books/030908623X/html/183.html#pagetop, 203.

[82] "SilentEyes Micro UAV At Edwards AFB", *Space Daily*, 4 August 2004, on-line, Internet, available from http://www.spacedaily.com/news/uav-04zz.html, n.p.

[83] Mark Hewish, "Small but well equipped," *Jane's International Defense Review*, October 2002, 57.

[84] "SilentEyes Micro UAV At Edwards AFB," *Space Daily*, 4 August 2004, on-line, Internet, available from http://www.spacedaily.com/news/uav-04zz.html, n.p.

[85] "Laboratories-on-a-chip foil terrorism," *U.S. Department of Energy Research News,* 2003, on-line, Internet, available from http://www.eurekalert.org/features/doe/2003-11/dnl-lft031804.php.

[86] Aerovironment's Black Widow MAV is a Micro UAV in development for U.S. Army Soldiers. The MAV will be small enough to be carried by a single soldier.

[87] James M. McMichael and Col. Michael S. Francis, *Micro Air Vehicles - Toward a New Dimension in Flight*, Defense Advanced Research Projects Agency, on-line, Internet, 10 January 2005, available from http://www.darpa.mil/tto/mav/mav_auvsi.html, n.p.

[88] Charlotte Adams, "UAVs That Swarm," *Aviation Today*, 2005, on-line, Internet, available from http://www.aviationtoday.com/cgi/av/show_mag.cgi?pub=av&mon=1003&file=1003uav.htm, n.p.

[89] Ibid.

[90] Sam Wilson, Micro Air Vehicle Project Letter, *DARPA Tactical Technology Office*, 27 February 2005, on-line, Internet, available from http://www.darpa.mil/DARPATech2002/presentations/tto_pdf/speeches/WILSONTT.pdf, 1-2.

[91] John A. Tirpak, "The New Way of Electron War," *Air Force Magazine* 87, no. 12 (December 2004), 29.

[92] Dr Anthony Finn, Dr Kim Brown, and Dr Tony Lindsay, *Miniature UAV's & Future Electronic Warfare,* Australian Department of Defence: Defence Science and Technology Organisation, EW and Radar Division, on-line, Internet, 6 January 2005, http://www.aerosonde.com/downloads/Aerosonde_DSTO_EW.pdf, 1-13.

[93] Predator costs approximately $4.5million per vehicle while the Aerosonde is approximately $30,000 plus jamming system ($15,000) for a total of $45,000. This is just a comparison and by no means is it meant to be 100% accurate.

[94] Dr Anthony Finn, Dr Kim Brown, and Dr Tony Lindsay, *Miniature UAV's & Future Electronic Warfare,* Australian Department of Defence: Defence Science and Technology Organisation, EW and Radar Division, on-line, Internet, 6 January 2005, http://www.aerosonde.com/downloads/Aerosonde_DSTO_EW.pdf, 5-6.

[95] Timothy Coffey and John A. Montgomery, "The Emergence of Mini UAVs for Military Applications", *Defense Horizons,* no. 22 (Center for Technology and National Security Policy: National Defense University, December 2002), 3-4.

[96] Ibid., 3.

[97] Ibid.

[98] USAF, "AGM-88 Fact Sheet," 20 February 2005, on-line, Internet, available from http://www.af.mil/factsheets/factsheet.asp?fsID=75

[99] Lockheed Martin, "LOCASS Fact Sheet," 20 February 2005, on-line, Internet, available from http://www.missilesandfirecontrol.com/our_news/factsheets/LOCAAS-factsheet.pdf, n.p.

[100] Ibid.

[101] Sandra I Erwin, "Air Force Wants Missile Redirected Inflight", *National Defense Magazine*, May 2000, on-line, Internet, available from http://nationaldefense.ndia.org/issues/2003/May/Air_Force_Wants.htm .

[102] Mark Hewish, "Small but well equipped," *Jane's International Defense Review*, October 2002, 54.

[103] Scott R. Gourley, "From Hunters to Killers," *Armed Forces Journal*140, no. 12 (July 2003), 39-40.

[104] Ibid.

[105] Boeing Aircraft, *Boeing ScanEagle UAV Demonstrates Communications Relay Utilizing Harris' Secure Wireless Technology*, on-line, Internet, 13 January 2005, available from http://www.boeing.com/news/releases /2004/q4/nr_041221n.html.

[106] DARPA, "Airborne Communication Node," 20 February 2005, on-line, Internet, available from http://www.darpa.mil/darpatech99/Presentations/Scripts/ATO/REICHLEN.WE.txt.

[107] Department of Defense, *Unmanned Aerial Vehicles Roadmap 2002-2027* (Washington D.C.: Office of the Secretary of Defense, December 2002), 37.

[108] Ibid., 41.

[109] Ibid.

[110] Dennis Busnell, *Future Strategic Issues/Future Warfare [Circa 2025],* NASA Langley Research Center, July 2001, on-line, Internet, available from http://www.dtic.mil/ndia/2001testing/bushnell.pdf, 44.

[111] Ibid., 94.

[112] David Frelinger, Joel Kvitky, William Stanley, *Proliferated Autonomous Weapons: An Example of Cooperative Behavior*, RAND Report, DB-239-AF (Santa Monica CA: RAND, 1998), iii.

[113] Jimmy Ennett, *The Impact of Emerging Technologies on Future Air Capabilities* [DSTO-GD-0186], Australian Department of Defence: Defence Science and Technology Organisation, Science Policy Division, on-line, Internet, 6 January 2005, available from http://www.dsto.defence.gov.au/, 28.

[114] Department of the Air Force, *Implications of Emerging Micro- and Nanotechnologies*, (Washington D.C.: Air Force Science and Technology Board [Committee on Implications of Emerging Micro-and Nanotechnologies], 2002), on-line, Internet, available from http://books.nap.edu/books/030908623X/html/183.html#pagetop, 183.

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