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The Emergence of Mini UAVs for Military Applications

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Overview

The successes of the unmanned aerial vehicle (UAV) in Afghanistan most likely will accelerate the introduction of UAVs into the military force structure. What emerged in Afghanistan was a tiered observation-detection-targeting system consisting of spacecraft, the Global Hawk UAV, the Predator UAV, and often a spotter on the ground. However, in complex terrain, as in Afghanistan, and in urban situations, airborne assets may be needed much closer to the ground. A low-altitude tier of UAVs—mini UAVs—could serve such a purpose.

This paper provides a basic understanding of the aerodynamic scaling of mini UAVs and a sense of how their capabilities could be matched with specific missions. Mini UAVs have substantial limitations, but the low radar cross section, low infrared signature, low acoustic signature, and birdlike appearance of these vehicles, combined with the remarkable capabilities of miniaturized payloads, make them contenders for certain missions and potential valuable tactical assets.

A New Class of Aircraft

A class of low-altitude unmanned aerial vehicles (UAVs) is currently under development. Several desirable features in their composition warrant discussion. This class of fixed wing vehicles is larger than the micro UAVs that have received publicity in the past several years,[1] but substantially smaller than the Predator class UAV. This paper considers vehicles, henceforth called mini UAVs, that have wingspans ranging between 6 inches and 10 feet and that fly in the 20- to 50-mile-per-hour (mph) range (the aerodynamic regime typical of model airplanes and birds). While this regime is not glamorous, significant developments have occurred in recent years. The new class of aircraft is more capable and rugged than typical model airplanes but less capable than birds, especially in terms of control systems. These developments, plus the arrival of a variety of low-cost but capable payload technologies, make this a subject worthy of consideration.

Mini UAVs would be more vulnerable to attack and loss due to their low-altitude missions and could suffer high attrition rates. Thus, they would have to be inexpensive enough to be expendable while also capable of flying useful payloads. To meet these requirements, we believe that these UAVs would have to be small and electrically powered and use mass-produced, commercial off-the-shelf (COTS) technology. Electrically powered motors were chosen for the mini UAVs discussed herein because of their low acoustic signature, ease of start, reliability, and relative performance insensitivity to altitude and temperature. Although the internal combustion engine produces a higher thrust-to-weight ratio than does the electric motor, the benefits of electric motors are significant. Some experimentation in this regard has begun through programs such as the Marine Corps Dragon Eye program.[2]

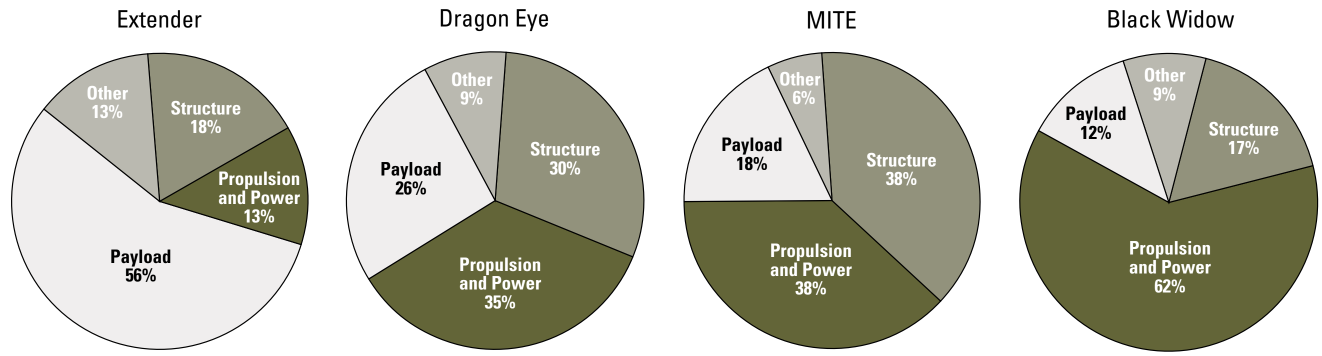
Aerodynamic Characteristics

To address the aerodynamic regime of interest, this paper examines five UAVs. The first three vehicles (Extender, Dragon Eye, and MITE) were developed by the air vehicles group at the Naval Research Laboratory.[3] The fourth vehicle was developed by the micro air vehicle design team at the University of Notre Dame.[4] The fifth vehicle, Black Widow, was developed by AeroVironment, Inc.[5] The physical characteristics of theses vehicles are summarized in table 1. All are electrically powered except for the Notre Dame one, which is included because detailed lift and drag data were available providing

Table 1. General Characteristics of UAVs

Unmanned Aerial Vehicle	Wing Span (inches)	Aspect Ratio	Weight of Structure	Maximum Gross Weight
Extender	122	11.35	5.76 lbs.	31.5 lbs.
Dragon Eye	45	3.75	1.5 lbs.	4.5 lbs.
MITE	18.5	1.85	4 oz.	10 oz.
Notre Dame vehicle	10	1	0.53 oz.	3.7 oz.
Black Widow	6	1	0.34 oz.	2 oz.

Figure 1. Weight Budgets for 20-Minute Flight



scaling to aspect ratio one. These data were not available for the aspect-ratio-one Black Widow vehicle.

For the purposes of this paper, we assume that the three design teams that developed the vehicles in table 1 have produced an optimized design for each aircraft. Our intention is to investigate the scaling of these aircraft as we vary the aircraft size and aspect ratio and determine how this relates to the payloads that this class of UAVs can carry for a specific mission and duration. As can be seen from table 1, the vehicles cover an order of magnitude range in wingspan and in aspect ratio and cover two orders of magnitude in vehicle weight. An immediate practical conclusion can be drawn from table 1 relating to the ability of these vehicles to fly autonomously. A competent, commercially available autopilot for low-flying vehicles will weigh from 4 to 6 ounces.[6] MITE and smaller size vehicles with their low weight restrictions will be hard pressed to undertake autonomous flight with present technology. Dragon Eye-class and larger mini UAVs have ample capacity to carry an autopilot, and we assume that they do in the remainder of this article.

Payload carrying capacity is key to assessing the mission capabilities of these vehicles. Figure 1 provides an estimate of the weight budgets for each electrically powered vehicle when sufficient battery power is provided for a 20-minute flight. Twenty minutes is selected because it begins to tax the smaller vehicles' ability to carry any sort of meaningful payload. Even for such short flight times, it is clear from figure 1 that power and propulsion begin to dominate the weight budget for the smaller vehicles.

Figure 1 shows that as one progresses from Extender to Black Widow, the available payload weight reduces almost 5 times more rapidly than the vehicle weight. For the smaller UAVs, the gross available payload weight of less than 7 grams severely limits the availability of useful sensors. It is also clear from figure 1 that one can trade battery weight for payload weight and vice versa. The maximum weight available for payload (W_m) is achieved when battery weight is reduced to zero and the maximum powered flight time is achieved when payload weight (W_p) is zero, with the payload being replaced totally by batteries. Assuming a linear variation between these two limits and using the data provided by the Naval Research Laboratory (NRL), we constructed figure 2, which estimates powered mission duration versus payload weight for each NRL vehicle. Data was not available for Black Widow, but it is expected to follow a curve similar to MITE. The Notre Dame vehicle was not electrically powered and therefore is not included in figure 2. Figure 2 is used in the following sections to examine various payloads that might fly on these or similar vehicles.

The term *powered flight* is used deliberately above. It will become clear in the following sections, as it does from figure 1, that powered flight duration will be very limited for the small, aspect-ratio-one vehicles. Increasing the reach of these mini UAVs will be necessary, and there are very desirable techniques to accomplish this. For example, these vehicles can undertake unpowered flight by gliding, providing an opportunity to increase range. From a 5-mile release altitude, the Extender has the capability for a 77-mile glide; the Dragon Eye, 37 miles; MITE, 34 miles; and Black Widow, 25 miles. Of course, technical issues connected with the release of the mini UAVs would need to be addressed.

These glide distances assume zero windspeed. Depending on windspeed and direction, the range could be reduced or extended. For some missions, the payload might be operated during the glide phase. Climb and glide strategies could be used for some missions due to ease of motor restart. Advanced strategies could exploit soaring for much longer duration in mountainous terrain, analogous to the seagull soaring stationary relative to a bridge updraft. One could speculate that under the right conditions, the aircraft might soar and windmill its props to generate direct current (DC) power from the DC motors. The mini UAVs could also be glided to rendezvous with users on the ground who would electronically capture and program them in flight for the local mission need.

The glide distance, therefore, is a definite factor to consider in the creative use of the mini UAVs. A "mother ship" might release the UAVs into unpowered flight at a safe altitude and distance from

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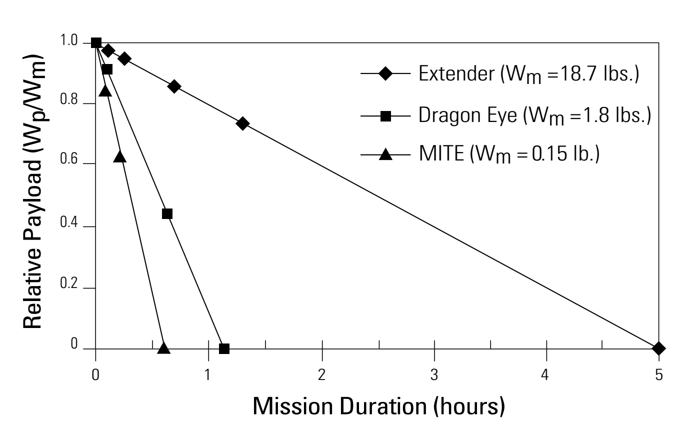
Figure 2. Payload vs Mission Duration



an area of interest that is reachable by gliding. Upon gliding to the mission area, the UAVs could then power up and undertake the desired mission. This scenario would exploit the ease of starting an electrically powered UAV as well as the small cross sections and low acoustic signatures. Depending on the mission, the UAVs might remain in contact with the mother ship. A variation on the mother ship approach would be to incorporate the mini UAV into a round that is fired from a gun or other launcher. When the round nears the end of its range, the UAV aerodynamically deploys and conducts its mission.

These scenarios assume that retrieval of the mini UAV will not be necessary. This requires an acquisition strategy that treats mini UAVs as expendable, much like the sonobuoys deployed by Navy P–3 aircraft. The use of COTS components would keep the price down and reduce the prospect of releasing sensitive technologies.

Since cost will be an issue regarding the employment of mini UAVs, we provide the following estimates for the cost to purchase the NRL vehicles in lots of 1,000 in a ready-to-fly state, but without the payloads: the Extender, $50,000; Dragon Eye, $10,000; and MITE, $700. The Extender and Dragon Eye numbers incorporate military frequency transceivers into the UAVs. The MITE class UAVs cannot carry the heavier, more capable military frequency transceivers and are priced assuming the incorporation of much lower cost COTS transceivers.

Proximity Effect and Radar Jamming

The general theme of this paper is that sensor technology, materials technology, power technology, and autopilot technology, including miniature high-accuracy global positioning system (GPS) navigation, have progressed to the point where rather small platforms can carry capable but inexpensive payloads and possibly accomplish meaningful missions. This offers the opportunity to place payloads close to targets and to benefit from this proximity. As a simple illustration, we consider the case of main-beam barrage jamming. In particular, we examine a recently developed jammer,[7] 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. This jammer could be flown in any of the UAVs discussed above in powered flight mode, except perhaps for the Black Widow. 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). If this were accomplished with a jammer standing off at 200 miles, then it would require an effective radiated power of 207 kilowatts, as compared with the 50 mW for the UAV-placed jammer.

The standoff jammer, of course, has some survivability advantage due to the standoff distance (however, new long-range missiles designed to attack such jammers may jeopardize this advantage). The price to be paid for this advantage is the need for large jammer power and a large aircraft. Additionally, high processing power is needed to handle the millions of pulses per second seen; great dynamic range is needed to handle weak distant sources and strong close sources; and high angular resolution is required to separate proximate emitters at great distance. Inadequate isolation between transmit and receive antennae means one must shut off the jammer briefly to detect signals. Modern radars can detect aircraft during this interval. Much of this is avoided for proximate jammers. If it were possible to place the jammer close to the target radar, then the power requirements would drop substantially. The advent of capable mini UAVs and technology opens possibilities in this regard.

The 50-mW case, of course, would be viable only if the jammer could be covertly placed 500 feet from the radar and turned on at the beginning of the attack. If one of the mini UAVs were able to accomplish this, then there could be a great cost advantage, since the small jammer package would be inexpensive enough ($50–$100) to be disposable. Indeed, if the covert placement problem were solved, placing a ring of small jammers around the target radar to mask a number of approach directions might be considered.

One way to accomplish this might be to have a Dragon Eye class vehicle carry approximately 10 of the miniature jammers discussed above. A 5-mile-high release would allow a 37-mile glide. Figure 2 shows that the UAV would have about 30 minutes of powered flight, allowing about 20 miles of flight. If the release were made in the dark, the UAV might be able to approach the radar at low altitude using its GPS navigation, circle the radar in a 500- to 1,000-foot radius, and precisely drop the miniature jammers, which could be either timed to activate or command-activated. After the drop, the UAV would fly some predetermined path until the power expired. If ground forces were within a few miles of the target radar, the Dragon Eye class UAV could be ground launched, fly the mission, and return to the launch point—obviating the need for a mother ship.

The case discussed above is extremely elementary, but it does illustrate that proximity, combined with inexpensive payloads, could be effective if the element of surprise can be maintained. The intrinsically low radar, infrared, and acoustic signatures of the mini UAVs may have some merit in this regard, and even modest attention to signature management might reduce these signatures below detectable levels at any range. Of course, the actual jamming scenarios would be far more sophisticated than that described above.

On the other hand, the general disposable character and proximity effect would be maintained. Also, if the radar were on a school, hospital, or mosque, hard-kill options might well be unacceptable, making the mini jammer approach even more attractive.

Optical and Infrared Payloads

In the previous section, substantial reductions in jamming power were achieved by placing the jammer in proximity to the radar being jammed. A similar situation develops in electro-optics. A nadir-looking camera flying 0.5-centimeter (cm) optics at an altitude of 100 meters (m) has the same spatial resolution as a camera with 30-cm optics flying at 6,000 m altitude. The obvious question is whether there are cameras that could fit into the UAVs discussed above. A search of the literature demonstrates that a wide variety of miniature cameras are available. There are miniature color video cameras on the market today in which the camera weighs about 2 grams, consumes about 150 milliwatts (mW) of power, and costs about $200, including the lens.

> **a very capable electro-optic/infrared payload could be placed on a Dragon Eye class or larger mini UAV**

There are also many S-band video transmitters that radiate about 100 mW of power, consume about 600 mW of power, weigh about 3 grams, and cost about $400. These transmitters have ranges for video detection of about 1 to 3 miles, depending on the receiver being used. Hence, at the low end, a color video camera with a 1- to 3-mile transmitter range will weigh about 5 grams without the batteries to power the camera. In order to estimate the payload weight, we need an estimate of the battery weight required to power the camera. For purposes of illustration, we assume the payload is powered by a standard 9-volt (V) lithium battery that weighs about 35 grams and can deliver 1,200 milliampere hours of current. We further assume that the weight of the battery required to accomplish a desired mission scales linearly with the required milliampere hours. For the case of the MITE vehicle, the maximum mission duration is, according to figure 2, 0.67 hours. Assuming a 9 V power supply, this payload would draw 83 milliamperes, leading to a requirement of 55.8 milliampere hours. From the assumption of linear scaling of battery weight, we estimate that this payload requires a battery weight of 1.6 grams or 0.06 ounces, leading to a total payload weight of 0.23 ounces. Since the maximum payload weight for MITE is 2.4 ounces, the ratio of payload to maximum payload becomes 0.09. In figure 2, we find that MITE could fly this payload for 37 minutes. Even if our payload weight estimate were underestimated by a factor of 2, the mission duration would still last 33 minutes. The Black Widow aircraft flew a similar payload for just over 30 minutes. Extender and the Dragon Eye UAVs could fly this particular payload for their maximum flight times.

A more capable video camera, which typically weighs 70 grams and requires 2.7 watts, clearly is not applicable to a MITE or Black Widow class UAV; however, it could fly on a Dragon Eye class vehicle. The Dragon Eye has flown with two such cameras mounted in it, one looking down, the other looking to the side. Repeating the calculation done above for these two 70-gram cameras flying on Dragon Eye, the powered flight time is 58 minutes. The images obtained from this class of camera on a Dragon Eye class UAV are of reconnaissance-level quality.

Considerable advances in the area of uncooled infrared cameras warrant notice. Indigo Systems recently announced the development of the UL3 infrared camera.[8] This camera, employing a 160-by-120-micro bolometer detector array, achieved a sensitivity of better than 80 MK using an F1.6 optic. The sensor weighs less than 200 grams, including the optics, requires a volume of 3 cubic inches, and also requires approximately 1 watt of power. It outputs analog video as well as 14-bit digital. The weight of this camera clearly precludes its use on MITE or Black Widow class UAVs, but Dragon Eye class aircraft should be able to fly the camera. Using the linear battery scaling, we estimate a required battery weight of 7 grams, leading to a total payload weight of 207 grams or 0.457 pounds. This produces a payload weight to maximum payload ratio of 0.253 and leads to a 54-minute powered flight time for the Dragon Eye vehicle.

The previously discussed small video camera could be added to this payload without substantially affecting the flight duration. Additionally, the two 70-gram cameras discussed above, if added to the UL3 payload, could fly on a Dragon Eye class vehicle for 39 minutes of powered flight. This combined electro-optic/infrared (EO/IR) payload could also be placed on Extender, which would have a nearly 5-hour powered flight duration. Large production runs likely will bring the cost of the UL3 camera down to several hundred dollars, making it expendable (assuming that there are no technology loss issues).

The examples above illustrate that a very capable EO/IR payload could be placed on a Dragon Eye class or larger mini UAV. At the Dragon Eye class, the cameras must be hard mounted to the airframe since no weight budget is available for gimbals and their control system. This means that the motion of the UAV will limit the quality of the image and the ability to do image processing. It should be noted, however, that the vehicles are inherently stable and have very low vibration levels due to electric propulsion. Although the angular rates at which they move about their axes are greater than those of larger aircraft, their distances from the targets are so much shorter that their images are surprisingly clear.

The imagery from this UAV class should be useful for reconnaissance. Its value for targeting depends on a number of factors. For example, if targeting quality data requires location to within 30 m, and the vehicle overflies the target vertically from 100 m and knows its location to about 7 m (available with undithered GPS) as well as its altitude, its proximity might well give targeting quality data. An Extender class vehicle should certainly be able to provide targeting quality data.

Chemical and Biological Surveillance

A topic of considerable concern today is a means for monitoring the release of chemical and/or biological agents. It is logical to ask if any of the mini UAVs might have a role here. As in the previous examples, small, commercially available, chemical agent detectors are now entering service. Some of these may be compatible with mini UAV use. Micro Sensor Systems, for example, has recently released a hand-held detector, HAZMATCAD, that detects and classifies chemical warfare agents, as well as industrial chemicals.[9] It uses both surface acoustic wave sensor arrays and electrochemical cells, and it also employs signal-processing techniques to provide low susceptibilities to false alarms. It detects the nerve and blister agents VX, GA, GD, GF, HD, HN3; the blood agents hydrogen cyanide and cyanogen chloride; and the choking agent Phosgene with a "fast response" mode of 20 seconds and a "sensitive" mode of 120 seconds. It has a data logging capability of 8 hours, recording alarm, level, time, and date. The basic instrument without batteries and case weighs about 7 ounces and costs about $8,000. While it is not suitable for MITE or Black Widow class air vehicles, it should fit in Dragon Eye.

For a Dragon Eye mission, the extra weight of the batteries to power this sensor can be ignored. Therefore, the payload would weigh 7 ounces, which is the same as the UL3 camera payload discussed earlier. Hence, Dragon Eye could fly the HAZMATCAD chemical agent sensor for 54 minutes or about 35 miles. This means it could sample a suspicious cloud 10 miles away and return with results or radio those results back to a receiving station. If a 30-minute mission could be settled upon, then, from figure 2, it is clear that about another half-pound of payload could be added. This could be a biological collection payload that collects samples at distances of about 5 miles and returns them to a laboratory for biological agent determination testing. The addition of the small video camera discussed above to this payload would have little impact on the mission duration. The resulting payload provides real-time in situ testing for chemical agents, real-time visible imagery, and remotely collected biological samples for laboratory testing. An Extender class UAV could fly this payload for several hours and cover more than 100 miles.

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As far as we know, there is no proven technology that can do an in situ determination of biological agents with a half-pound payload and report results via a communication link. There are, of course, antibody-based coupons that can detect biological agents and that could be read upon the return of the UAV. Devices capable of in situ detection and reporting have been built, but they are too large to fit on a Dragon Eye class vehicle. One such device is the RAPTOR, built by Research International in cooperation with the Naval Research Laboratory.[10] This device, when stripped of its casing and provided with batteries suitable for an Extender mission, weighs about 8 pounds. This leads to a payload ratio of 0.42, which, again from figure 2, shows that Extender could accomplish approximately a 3-hour mission. The agents that this device can detect include SEB, cholera toxin, ricin, plague, *Bacillus anthracis*, botulinum toxin, *Brucella abortus*, and *F. tularensis*.

We can imagine employing the mother ship approach in which Dragon Eye or Extender class vehicles with suitable chemical and biological detection sensors are transported large distances by another aircraft and then released at an altitude safe for the mother ship. The mini UAVs would then glide/fly to the area of interest, perform their measurement mission, and either radio the findings back to the mother ship or collect samples and fly them to a predetermined location. The Defense Threat Reduction Agency (DTRA) is operationally demonstrating the chemical portion of this concept as part of the Second Counterproliferation Counterforce Advanced Concept Technology Demonstration (CP2 ACTD).

The ACTD provides kits for the Air Force MQ–1 Predator UAV to employ two NRL Flight Inserted Detection Expendables for Reconnaissance (FINDER) mini UAVs (103 inches in wing span) along with a passive standoff sensor as part of the chemical combat assessment system. The two FINDERs are carried on the outboard wing hardpoints of a Predator UAV. The FINDER sensor payload weighs about 14 pounds and consists of dual ion mobility spectrometers and a sample collection subsystem. The mission is to detect, identify, track, and characterize chemical plumes that might result from strikes on adversary chemical weapon production and storage sites. The FINDER mini UAVs will be released from the Predator, fly into the plumes, and report their findings in near-real-time through the Predator air vehicle to a ground control station for distribution to the warfighter. The collected samples can be retrieved for laboratory testing and further exploitation and reporting post-strike. As a follow on, DTRA has formulated an ACTD to provide the biological solution called the Biological Combat Assessment System.

Signals Collection

The collection and interpretation of electronic signals are important aspects of modern military operations. Substantial resources, as well as very capable and elegant technologies, are routinely deployed in this quest. It is logical to ask whether the mini UAVs might have a contribution to make in this area. For obvious and valid reasons, much of what is done in this area is highly classified and would lie outside the scope of this article. Our objective is to stimulate a general discussion on the potential use of the mini UAVs rather than to design a solution to a particular problem. Therefore, to address the potential use of mini UAVs in the signal collection area, we illustrate with an elementary discussion of cellular telephone signal collection. Perhaps the simplest way to intercept cell phone signals is *with* a cell phone. A cell phone, after all, is a scanner, receiver, and transmitter. Each phone is identified by an electronic serial number (ESN) and a mobile identification number (MIN).

To use a cell phone, the ESN and MIN must be passed between the phone and a cell tower. When the information being passed is not encrypted, which is often the case, collecting the ESN and MIN is a straightforward process. Once these numbers are known, the cell phone collector can be instructed to report when a particular phone becomes active and then record the conversation associated with that phone. If the information is encrypted and the encryption algorithm has been obtained, then the same game can be played. If all else fails, one could simply record all cell traffic in a particular area and bring it back for processing. Today, flash memory cards are available that hold about 8 hours of cell phone conversation.

Since cell phone radio frequency (RF) sections without batteries and housing weigh only 15 to 20 grams, one could imagine a cell phone suitably reprogrammed and modified for cell phone signal collection flying on a small UAV. If the UAV flies at an altitude of 1,000 feet, then the area to which the vehicle has a line of sight is approximately 1,500 square miles. A collection made at 20,000 feet would cover a region about 30,000 square miles, while a collection made at 60,000 feet would cover 90,000 square miles. Although the higher altitude has an advantage, it also requires greater on-board processing power and dynamic range because of the increased traffic collected against. Additionally, more sophisticated collectors are required because of the reduced signal strength.

communication limitation is a serious restriction on the missions that the smaller mini UAVs can undertake

For certain applications in which there is interest in collecting cell phone signals in a small area, the mini UAVs might be useful. An appropriately modified cell phone could serve as the collector, presumably on a mission in which long duration is important. One would likely use an Extender class vehicle where several hours of collection could be made. Of course, if the UAV landed and then collected, it might do so for quite a while over a more limited region. Also, the UAV might call home literally via the targeted cellular network to deliver data or receive commands.

Other Considerations

We have seen that video transmission distances from small UAVs are typically a few miles. This requires a power investment of about one-half watt, and the transmission is omnidirectional. At the smaller end of the mini UAVs, the omnidirectional transmission is required because the vehicle is unable to house and point a directional antenna. Therefore, for these vehicles, the power required to achieve larger ranges will increase with the square of the distance. Achieving an order of magnitude increase in range will require two orders of magnitude increase in power (that is, 50 watts). This may be possible for the Extender class vehicles, but it is not available for the Dragon Eye class or smaller vehicles. At the larger end of the mini UAVs, the payload carrying capacity is sufficient to allow directional antennae, and enough power may be available to reach long distances and communication satellites. Under some circumstances, the smaller mini UAVs may be able to communicate to a mother ship, which would act as a communication relay. This is how the FINDER UAV communicates via Predator, which launches it. In other circumstances, it may be possible to communicate with other mini UAVs that could act as communication relays, but this option will not be viable in most applications envisioned here. This communication limitation is a serious restriction on the missions that the smaller mini UAVs can undertake.

The omnidirectional transmission is also a problem with the covert applications of these vehicles. Some attempts have been made to remove the transmission problem from the small UAV by placing the transmitters on the ground. One such approach has been discussed by Gilbreath et al., using the concept of the modulated retro-reflector.[11] The basic idea is to place a semiconductor optical switch based on multiple quantum well (MQW) technology in front of a retro-reflector that reflects an incoming laser beam back to its origin. The MQW has the property of blocking the transmission of the incident light when it is in its quiescent state. When a moderate voltage is applied to the MQW, the absorbance shifts, and light is transmitted to the retro-reflector, where it is sent back to its original direction. This allows a signal to be produced that can be encoded in an on-and-off keying format. In other words, an incoming laser beam can be encoded with information gathered by the UAV and sent back to its source where it is collected and decoded.

Each retro-reflector weighs a few grams (plus housing), has a field of view of about 20 degrees, and requires 15 to 50 milliwatts depending on the size of the multiple quantum well modulator. Five of these MQW devices properly arrayed give a field of view of about 60 degrees, weigh a few tens of grams (plus housing), and have a power requirement of 85 to 250 milliwatts. No gimbaled telescope or laser need be flown on the UAV. This burden is transferred to the ground or another platform where power and weight may not be such a problem. A 5-watt, 1,550-nanometer eye-safe laser will provide ranges of about 10 km in clear air and about 5 km in light rain. This system has been shown to achieve 10 megabit-per-second transfer rates.

In addition to potentially relieving the communications power problem for the smaller UAVs, a laser could provide for encryption and low observability of the communication signal. This approach, while promising, has a fundamental limitation in that the atmosphere, under the worst conditions in which one would likely fly a mini UAV, will limit the range to about 10 miles regardless of the laser power. Also, at the time this article was written, the data compression and encoding electronics weighed about 1 pound and required about 10 watts of power. This would limit this technique to an Extender class vehicle, which already has sufficient payload capacity to carry more conventional communications technology. If progress can be made to reduce the size and power requirements of the compression and encoding electronics, then the modulated retro-reflector could be useful for providing a stealthy communications link for the small mini UAVs to ranges of 10 miles or more. One might adapt the laser designator on, for example, Predator to perform this function as an alternative mode for some applications. The UAV could report its location via a low data rate channel to allow the required pointing by the Predator laser.

It is clear that mini UAVs with wingspans smaller than a few feet have very limited capability and flight duration. This makes it difficult to find meaningful missions. One application that may be worth consideration is that of leave-behind capability. Often, a military aircraft will spot something on the ground that it does not have time to investigate. The aircraft may also be painted by an electromagnetic field, such as a radar pulse, whose origin is not obvious but may be of concern. For example, through the use of camouflage and thermal signal suppression techniques, a prepared adversary can make it difficult for a high-flying imager to detect his presence. A small leave-behind mini UAV may be able to detect activity, which begins after the primary surveillance asset leaves the scene. Under these circumstances, it might be useful to be able to eject a small mini UAV to glide and fly to investigate the area of interest. The mini UAV payload may consist of a small GPS sensor, a small camera, or an electronic warfare support measures sensor, or a signal intelligence sensor and some limited communications capability, through which it intermittently transmits its location and a short description of what it has found. Low-power tracking technology such as that developed by Skybitz[12] for reporting the position of transportation containers may be useful here.

The most significant limitation on the mini UAVs is power supply. As one approaches the small end of the mini UAVs, power and propulsion become the dominant component of the weight budget. Improvements in the energy storage capacity of batteries would translate directly into increased payload or increased mission. Suggestions have been made to move from batteries to solid oxide fuel cells in which the energy density is at least twice that of today's batteries. One problem with this approach is that the solid oxide fuel cells operate at temperatures between 600 and 1,000 degrees centigrade. Isolating these fuel cells from the structure will undoubtedly introduce weight in an already weight-constrained environment. The fuel cells will also introduce a thermal signature not present with batteries. Currently, it is not clear that science or technology has a solution for the power problem. However, investment in military specific technologies that might not be commercially viable might have very high payoff in terms of mission capability. The need for a great advance here is even more urgent for the micro UAVs.

Additional Potential Uses

As examples of the potential uses of mini UAVs, this article discussed radar jamming, EO/IR imaging, chemical and biological detection, and cellular telephone signals collection. There are many more applications to which these vehicles can be put. Tables 2 and 3

Table 3. Countermeasures Payloads for Mini UAVs

Radar Jammers	Communication Jammers	EO/IR Jammers	Decoys and Deception	Navigational Denial
Smart jammers	PCS jammers deception	Detection denial	EO/IR decoys	GPS
Coherent jammers	Satellite receiver jammers	Imager disruption	Radar decoys	GLONASS
Preemptive jammers	Hand-held radio jammers	Trackbreak	False target generators	LORAN
Networked jammers	Denial of service	Coherent	Networked	Beacons
False target generators	Relay jammers	Incoherent	Clutter generators	
	TV/radio	LED based		

Table 2. Potential Sensor Payload for Mini UAVs *(read columns vertically)*

Electro-optic/Infrared Sensors	Acoustic Sensors	Passive RF/mm Wave	Radar	Relays/ Responders	Chemical/Biological/ Radiological	Others
Thermal		**ESM**	**Search/Track**	**Communications**	**Chemical**	
Long-wave	Imagers	FMCW detection	Microwave	Repeater	Collectors	Gravitational
Short-wave	Range finders	mm Wave receivers	mm Wave	Transponder	Analyzers	Meteorological
Sky-shine	Scanners	Superhetrodyne receivers	Impulse	Translator	**Biological**	Magnetic
Firing locations	Motion	Channelized receivers	Homing	Satellite	Collectors	Electric
Electro-optic	Shock wave	Unintentional radiation	Navigation	**Navigation**	Analyzers	
Intensifiers	Firing locations	PCS receivers	FMCW	GPS surrogate	**Radiological**	
Low light TV		Hand-held radio detectors	**Imaging**	Beacons	Collectors	
Color TV		**Radiometric**	SAR	Transponders	Analyzers	
Black and white TV		mm Wave imager	High resolution	**Tracking beacons/ Tags**		
Laser range finders		**Passive geolocation**	Through wall	Markers		
Laser imagers			**Bi-static**	GPS tags		
Laser velocimeters			Cell phone towers	Spectral		
Flow rate sensors			TV/radio			
			Radio illuminators			
			Special illuminators			

summarize where we believe some of these applications will be found in the area of sensors and countermeasures.

Each of the applications outlined in tables 2 and 3 requires a detailed tradeoff analysis among desired capabilities, class of mini UAV, and available technologies in order to lead to an optimal mission. Because of the relatively low cost of pursuing the mini UAV approach to the missions envisioned in tables 2 and 3, a "build a little, test a little" strategy would be quite viable.

The analysis and discussion in this paper is intended to provide the reader some rough sense of the scaling of the mini UAVs, the technologies that might be compatible with them, and some of the problems confronted by mini UAVs. Because of the serious constraints confronting the mini UAV, a very detailed and painstaking design is required that consistently makes the necessary tradeoff to construct a viable mini UAV. It should be clear that within the constraints of current technology, there are many missions that are simply not credible for mini UAVs. This is especially true for the smaller of the mini UAVs. However, the simple arguments and scaling presented here indicate that a carefully designed mini UAV built around carefully selected technology can conduct some important missions.

Conclusions

This paper has attempted to provide insights into what role mini UAVs might have in military operations. Major findings include the following:

- The power of proximity to the area of interest tremendously enhances the capability of mini payloads (for example, higher ratio of received power level of a jamming signal and the desired signal, lower receive sensitivity, fewer signals to process, lower required resolution for the same feature size).
- The ability to arrive at lower cost by drawing on commercial production quantities allows for expendability.
- The potential exists for extreme stealthiness and covert advance preparation of the battlespace.
- GPS allows precise autonomous navigation and position reporting for the mini UAVs, which are critical to the military application of these vehicles.
- Currently available technology offers useful surveillance, reconnaissance, and other missions for mini UAVs with wingspans of about 4 feet. Capability increases rapidly for wingspans greater than 4 feet.
- For mini UAVs with wingspans less than 2 feet, currently available technology appears to offer very few missions. However, there may be a limited leave-behind mission.
- Power technology appears to be the biggest problem inhibiting the mission capabilities of the mini UAVs. It is not clear that anything on the horizon will resolve this problem. A high-impact opportunity certainly exists for the investment of science and technology funds.
- Communications from the mini UAVs is a serious mission inhibitor, especially so for the smaller mini UAVs.
- The employment of mini UAVs from a mother ship shows promise in enhancing the capabilities of the mother ship and improving the communication prospects for the mini UAVs.

The aerodynamic regime of the mini UAVs is that occupied by birds. Birds have prospered for over 50 million years working out strategies for both short- and long-distance flights. While we have not discussed control systems here, it should be clear that by millions of years ago, birds had evolved control systems that are far more sophisticated and capable than those we have available for the mini UAVs. Perhaps the rapid advances in computer power, information storage technology, and artificial intelligence will provide an opportunity to narrow this gap. At the present time, birds have far more sophisticated control of their aerodynamic structures than do mini UAVs. They change the wingspan and aspect ratio at will and vary the location of center of gravity relative to the center of lift by shifting wing positions. Perhaps advances in smart materials will hold promise in this regard for future mini UAVs. Advances in biotechnology may also have a role to play. More than 100 years ago, modern aerodynamics emerged from studies of birds. It may now be time to return to the study of birds if we are to make the most of the potential offered by the mini UAVs.

Notes

[1] See J.M. McMichael and M.S. Frances, "Micro Air Vehicles—Toward a New Dimension in Flight," accessed at <www.darpa.mil/tto/mav/mav_auvsi.html>; and M. Hewish, "A Bird in the Hand," *Jane's International Defense Review* (October 1999), 22–29.

[2] "Sight for Corps Eyes," *Popular Science* 46 (December 2001); and "War in the Sky," *Popular Science* 46 (December 2001), 71–72.

[3] Private correspondence from the Tactical Electronic Warfare Division, Naval Research Laboratory, January 2002.

[4] G. Torres and T.J. Mueller, "Micro Aerial Vehicle Development: Design, Components, Fabrication, and Flight Testing," accessed at <www.nd.edu/auvsi>.

[5] J.M. Grassmeyer and M.T. Keennon, "Development of the Black Widow Micro Air Vehicle," AIAA–2001–0127 (1–9).

[6] See <http://www.micropilot.com>.

[7] Private communication from the Electronic Science and Technology Division, Naval Research Laboratory, February 2002.

[8] See <http://www.indigosystems.com>.

[9] See <http://www.raeco.com>.

[10] See <http://www.resrchintl.com>.

[11] G.C. Gilbreath et al., "Large-Aperture Multiple Quantum Well Modulating Retro-Reflector for Free-Space Optical Data Transfer on Unmanned Aerial Vehicles," *Optical Engineering* 40, no. 7 (July 2001), 1348–1356.

[12] See <http://www.skybitz.com>.

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