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# MICRO-AIR VEHICLES IN THE SERVICE OF AIR FORCE MISSIONS

by
Arthur F. Huber II, Lieutenant Colonel, U.S. Air Force

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Center for Strategy and Technology
Air War College

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Maxwell Air Force Base, Alabama

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## Contents

## Disclaimer

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## Tables and Illustrations

## Preface and Acknowledgments

What are the potential Air Force applications of emerging micro-air vehicle (MAV) systems and supporting technologies and what are the implications of this potential for the execution of military operations? These are the central questions that motivated the development of this research paper. As an Air War College (AWC) student in an elective class sponsored by the Center for Strategy and Technology (CSAT), I was afforded the chance to delve into this area, one that I have been watching with interest for several years. I have found this area to be of personal and professional interest, because it harks back to the aerodynamics research I conducted as a graduate student at the University of Notre Dame. Also, it opens up possibilities for enhancing the asymmetric advantages of air power enjoyed by the United States as compared with the rest of the world.

While I am solely responsible for the work represented by this research paper, it could not have come to fruition without the key contributions of several people. At the top of the list are my wife, Beth, and daughter, Juliann, who endured many late nights during which I worked away on this research. I am pleased to acknowledge the sage guidance and key insights provided by my CSAT advisors, Dr. Grant Hammond and Colonel (Ret., USAF) Ted Hailes. Several professionals in the field of micro-air vehicle development also deserve praise for reviewing this manuscript and they include Dr. William Davis and Mr. David Johnson of MIT Lincoln Laboratory, Dr. Thomas Mueller of the University of Notre Dame, and Dr. Steven Walker of the Air Force Office of Scientific Research. Lastly, I thank my fellow CSAT and AWC Seminar 3 classmates for their genuine interest in this research topic and their constructive comments to make it a better product.

## The Author

Lieutenant Colonel Arthur F. Huber, II, is a flight test engineer whose career has spanned various assignments within the weapon systems acquisition process. He holds Bachelor degrees in Aerospace Engineering and Government & International Relations as well as a Master of Science degree in Aerospace Engineering, all from the University of Notre Dame. He is a distinguished graduate of the Air Force Reserve Officers Training Corps and Squadron Officer School. He has served as an Air Force Fellow at RAND for in-residence Intermediate Service School, and is a recent graduate of the Air War College.

Lieutenant Colonel Huber started his military career assigned to the Air Force Space Technology Center as a staff plans officer, space-based surveillance technology program manager, and executive officer to the commander. While there, he was selected to attend Air Force Test Pilot School and graduated in June as a flight test engineer. He was then assigned to the 46th Test Wing where he was a branch chief while managing flight test activities for technology demonstrations, air-to-air missile development, safe separations, and avionics integration. While assigned to RAND, Lieutenant Colonel Huber performed policy research on military acquisition reform, counter-proliferation of weapons of mass destruction, laboratory quality measurement, and "reachback" operations. Subsequently, he transferred to the Pentagon where he performed duties as a Program Element Monitor for electronic warfare and air-to-air missile programs within the Office of the Assistant Secretary of the Air Force for Acquisition. Thereupon, he was selected to command the 413th Flight Test Squadron during its busiest period ever accruing over 2000 test hours per year in support of electronic warfare systems development and testing.

Lieutenant Colonel Huber has flown in multiple aircraft systems accruing approximately 100 hours in utility class planes and another 425 hours in high-performance aircraft to include the F-4, F-15, F-16, and T-38.

## Abstract

Technological progress in a number of areas to include aerodynamics, micro-electronics, sensors, micro-electromechanical systems (MEMS), and micro-manufacturing, is ushering in the possibility for the affordable development and acquisition of a new class of military systems known as micro-air vehicles (MAV). MAVs are a subset of uninhabited air vehicles (UAV) that are up to two orders of magnitude smaller than the manned systems that permeate our contemporary life. Recent advances in miniaturization may make possible vehicles that can carry out important military missions that heretofore were beyond our reach or could only be attained at great risk or resource expenditure. These missions will be possible if MAVs can fulfill their potential to attain certain attributes to include: low cost, low weight, little to no logistical "footprint," mission versatility, range, endurance, stealth, and precision.

A review of the literature in this area indicates that the military potential of this emerging field remains on the "technological push" side of the equation with little to no "requirements pull" from the user community. Accordingly, concepts of operations deriving from the war fighting community – particularly the United States Air Force (USAF) – are sparse. At a higher level, the potential of micro-air vehicles opens up new possibilities in the formulation of military strategies that require investigation. This paper provides an outline of the contemporary technological dimension of MAVs and contemplates how they might be used to enhance Air Force operations.

# I. Introduction

> *A two-ship of enemy fighters taxies to the end of the runway to conduct their last checks before take-off. Just as the aircraft rev their engines a handful of aircraft a bit smaller than model airplanes dive down from an altitude of 300 feet. Unseen by airfield observers because of their small size, these innocuous vehicles home in on the fighters' engine intakes using a combination of imaging infrared and acoustical sensors. Darting into the intakes they quickly cause foreign object damage and engine shutdown. There will be no glory in aerial combat for these fighters today.*
>
> *—A possible wartime scenario in the not too distant future*

There are many pressures on today's U.S. military. The variety and the nature of threats and other challenges expands daily. Potential adversaries get smarter all the time and their access to modern weaponry appears uninhibited. There is no reduction in operations tempo. The lag between cutting edge technologies and those installed in newly fielded military systems appears to be worsening, and efforts to contain costs meet with limited success at best.

That the U.S. continues to exercise its unqualified leadership in military matters around the globe in the face of such pressures is a tribute to its leaders' vision as well as the hard work and ingenuity of its people. The soundness of such leadership and its underpinnings are attested to by the preeminence of our nation's air forces, which more and more are being pushed to the "front lines" of conflict. They have become the weapons of choice for handling difficult duties throughout the world. Without taking anything away from the military people who make this preeminence a daily reality, it is no less founded on the superior war fighting capabilities inherent in our systems and technology. These advanced technologies provide an asymmetric advantage to U.S. forces, at least to the extent the U.S. acquires them first, and forges their incorporation into concepts of operation.

One area of technological advancement that holds promise to help the U.S. maintain its military leadership is the emerging field of micro-air vehicles (MAV). Technological progress in a number of areas including, but not limited to, aerodynamics, microelectronics, sensors, micro-electromechanical systems (MEMS), and micro-manufacturing, is ushering in the possibility for the affordable development and acquisition of this new class of military systems. MAVs are a subset of uninhabited air vehicles (UAV) that are roughly two orders of magnitude smaller than the manned systems currently in use. Recent advances in miniaturization may make it possible for very small vehicles to carry out important military missions that are either too risky or too expensive to conduct today. These missions should be possible if MAVs achieve the characteristic attributes of being low cost, low weight, having little to no logistical "footprint," mission versatility, range, endurance, stealth, and precision. Micro-air vehicles may represent a pioneering advancement providing the U.S. a new asymmetric advantage.

A review of the literature in this area indicates that the military potential of this emerging field remains on the "technological push" side of the equation with little to no "requirements pull" from the user community. Accordingly, concepts of operations deriving from the war fighting community – particularly the United States Air Force – are sparse. At a higher level, the potential of MAVs opens up new possibilities in the formulation of military strategies that require investigation. This paper undertakes to ask and provide answers to two essential questions: What are the potential Air Force applications of emerging micro-air vehicle systems and supporting technologies and what are the implications of this potential for the execution of military strategy?

To answer these questions this paper will start with a generic overview of what is unique about MAVs that makes their development inviting and how they compare to other UAV systems. Then, it will assess their potential and the interest in them and their applications within the Air Force, the other military services, and the civilian arena. Subsequently, a thorough review of MAV technologies will be presented followed by investigation of military functions they might fulfill and potential contexts in which they might be employed.

# II. Why Micro-Air Vehicles?

## What Makes Micro-Air Vehicles Unique?

MAVs are a subset of UAVs characterized by their relatively small size. With wingspans in the fifteen-centimeter range, MAVs have a number of advantages including the following:

- MAVs may be more amenable to a "faster, better, cheaper" approach to their development, procurement, and fielding
- It should be possible to design MAVs to have a small (even negligible) logistics footprint
- MAVs may afford a "commodity" approach to mission accomplishment either by enabling a variety of payloads to be manufactured for a single airframe or by proving flexible enough to permit payload variation in the field
- MAVs may prove a cost-effective augmentation to existing, low-density, high-demand systems
- MAVs may bring mission capabilities to smaller units that heretofore were not large enough to justify possession and operation of traditional systems providing such capabilities
- MAVs may afford the U.S. asymmetric avenues in the conduct of warfare

While the diminutive nature of micro-air vehicles makes possible their employment in a variety of military settings, it also comes with constraints that must be acknowledged and taken into account for proper tactical use. Likewise, the fact that MAVs can be found within a spectrum of UAV capabilities provides an onus to avoid redundancy and to optimally focus use on applications that leverage their unique characteristics.

Table 1 below provides a listing of the spectrum of UAVs and the relative place of micro-air vehicles within it.

# Table 1. UAV Classifications, Characteristics, & Examples

| Categories | Abbreviation | Data link Range (km) | Endurance (hours) | Maximum Flight Altitude (m) | Launch Method | Recovery Method |
|---|---|---|---|---|---|---|
| Tactical UAVs | | | | | | |
| Nano | | Unknown | Unknown | Unknown | Unknown | Unknown |
| Example Missions: speculative. Example Systems: none known. | | | | | | |
| Meso | | Unknown | Unknown | Unknown | VTOL | Belly Expendable |
| Example Missions: wide-area sensing (in swarms), planetary exploration. Example Systems: Mesicopter | | | | | | |
| Micro | µ | < 10 | 1 | 250 | H/HL/VTOL | Belly, skids Expendable |
| Example Missions: RSTA, comms relay, scouting, NBC sampling, EW. Example Systems: MicroStar, Hyperav+, Black Widow, Microbat. | | | | | | |
| Mini | Mini | < 10 | < 2 | 250 | HL/L/VTOL/ Wheels | Belly, skids Wheels Parachute |
| Example Missions: film and broadcast industries, agriculture, pollution measurements.<br>Example Systems: Aerocam, RPH2+, R50+, Rmax+, SurveyCopter. | | | | | | |
| Close Range | CR | 10-30 | 2-4 | 3,000 | HL/L/VTOL/ Wheels | Belly, skids Wheels Parachute |
| Example Missions: Recon, EW, artillery correction, mine detection, search & rescue.<br>Example Systems: APID+, Camcopter+, Cypher, Dragon, Javelin, Luna, Mini Tucan, Mi-Tex Backpack, Observer, Pointer, Vigilant, Vigiplane | | | | | | |
| Short Range | SR | 30-70 | 3-6 | 3,000 | L/VTOL/ RATO | Belly-skids Parachute/airbag |
| Example Missions: RSTA, BDA, EW, NBC sampling, mine detection<br>Example Systems: Crecerelle, Dragon, Eyeview, Fox, Heliot+, Mirach 26, Phantom, Phoenix, SoOJKY, Sperwer, Vulture | | | | | | |
| Medium Range | MR | 70-200 | 1 | 3,000-5,000 | L/VTOL/ Wheels/ RATO | Skids Wheels Para/airbag |
| Example Missions: RSTA, BDA, artillery correction, EW, NBC sampling, mine detection, comms relay<br>Example Systems: Brevel, CL327+, Eagle Eye+, Mucke, Outrider, Pioneer, Prowler, Ranger, Searcher, Seeker, Sentry, Shadow 200, Skyeye, Sniper | | | | | | |
| Low Altitude Deep Penetration | LADP | > 250 | 1 | 0.12-9,000 | RATO | Para/airbag |
| Example Missions: Recon. Example Systems: CL89, CL289, Mirach 100, Mirach 150 | | | | | | |
| Long Range | LR | > 500 | 6-13 | 5,000 | Wheels/ RATO | Wheels |
| Example Missions: RSTA, BDA, comms relay. Example Systems: Hunter | | | | | | |
| Endurance | EN | > 500 | 12-24 | 5,000-8,000 | Wheels/ Launcher | Wheels Para/airbag |
| Example Missions: RSTA, BDA, comms relay, EW, NBC sampling<br>Example Systems: Aerosonde, Hermes 450, Prowler II, Searcher II, Shadow 600, Super Vulture | | | | | | |
| Strategic UAVs | | | | | | |
| Medium-Alt. Long-Endurance | MALE | > 500 | 24-48 | 5,000-8,000 | RLG | RLG |
| Example Missions: RSTA, BDA, comms relay, EW weapons delivery<br>Example Systems: Altus, Hermes 1500, Heron, I. Gnat, Perseus, Predator, Theseus | | | | | | |
| High Altitude Long Endurance | HALE | > 1,000 | 12-40 | 15,000-20,000 | RLG | RLG |
| Example Missions: RSTA, BDA, comms relay, EW, boost phase intercept launch vehicle. Example Systems: GlobalHawk, Raptor, Condor | | | | | | |
| Special Purpose UAVs | | | | | | |
| Lethal | | 300 | 4 | 3,000-4,000 | Launcher/RATO/ Air-Launch | Expendable |
| Example Missions: Anti-tank/vehicle, anti-radar, anti-infrastructure, anti-ship, anti-aircraft<br>Example Systems: Harpy, K100, Lark, Marula, Polyphem, Taifun, Sea Ferret, MALI | | | | | | |
| Decoys | | 0-500 | <1 to few | 30-5,000 | Canister/ RATO/ Air-Launch | Expendable |
| Example Missions: Aerial and naval deception. Example Systems: Chukar, Flyrt, MALD, Nulka | | | | | | |
| Acronyms:<br>BDA: battle damage assessment L: launcher RSTA: recon, surveillance, target acq<br>EW: electronic warfare NBC: nuclear, biological, chemical VTOL: vertical take-off & landing<br>H: hand-launched RATO: rocket-assisted take-off<br>HHL: hand-held launcher RLG: retractable landing gear | | | | | | |

**Source:** adapted from Peter Van Blyenburgh, "UAVs – Where Do We Stand?" *Military Technology*, March 1999, 29-30. Used with permission from Monch Publishing, Bonn, Germany.

As can be seen from this table, micro-air vehicles occupy a niche very near the bottom run of UAV systems. MAVs possess wingspans in the range of fifteen centimeters (about six inches) as compared to the high end UAVs, which can have wingtip-to-wingtip measurements of up to 3500 centimeters, as in the case of Global Hawk. This represents over two orders of magnitude difference in size. Figure 1 below provides some perspective for this difference in scale. The horizontal axis in the figure uses "Reynolds Number" which is an aerodynamic scaling function directly proportional to size and speed. As shall be discussed later, the small size of MAVs has profound consequences for their design with regard to aerodynamics and systems integration as well as for their mission utility. The example missions listed for MAVs in Table 1 are verbatim from the table's source, but as shall be seen later, are only a partial listing of the possible mission set.

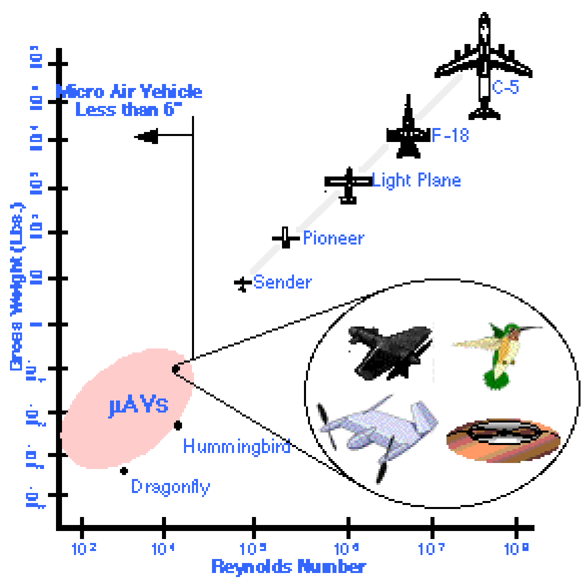


**Figure 1. Comparison of the Micro Air Vehicle (μAV) Flight Regime with Others[1]**

## What Is the Basis for an Air Force Interest in MAVs?

From a military point of view, micro-air vehicles are attractive for a number of reasons. The leading motive would appear to be the promise they hold in the realm of information operations, particularly support for intelligence, surveillance, and reconnaissance (ISR) before, during, and after events of interest. These functions will be executed through carriage and operation of miniaturized sensors, a key element of *Joint Vision 2020*.[2]

The goal here is greater battlespace awareness and reduced decision cycle times. To the extent MAVs contribute favorably to these goals, compared to other alternatives, their use in military contexts will appear inviting.

The USAF is fully on board with this Joint Staff vision. In *America's Air Force Vision 2020*, the Air Force leadership states,

> [W]e'll provide the ability to find, fix, assess, track, target and engage anything of military significance, anywhere. . . . Information superiority will be a vital enabler of that capability. . . . Capitalizing more fully on a set of revolutionary technologies – like stealth, advanced airborne and spaceborne sensors and highly precise all-weather munitions – we'll operate with greater effectiveness . . . With advanced sensors and a range of precise weapons, from large *to very small*, we'll be able to strike effectively wherever and whenever necessary with minimum collateral damage.[3] [emphasis added]

With this statement, the central importance of information superiority is acknowledged, while the solution space is left open to systems of any size that can get the job done.

Though such vision statements are necessarily broad in scope, the Air Force has made a limited number of pronouncements that are more specific in their endorsement of systems and technologies similar in kind to MAVs. In *New World Vistas Air and Space Power for the 21st Century*, published in 1995, the Air Force Scientific Advisory Board laid out predictions for technologies relevant to the future of the Air Force. To their credit, the Study Board members prefaced their predictions with an assumption on what the future combat environment will look like. To summarize, the Scientific Advisory Board foresees a smaller Air Force having to fight a long way from home, in urban and jungle terrain, against adversaries from the nation-state level down to terrorist cells, attacking a wide variety of targets from conventional weapons to information systems, and having to deal with nuclear, biological, and chemical (NBC) weapon threats. In order to help address these challenges, the study asserts that it should be a "goal" of the Air Force to "know at all times the relevant global military situation," and ensure "such awareness should be in near real time."

In addition to "Global Awareness," the study goes on to outline five other "capabilities" that it sees as necessary for the Air Force "to continue into the 21st century as the world's best and most respected" aerospace power and posits a number of system concepts to provide such capabilities. One "Global Awareness" system mentioned is a "miniature UAV" (itself carried aboard a "larger UAV") that could deploy ground sensors. Of the other five "capabilities," one has some relevance to MAVs, that being "Projection of Lethal and Sublethal Power." A system proposed in this vein is a "robotic micro munition" designed "to attack deeply buried hard targets." The study also identifies key technologies for development that will support its vision. Among those worth highlighting are micro-sensors having "novel readout methods" and "low probability of intercept" as well as "[m]icro-electromechanical systems for sensing and manipulating."[4]

One other official document which speaks to MAV-like systems resulted from an effort directed by the Chief of Staff of the Air Force known as *Air Force 2025*. This study outlined several "alternate futures" or environments to facilitate its strategic planning methodology and defined them as "an array of [possible] future worlds in which the U.S. must be able to survive and prosper." Within this context the study team identified ten "top systems" among forty-three envisioned, including a concept known as "attack microbots." This concept is described as

> . . . a class of highly miniaturized (one millimeter scale) electromechanical systems capable of being deployed en masse and performing individual or collective target attack. Various deployment approaches are possible, including dispersal as an aerosol, transportation by a larger platform, and full flying and crawling autonomy. Attack is accomplished by a variety of robotic effectors, electromagnetic measures, or energetic materials. Some sensor microbot capabilities are required for target acquisition and analysis. Microbots could provide unobtrusive, pervasive intervention into adversary environments and systems. The extremely small size provides high penetration capabilities and natural stealth.

In assigning this concept a role in future interdiction missions the study said, "Penetrating sensors and designators, coupled with micro-technology, will permit weapons to have the processing power required to 'touch' targets in the right spot."[5]

While not one of the "top 10," the *Air Force 2025* study also identified a concept known as "miniature unattended ground sensors" to support the intelligence, surveillance, and reconnaissance function. These devices would be air-dropped as a "swarm" in the vicinity of a "supply chokepoint and become a remote sentry reporting on enemy activity." In this capacity, miniature unattended ground sensors would help guide munitions as well as report on munitions effects. Predicting just how far the technology might advance, the study asserted that miniature unattended ground sensors of 2025 with a complete suite of communications and power capabilities, camouflage, and either motive or adhesive systems would be one centimeter square by one millimeter thick." It further stated that miniature unattended ground sensors would be "ideal for detecting weapons of mass destruction and operating in urban environments."[6]

To enable these and other concepts to become a reality, the *Air Force 2025* study identified six "high leverage technologies," which "stood out because they are important to a large number of high-value system concepts." Among these were "micro-mechanical devices" which has already been alluded to above as MEMS.[7] Such devices are sized on the order of hundreds of microns and represent fully functional mechanical machines – sometimes combined with electronic devices – and manufactured through lithography or similar techniques used in computer chip production. Given the centrality of micro-electromechanical systems to MAVs and other micro-robotic systems, their development should be viewed as a "critical path" item.

Another organization expressing interest in micro systems for Air Force application is RAND. While not an "official" source of Air Force opinion, RAND has nonetheless proven itself a significant influence over Air Force thinking in the realms of technology and policy. In *Technology Trends in Air Warfare* senior RAND analyst, Benjamin Lambeth, envisions "[m]icrosensor-directed micro-explosive bombs . . .able to kill moving targets with just grams of explosive." Additionally, he sees a time when "[g]round weather sensors can be delivered by small UAVs aboard larger UAVs."[8] Another RAND study, *Military Applications of Microelectromechanical Systems* (MEMS), posited a number of concepts to demonstrate how MEMS could have military utility. While none of them was specifically a micro-air vehicle type system in itself, each could be married up to a MAV to enable a useful mission. These concepts included the following:

- Chemical sensor for the soldier
- Identification friend or foe
- Active surfaces
- Distributed sensor net
- Micro-robotic electronic disabling system

The first concept, if carried aloft by a MAV, would allow remote sensing of noxious battlefield agents such as nuclear, biological, and chemical products. The second could be delivered by MAVs to facilitate targeting of enemy resources and avoidance of fratricide. The third could be a means at the subsystem level to enhance MAV aerodynamic performance. The fourth MEMS concept would "allow the commander to blanket an area [with micro-sensors] with a single shot, or to use micro-sized UAVs for seeding."

The micro-robotic electronic disabling system concept involves target attack and disabling via infiltration of the target's electronics. It would be dispensed in the general neighborhood of the target via carrier vehicle such as an UAV. The micro-robotic electronic disabling system would be contained within small canisters that would fly or glide (via "aerobot," parafoil, etc.) to within a short distance of their target(s). From there they would then move on their own to infiltrate and deliver the kill mechanism. Targets vulnerable to micro-robotic electronic disabling systems would include: power plants and relay stations, transportation grid nodes, airports, seaports, switching yards, major freeway intersections, television and radio stations, telephone exchanges, computer based research centers, and electronics at key industrial sites.[9]

As can be seen from this limited set of sources, the Air Force certainly has reason to be interested in micro-air vehicles. They hold potential to provide military worth by supporting "global awareness" and power projection operations. Despite such potential, there is only one dedicated research and development (R&D) program under Air Force sponsorship known to the author that is looking at how MAVs could be optimized for Air Force missions.[10] Instead, interest appears to be greater in other military circles.

## Who Else Is Interested in MAVs?

The Army, Navy, and Marines currently appear to be showing much greater interest in micro-air vehicles than the Air Force. Interest in these aircraft has also appeared from civilian quarters as well.

### Military

Currently, the bulk of U.S. R&D sponsored by the military in micro-air vehicle technologies comes from the Defense Advanced Research Projects Agency. They are now in the third year of a $35 million four-year program in which MAVs and supporting technologies are being developed and demonstrated.[11] This program can trace its roots back to two workshops hosted by RAND in the early 1990s in which several technologies were identified "warrant[ing] greater U.S. defense R&D investment." Among these promising program areas was development of "miniature (e.g., fly-size) flying and/or crawling systems capable of performing a wide variety of battlefield sensor missions."[12] Later, in the mid-1990s, the Massachusetts Institute of Technology Lincoln Laboratory did some technical analyses which pointed to the feasibility of MAVs. Not stopping there, they devised a conceptual design and presented it to then Vice Chairman of the Joint Chiefs of Staff, Admiral William Owens. Upon being asked if he saw potential utility in such a machine, the Admiral was impressed enough to encourage the Lincoln Laboratory researchers to continue their work in the field and to challenge his brethren in the naval R&D community to do the same.[13]

According to the Defense Advanced Research Projects Agency (DARPA) micro-air vehicle program representatives, a shift toward a more diverse array of military operations, often involving small teams of individual soldiers operating in non-traditional environments is already evident in the post-cold war experience." As a result, there is a need for small reconnaissance sensors to provide "greatly enhanced situational awareness for the small unit or individual soldier."[14]

The focus of thinking within DARPA is support for the "over-the-next-hill" and "around-the-corner" reconnaissance needs of foot soldiers either individually or in small units. Special operations units also function in small groups, often performing missions of extreme sensitivity and imminent danger. Thus, it is no surprise that the U.S. Special Operations Command saw fit to draft a "first operational requirements document for an MAV" in June, 1998.[15] The U.S. Army's Armor Center and the United States Marine Corps are also reportedly in the midst of drawing up requirements documents for MAV (or slightly larger mini-UAV) systems.[16]

The Naval Research Laboratory has cooperated extensively with DARPA on micro-air vehicle work, receiving funding from the latter, but has focused MAV payload work in a direction different than intelligence, surveillance, and reconnaissance. Instead, the Naval Research Laboratory has looked to MAVs to act as a means to carry out the suppression of enemy air defenses mission.[17] Their concept of operations has either foot soldiers or larger UAVs carrying the MAV to within several kilometers of the target. Then, it would fly autonomously with its miniature jammer package to a landing on the threat radar whereupon it would commence interfering with the radar signal. What the jammer lacks in power, would be compensated for by reduction in distance to the victim receiver.[18]

**Civilian**

It is difficult to gauge how much R&D is being conducted by commercial firms, insofar as almost all the literature dealing with the subject relates to military sponsored work. Even for efforts paid for by the military, the developers are quick to point out civilian applications for MAV systems. Dr. Samuel Blankenship at the Georgia Tech Research Institute (GTRI) foresees use of MAVs by police and fire officials, scientists, and farmers. Tasks might include killing harmful insects, measuring smokestack emissions, monitoring concentrations of chemicals in agricultural or industrial spills, surveying wildlife, and providing recreation as toys.[19] Still other possibilities mentioned include: traffic monitoring, border surveillance, forestry, power-line inspections, real-estate photography,[20] hostage crisis monitoring,[21] search and rescue (such as maneuvering through damaged buildings looking for survivors after a disaster), locating illegal drugs or weapons,[22] surveillance of criminal activities,[23] replacing weather balloons, serving as temporary antennas,[24] crowd monitoring and control,[25] home security, and the entertainment industry.[26]

In the aftermath of the terrorist attacks of September 2001, other uses of MAVs have come to the forefront. MAVs may be useful for homeland security and anti-terrorist applications to include detection of weapons, and tracking targets of interest such as personnel or shipments.

It appears that unlike other trends in defense related R&D, the tide has not yet turned for micro-air vehicle technologies. As a result, the military cannot yet depend on commercial interests to lead the way in development as has occurred in the microelectronics industry. Instead, the military will have to continue to provide the "seed" resources and leadership to promote advances in this area. Still, as shall be seen, enough progress may have been made over the past decade that more of the R&D burden can be shared between these communities in the future.

# III. The State of Micro-Air Vehicle Technologies

*We're at the Wright Brothers stage.*[27]

—Richard Wlezen
*DARPA's Acting Program Manager for MAVs*

The quote above from Richard Wlezen says a lot about the state of the art of micro-air vehicles, but it should not be misinterpreted to mean that useful military applications for MAVs are a long way away. Even in the case of the Wright Brothers, aircraft were flying military missions within a decade after their first flight in 1903. Despite the many technical challenges remaining for MAV development, "many people working on micro air vehicles . . . assert that the necessary technology is rapidly becoming available."[28]

If size is the driving parameter in micro-air vehicle development, what sorts of requirements exist in this vein? As it stands now, no "Analysis of Alternatives" has been conducted by any military department to provide a bounded trade space for mission performance requirements versus cost and technological feasibility. Lacking such guidance, the development community has had to make their best guess as to what this trade space should be. Accordingly, DARPA, in its current program, has set out the following goals:

- A dimensional limit of fifteen centimeters in length, width, and height
- An approximate vehicle weight of fifty grams[29]
- A useful payload weight of about twenty grams
- An endurance of twenty to sixty minutes
- An operating range out to ten kilometers
- A cruising speed of between ten and twenty meters per second[30]
- A unit production cost of $5,000 (near term) down to $1,000 (far term)[31]

The dimensional limit chosen by DARPA "was no accident" as both physics and technology considerations come into play.[32] As shall be discussed below, aerodynamic characteristics begin to diverge from the norm at this size and miniaturization of components becomes hard pressed as well. Furthermore, DARPA desired "to push the technology involved, on the grounds that this value [fifteen centimeters] 'is half a foot, and a foot looked too easy.'"[33]

It is self evident that a micro-air vehicle is a system composed of constituent subsystems. It is at this subsystem level that many of the technology challenges present themselves. That said, it is very important to realize that unlike many other, larger systems, MAVs present a rather difficult systems engineering challenge. This is because for MAVs to be successful, they will require "high degrees of system integration with unprecedented levels of multifunctionality, component integration, payload integration, and minimization of interfaces among functional elements."[34] Additionally, extremely constrained weight and volume limits and high surface-to-volume ratios mean the traditional practice of "stuffing more" into the airframe shell will probably not suffice. Instead, each of the MAV's components must perform as many functions as possible.[35] An example of this might be antennas embedded in the surface skin of the MAV providing signal reception as well as bearing structural loads. Beyond the surface, weight, and volumetric concerns; close coupled, dynamic electromagnetic and thermal interactions will be even greater issues than they are for larger systems.[36]

**Table 2. Baseline MAV Weight Distribution**

| Component | Weight in grams (ounces) |
|---|---:|
| Airframe | 6 (0.2) |
| Propulsion | 36 (1.7) |
| Flight Control | 2 (0.1) |
| Communications | 3 (0.1) |
| Visible Sensor | 2 (0.1) |
| Total Weight | 49 (1.7) |

**Source:** Adapted from W. R. Davis, et al., "Micro Air Vehicles for Optical Surveillance," *The Lincoln Laboratory Journal* 9 (1996): 197-214.

Despite the high level of integration and multi-functionality required, it is still useful to break out each major aircraft subsystem to discuss the progress made by and issues facing micro-air vehicle designers. Table 2 above provides an example breakout that reflects mid-1990s technological limitations in which propulsion weight (and most likely energy storage/conversion as well) dominates.

While this "component" or subsystem listing is a somewhat representative one, the discussion here will use a slightly different breakdown. To this end the following areas will be treated individually: aerodynamics, propulsion, energy generation and storage, guidance and navigation, communications, and finally payloads.

## Aerodynamics

Aerodynamic considerations for micro-air vehicles may motivate design engineers to move away from the conventional fixed wing to blended wing-body lifting shapes, rotary wings and maybe even flapping wings.[37] In any case, this area will be dominated by unusual flow phenomena and flight control challenges.

### Flow Character

For the flight regime in which micro-air vehicles operate, the dominating function is the Reynolds Number, an engineering scaling parameter that effectively describes the character of the flow in which an object moves. Reynolds Number is essentially the ratio of inertial forces to viscous forces that are developed as a vehicle moves through a medium such as air. The Reynolds Number is defined by the following equation:

$$\text{Reynolds Number} = \frac{\rho V c}{\mu}$$

where $\rho$ is the density of the fluid (air), V is the velocity of the vehicle, c is the wing chord length at mid-span (i.e., distance from leading edge to trailing edge), and $\mu$ is the viscosity of the fluid (again, air). For typical aircraft designs, the Reynolds Number ranges between 1 million and 100 million ($10^6$-$10^8$) and inertial forces (due to speed) dominate. However, given the small sizes and relatively slow speeds of MAVs, this parameter drops to between 5,000 and 80,000 where viscous forces hold much greater sway.[38] Under these conditions, the flow behaves quite differently and aerodynamic performance is much degraded. While the flow tends to remain laminar (i.e., smooth), it separates easily leading to stall, which is a major loss of lift and increase in drag. More generally, lift performance is rather poor in this regime and skin friction drag is elevated due to relatively large viscous forces. Thus, while MAVs are likely to see lift-to-drag ratios of about five to ten whether the system uses a fixed wing with propeller, rotor, or flapping wing design; higher Reynolds Number flight vehicles will possess lift-to-drag ratio values on the order of three to four times higher.[39] As one observer put it, flying at these conditions would be akin to swimming in honey if translated to the scales to which humans are accustomed.[40]

At low Reynolds Numbers, the unsteadiness in the free-stream velocity becomes more significant which means phenomena such as gusts can effect a small vehicle considerably.[41] Additionally, a characteristic known as hysteresis becomes a problem as well. Hysteresis is a performance anomaly in which the lift and drag developed by an airfoil (wing shape) vary at a given angle of attack depending on whether that incidence to the flow was approached from lower or higher values.

**Flight Controls**

Given these unusual flow phenomena, achieving efficient and stabilized flight is a significant challenge. The answer may lie in the pursuit of passive and/or active control strategies using micro-electromechanical system type devices to improve aerodynamic performance and control. For example, it may be possible to create and install tiny sensors and actuators to dynamically adjust the camber (i.e., curvature) and shape (i.e., profile) of the wing depending on the instantaneous conditions.[42] These miniature actuators could also be used to move control surfaces like rudders, ailerons, and flaps. Flow character over the wing could be controlled by sensor arrays that detect the shear stresses or fluid vortices at the wing surface coupled with flexible membranes or micro-flaps to affect the flow as desired.[43] Flow separation could also be mitigated employing such exotic approaches as air suction/injection along the wing surface (which might require micro-valves and micro-pumps), wall heat transfer, or electromagnetic body force.[44] Another proposed approach, called "circulation control," is to take advantage of what is known as the Coanda effect.[45] In this technique, engine thrust, or exhausted air, is directed across a wing surface or out the trailing edge so as to help the flow stay attached and generate additional lift.[46] Blown air could also be used for providing flight control to include stabilization and maneuvering, potentially obviating the need for moving control surfaces.[47]

Stabilization will require optimized design and integration of whatever sense and control schemes are employed. On the sensor side, angular rate, pressure, or acceleration transducers could be used to help provide stability augmentation. Micro-motors, piezoelectric devices, electrostatic or electromagnetic mechanisms, magnetoelastic ribbons, or Terfonol-d rods are all alternatives for performing the actuator function in a flight control system.[48] Flight controls will range from the straightforward to the complex, but even the least ambitious will require a microcontroller to implement the control scheme selected. In this vein, commercial devices will suffice for near-term micro-air vehicles, but those employing advanced concepts may require custom chips.[49] Processing for these control systems may use "soft computing" techniques that include fuzzy logic, neural networks, genetic algorithms, pattern recognitions, or knowledge-based systems."[50] The field of genetic algorithms, which uses "global parallelism" for search, optimization, and machine learning, holds much promise in this regard.[51]

## Propulsion

*The biggest challenge we need to overcome is propulsion.*[52]

—William R. Davis
*Massachusetts Institute of Technology Lincoln Laboratory*

Propulsion systems for micro-air vehicles will have to satisfy challenging requirements for high energy density and high power density. They will have to exhibit low vibration, so as not to interfere with payload operation such as imaging, and be acoustically quiet to assure covertness.[53] In general, it appears that near-term, fixed-wing MAVs weighing about fifty grams will require on the order of ten watts of electrical power, of which the propulsion system will consume about ninety percent.[54] To meet this demand, a variety of alternative technologies are possible to include: thermal-cycle machines (internal-combustion engines, pulse jets, and micro-turbines), electric motors, and reciprocating chemical muscles.

**Internal-combustion Engines**

Internal-combustion engines appear to be one of the best bets for near-term micro-air vehicle designs.[55] While their thermal efficiencies at MAV scales are low, only about five percent, their power densities are typically about one watt per gram and they use high-energy fuels.[56] Such engines have already been developed and put to use by model plane enthusiasts. One example is the Cox® Tee Dee® .010 which is only 0.01 cubic inch in volume and can produce about twenty watts of power. However, the high thrust specific fuel consumption (pounds of fuel per hour per pounds of thrust) of these engines will limit MAV range and endurance.[57] Furthermore, engines in this class do not meet requirements for weight, noise suppression, and reliability.[58] According to Lincoln Laboratory engineers, a fifteen-centimeter propeller-driven MAV with an lift-to-drag ratio of five will require about five watts of shaft power for climbing, turning, or hovering and about half that for cruising. Thus, such engines are relatively overpowered.[59] Lastly, internal combustion engines are also sensitive to low temperatures and humidity, which adversely affect starting. Restarting in the air also remains a major obstacle.[60]

**Pulse Jet Engines**

Pulse jet engines consist of hollow tubes with a flapper valve at the front end to admit air, a hole in the side for injecting fuel and a pair of electrodes to create a spark. These have the advantage of almost no moving parts. Researchers at Georgia Tech are working on pulse jet engines about the size of a "fat fountain pen" and have built a demonstrator. Nevertheless, a pulse jet compatible with micro-air vehicle requirements is still some years away. Using conventional fabrication approaches, weight remains an issue, and micro-electromechanical-system-based designs need to overcome high operating temperature limitations.[61]

## Microjets

A promising, but technically difficult, propulsion and/or power source is the microjet, a micro-electromechanical system based device about the size of a dime. These devices are based on micro-turbines that are characterized by high power densities, high flight speeds, and relative freedom from vibration. Despite such advantages, difficult design and production challenges must be overcome.[62] Fabrication techniques are a major hurdle, and air-bearing dynamics have been characterized as "uncharted territory."[63] Still, this technology could conceivably be available within a year or two.[64] The Massachusetts Institute of Technology Gas Turbine Lab is working on a silicon carbide engine that weighs one gram, is only one centimeter in diameter, and 0.3 centimeters thick, yet produces ten to twenty watts of power. A working combustor has been built, but the compressor, generator, and bearings have yet to be perfected at micro scales.[65] The program goal is for the engine to achieve a thirteen-to-one thrust-to-weight ratio.[66] Eventually, these ratios will approach 100:1, a full order of magnitude better than modern fighter aircraft engines, and fuel consumption rates of ten grams per hour should be possible using hydrogen fuel. Design challenges remain, however. To achieve the above goals, MIT's calculations indicate that the combustor exit temperature needs to reach 1,000 to 1,500 degrees Centigrade with rotor peripheral speeds of between 300 and 600 meters per second.

MIT is not the only one working in this area as the United Kingdom's (UK) Defence Evaluation and Research Agency (DERA) has successfully produced and demonstrated an early version of a microjet. Their device is 1.3 centimeters long by 0.5 centimeters diameter and weighs less than two grams. It uses a hydrogen peroxide-kerosene fuel mixture and has achieved 6.4 grams of thrust (thrust to weight ration of nearly four-to-one) with flight duration times of up to an hour. Starting and stopping the engine has proven simple and reliable.[67]

## Electric Motors

When paired with propellers on fixed wing designs or rotor blades on helicopters, electric motors are another propulsive option for micro-air vehicles. They are quiet, reliable and don't produce much vibration, but suffer the disadvantage of low power to weight ratio when coupled with batteries or other power-generation sources.[68] According to the NRL, small new motors using a brushless neodymium-iron-boron magnet design can achieve ninety percent efficiencies. A lightweight system based on a high-efficiency electric motor and top-of-the-line lithium batteries could run for twenty to thirty minutes. In its sponsored research, the NRL is working toward a pencil-shaped motor weighing less than six grams with a desired output power of two watts and a system efficiency of eighty percent.[69]

**Reciprocating Chemical Muscle**

Georgia Tech is pursuing a flapping wing design they have dubbed a "microflyer," but which others using similar approaches call an "entomopter" or "ornithopter" in reference to its insect-like or bird-like characteristics. This micro-air vehicle variant employs a reciprocating chemical muscle which uses a monopropellant fuel to generate an up and down or back and forth motion such as the beating of wings or scurrying of feet. Like the micro-turbine, the reciprocating chemical muscle can also be used to generate electricity that could be used to power sensors or other on-board systems. Georgia Tech researchers believe a "self-consuming" system is possible in which the microflyer would consume itself to generate energy as it flies. Alternately the reciprocating chemical muscle concept is even amenable to conversion of biomass into usable fuel reactions. Thus, future microflyers may be able to gather fuel from the environment to continue their operations.[70] A fifty-gram microflyer possessing a reciprocating chemical muscle with 100 percent efficiency would need just over a watt of power. One cubic centimeter of fuel would suffice for three minutes of flight.[71]

## Energy Generation and Storage

As was observed in the last section, internal combustion engines and micro-turbines can be used to convert liquid fuel into thrust and electricity for use by other subsystems. That said, whether the energy comes as a by-product of the propulsion process or from a separate dedicated on-board source, the relatively large amount of power that must be supplied to the propulsion system means less is available for other subsystems. Therefore, challenges for micro-air vehicle design are to generate and/or store sufficient energy within the tiny craft (i.e., attain high power density) and to adhere to strict power budget allocations. As far as energy source options, the two leading contenders appear to be lithium batteries and fuel cells with the former more likely to find near-term application. Beamed microwave energy is also being investigated.

Compared to a rechargeable NiCad battery of the same weight and at a high discharge rate, a lithium battery delivers several times the energy.[72] Nevertheless, lithium batteries need to advance in terms of energy density from 200-500 joules per gram to the range of 700-900 joules per gram. Likewise, power drain rates need to increase from the present level of 0.06-0.2 watts per gram to about 0.5 watts per gram to enable sustained climbing flight.[73] One recent advance of note is a new lithium battery that can be recharged by sunlight and which comes as a thin, flexible sheet. This configuration may allow the battery to double as the surface of a MAV."[74] One estimate is that this thin-film lithium battery technology could "provide enough power to allow one gram to hover almost five hours or fly ten kilometers and still retain eighty percent of its energy."[75]

While fuel cell technology is less mature, it should provide two to four times the energy density of a lithium battery. Fuel cells promise clean, quiet operation with instant start-up and cold-weather operation. They are also non-toxic and have virtually unlimited shelf life with no required periodic maintenance. DARPA is sponsoring development of a small, lightweight, one-time use, non-regenerative solid-oxide fuel cell roughly one centimeter tall and weighing just twenty-five grams. Such a fuel cell would run to completion once the reaction is started, last about one to two hours, and provide "all the power a MAV should need." All in all, this technology could be ready in the next few years.[76]

A last option is to dispense with on-board carriage of stored or generated energy and to beam microwave power to the micro-air vehicle from the ground. Obviously, the drawback to such a scheme is that it depends on a microwave source that must contain a variety of equipment including a transmission dish, tracking system, beaming equipment, and a transportation system.[77] Researchers at the Naval Postgraduate School are working on ways to beam power to a MAV. Included in their efforts is a multi-directional antenna able to beam energy to the MAV no matter where it is. They have demonstrated power transfer via microwaves using the body of the aircraft as an antenna and have resolved a number of safety issues. Next, they plan to show how MAVs can be powered using surface search radar systems that are commonly found in the Navy.[78]

## Guidance and Navigation

Guidance and navigation requirements for micro-air vehicles will depend greatly on the desired mission applications, the technology available, and the concept of operations. For example, if a "swarm" of MAVs is designed to share geo-spatial data, it could use such knowledge to develop situation awareness that a single MAV would have to develop by itself. If the goal is to make MAVs fully autonomous, such that they will be able to navigate inside buildings or under forest canopy, they will have to be able to use sensory data and on-board processing to avoid obstacles.[79]

Whatever the requirements, those working in this area currently see a combination of Global Positioning System (GPS) and inertial sensing as a minimum capability that will be necessary to meet most guidance and navigation needs. That said, the state of the art in GPS systems is that they are currently too large, heavy, and power-intensive to meet MAV needs. Inertial navigation systems require development of better low-drift micro-gyros and accelerometers.[80] Until such time as these challenges are met, MAVs may require real-time human interaction to provide vehicle stabilization and guidance. In time, however, more demanding MAV requirements will likely make continuous dependence on remote control less desirable.[81]

GPS systems are getting smaller, and are approaching a size useful to MAVs. Only a few years ago, GPS systems were not much smaller than about 7.5 centimeters, operated on a minimum of 0.5 watts of power, possessed antennas weighing twenty to forty grams and required substantial data-processing power.[82] However, since then the trend has been toward greater integration of navigation, guidance, and control on a single board with the goal to get it on a single chip.[83] This will help enormously in meeting micro-air vehicle size, weight, and power constraints. Greater autonomy could also be facilitated if the MAV were endowed with a geographic information system to provide a map of the terrain and/or infrastructure layout.[84]

The guidance and navigation area is one in which micro-electromechanical systems could be the saving solution. Micro-electromechanical system pressure sensors are being used as altimeters for hang-gliders, and the auto industry is seeking to use micro-electromechanical systems in cars as part of an inertial navigation system, which would calculate the vehicle's coordinates relative to its starting point.[85] According to one source, two new micro-sensors – a hinged torsional resonator and a micro-gravity force-balance – will allow micro-electromechanical system accelerometers to be used in navigation and guidance systems in airplanes and missiles.[86] Under DARPA sponsorship, Sandia National Laboratories is scheduled to complete the development of an autopilot/guidance package weighing fifty grams in 2002. Sandia's "MicroNavigator" is supposed to integrate the electronics for gyroscopes, three-axis accelerometers, a GPS receiver and the associated processing on to a single silicon chip. Another DARPA-sponsored effort is to result in an ultra-wideband altimeter and obstacle-avoidance sensor that weighs forty grams, draws "little" power and is capable of resolving distances to less than thirty centimeters.[87] Eventually, extremely small-scale GPS units could even become a possibility using micro-electromechanical systems. One ambitious future concept proposes "centimeter-level position sensing using carrier-phase differential GPS" with a flight system weight on the order of one gram.[88]

A completely different alternative for flight guidance and navigation could be in the field of "optic flow sensors." Successes achieved to date in this field have made these sensors a possibility for providing "small-scale navigation capability" for micro-air vehicles. These sensors are based on the principle of "optic flow," which "refers to the speed at which texture moves in an image focal plane as a result of relative motion between the observer and objects in the environment."[89] Optic flow sensors could be used for flight stabilization in the same manner as a gyroscope and are capable of being configured to determine altitude or perform wall "flanking" as a means of obstacle avoidance. Similar to wall flanking is flying down the center of a tunnel or hallway.[90]

## Communications

Many projected micro-air vehicle missions require that the MAV be able to communicate with someone for flight control and/or return of data. These communications will occur with the MAV as the originating source or serving a relay function. While the simplest form of communications link is a direct line-of-sight system, there are situations beyond or below line of sight in which there would be need of some sort of overhead communications relay – either a satellite or another vehicle.[91] Line-of-sight limitations impose severe constraints for military operations in urban terrain, so other approaches, such as cellular communications architectures, will have to be found.[92] Whether line-of-sight or over-the-horizon, a number of missions will require secure links which complicates the engineering design and operational trade-offs.[93]

The principal communications challenges are due to the small size of the micro-air vehicle, which forces the use of small antennae and limits power. Thus, the communications subsystem is one that will likely be heavily integrated with other subsystems. Wings and other airframe components may serve as antennae. The limited power budget creates challenges for omni-directional transmissions which will need to be somewhere in the range of two to four megabits per second.[94] Microwave frequencies will be attractive for this application because of their high data bandwidths and their wavelengths of only a few centimeters, which translates into small antenna size. As it stands now transmission ranges are on the order of a couple kilometers but this should improve in time such that ten kilometers will soon be possible.[95] As an example of progress in this area, the MicroStar program sponsored by DARPA is developing a digital datalink that will provide a range of four to five kilometers while supporting a one megabit per second transmission rate and using only about 200 milliwatts of power.[96]

## MAV Payloads

The number of useful military functions a MAV could perform is limited only by the ingenuity of designers and the pace of technological improvement. Such promise is magnified by the inherent flexibility of the MAV concept itself. In those cases where the need for subsystem integration is not too great, MAVs could be built to allow swap out of some payloads for others in the field. While the number and variety of possible payloads is numerous, this section will focus on what has been described beyond the stage of a simple concept. Other proposed payloads will be mentioned but not elaborated upon.

### Imaging Sensors

The intelligence, surveillance, and reconnaissance function is probably the leading driver behind the first generation of micro-air vehicles because of its military utility and the maturity of the supporting technologies. "Chip-on-Flex" technology is being employed to miniaturize payload electronics packaging significantly.[97] Both tiny charge-coupled-device array cameras and infrared sensors can support applications for day/night imaging to sufficient quality to meet mission needs today. Miniaturization has advanced to the point that researchers at Oak Ridge National Laboratory have created a camera lens smaller than a coat button.[98] An off-the-shelf, one-inch long 300 x 240 pixel, black and white video camera weighing 2.2 grams and including a converter for standard National Television Systems Committee output, has flown. A fifteen-gram color camera with a 2.4 gigahertz downlink transmitter has also been demonstrated.[99]

Another program plans a 512 x 512-pixel day/night camera that can be set to take thirty frames per second or freeze frames once per second.[100] This capability should prove particularly useful considering recent experiences in the Balkans with UAV operations. When Predator UAV imaging was first made available, fighter aircrew were provided full-motion video in which the total delay between the real-time event and image presentation was only 1.5 seconds. However, after working with this capability, aircrew showed a preference for freeze-frame images updated every few seconds. This allowed them to better orient themselves on the target as they began their attacks and to obtain battle damage assessments within a few seconds of their weapons impact on or near the targets.[101] This human factors consideration should allow "engineering and operational cleverness" to create significant reductions in imager power requirements through adjustment of video frame rates.[102]

Still another example is the "Black Widow" micro-air vehicle that is reported to have carried "the smallest video camera ever flown on a remotely piloted aircraft."[103] The Black Widow was equipped with a commercial low-resolution, "sugar-cube-sized" video camera that weighed two grams. The MAV's builders were able to greatly reduce the camera's size and weight by integrating the support logic with the camera's lenses in contrast with traditional digital systems that consist of a charge-coupled device imager wired to four or five support chips.[104]

The near future could see a visible-light camera, occupying a volume of one cubic centimeter and weighing less than one gram. Such a camera has been designed by Lincoln Laboratory and would be based on a silicon charge-coupled device. It would have an aperture of approximately one-tenth of an inch across, contain 1,000 x 1,000 pixels, and produce an image every two seconds using as little as twenty-five milliwatts of power.[105] By providing an angular resolution of 0.7 milliradians with a million pixels, this camera could produce high-definition television quality images that would enable viewers to tell the difference between a tank and a truck.[106]

The Jet Propulsion Laboratory (JPL) at the California Institute of Technology is also pushing the state of the art in miniature solid-state imaging sensors. JPL has developed ultra-low-power active pixel sensor technology that rests on the commercially available complementary metal-oxide-semiconductor device fabrication process. This process allows many components performing different functions to be integrated on a single chip thus producing cost savings and making possible reductions in system power consumption by a factor of anywhere from 100 to 1,000.[107]

### Nuclear, Biological, and Chemical (NBC) Agent Sensors

The common wisdom is that biological and chemical agent detectors will require substantial development before they can find application on micro-air vehicles. The anticipation is that "gradient biochemical sensors . . . will be able to map the size and shape of hazardous clouds and provide real time tracking of their location."[108] Cited as proof of the challenges ahead, is that airborne chemical sensors now weigh about five kilograms while biological sensors of acceptable military utility and suitability have yet to be fielded.[109] However, the situation may not be so bleak as at first appears. Sandia has unveiled on-going work developing its "Lab on a Chip" which essentially is a miniaturized microchemistry lab that will be capable of collecting, concentrating, and analyzing chemical and biological agents "weighing less than a single bacterium." According to Sandia's managers, the miniature labs should be available within the next decade.[110]

Research on chemical and biological sensors is also in progress at Georgia Tech. There,

> [t]he prototype chemical and biologic sensors are basically small chips of glass with optical wave guides fabricated on their surfaces which can trap and manipulate light. On the most basic level, the sensor would have two channels: sensing and reference. When a laser beam is passed under the strips, the phase of the light contained in the guides is altered by the change in refractive index that occurs when the sensing channel interacts with the chemical or biological species it is designed to measure.

> The information contained in the light is read after the laser beams passing under the sensing and reference channels are combined to generate a unique interference fringe pattern, which moves past a solid-state detector array in proportion to the phase change that has been caused by the sensing interaction. . . .
>
> [U]p to two dozen channels [can be put] on a sensor chip to determine what [an MAV] is flying through. . . .
>
> Already small (about 1 centimeter by 2 centimeters), the sensors will need to be further reduced.[111]

Little has been said in the literature about any progress in miniaturization of radiation sensors that would enable characterization of nuclear environments. Such environments could come about as the result of the explosion of a nuclear device or damage done to a nuclear weapons facility. Should it be possible to sufficiently miniaturize a sensor for such a mission, it will most certainly find its way on to a micro-air vehicle.[112]

## Targeting, Tagging, and Identification Friend or Foe (IFF)

Use of micro-air vehicles for the functions of targeting, tagging, and identification friend or foe has been mentioned, but little information appears available about what the state of technology is in this regard.[113] The U.S. Army Dual Use Science & Technology program has proposed a micro-laser rangefinder and designator, as part of a more extensive "micro drone" payload.[114] A radio-frequency tag would presumably be similar in technology to a communications payload, but attributes of low probability of intercept (LPI) might be necessary when it is used for strike mission applications.[115] Since a radio-frequency tag used in this context is essentially a homing beacon, a LPI capability would mitigate against discovery and removal before a strike attack is completed. Lastly, a variant of a tag could be used for IFF purposes to aid in sorting friendlies from the enemy on a chaotic battlefield. An IFF system would essentially be different from a tag in its ability to remain quiet until responding to an interrogation.

## Explosives and other Lethal Payloads

Although the diminutive size of micro-air vehicles does not inspire thoughts of their use as explosives delivery platforms, it is possible.[116] The Air Force Research Laboratory currently sponsors work in lightweight, high-energy explosives technology, which could lead to munitions suitable for delivery by MAVs. It does not necessarily take a lot of explosive energy to severely damage a "soft target" like a surface-to-air missile tracking radar if it is hit in the right place. Some observers have also proposed MAVs as aerial mine-laying platforms, which could have lethal consequences for individual personnel or debilitating effects on light vehicles.[117]

One way a micro-air vehicle could deliver a lethal payload would be to employ poisons of various kinds. Poisons could take the form of a sting or needle in which a toxin is injected into the victim or a dose introduced into something more widely distributed like a city water supply.[118] Such payloads would have the advantage of being passive, lightweight, and involve available technologies for manufacture, storage, and injection. However, such options are not compatible with U.S. moral sensitivities at least absent an earnest attempt at warning.

## Electronic Warfare Payloads

Micro-air vehicle payloads for electronic warfare functions are a serious possibility. The NRL is sponsoring work to develop a fourteen-gram radar-jamming payload. The concept behind this approach is that the mission MAV would be delivered to the vicinity of the target by a larger, longer-range aircraft whereupon it would then seek out and fly to a victim radar. Then, the MAV would land on the radar near its receiver(s) and transmit its jamming energy. What the MAV would lack in transmit power would be made up in reduced range.[119] There is no reason a similar approach could not also be used to jam radio frequency communications systems.

With signals intelligence payloads, micro-air vehicles could assist in enemy electronic order of battle determination to include emitter types and locations. It would take several intelligence MAVs to perform emitter location through the time-difference-of-arrival technique, but this would require extensive avionics miniaturization and access to a good time standard, perhaps through GPS.[120] Another possibility is a MAV payload optimized for communications intercept to assist in intelligence activities by capturing emission externals (frequency, waveform, etc.) or internals (voice, data, etc…).[121]

### Sniffing Sensors

Still another set of potential payloads includes microelectronic "sniffers." These payloads could be used to uncover the existence of conventional explosives such as mines, nuclear, biological, and chemical weapons, or illegal drugs.[122] One proposal even has sniffers being developed to "track individuals by their scent alone."[123] However, little exists in the literature to describe how such payloads would work or if it is reasonable to predict that they will be available any time soon for integration on MAVs.

### Acoustic Sensors

While the details on the workings of acoustic sensors for micro-air vehicle applications are slim, there is evidence of progress in this area. For example, the Small Business Innovative Research program within the U.S. Army is sponsoring work to "develop an inexpensive micro-acoustic sensor for UAVs that would detect and identify ground vehicles and provide their location." Although a bit large by MAV standards, the sensor would be similar in size and cost to a commercial pager and would possess a range of several kilometers.[124] Work sponsored by DARPA developing the "Microbat" MAV is also reported to include an option to fly a test vehicle fitted with a microphone array for "acoustic homing on sounds."[125]

### Other Payloads

Two other areas where specialized payloads could be placed on micro-air vehicles include applications supporting combat search and rescue, and weather measurement. One proposal has MAVs being packed into the ejection seat mechanisms of high-performance aircraft, which would deploy as the aircrew parachutes to Earth.[126] Alternatively, a MAV could be placed in aircrew survival gear for hand launch after parachute landing. These MAVs could carry signal sources, imaging sensors, or communications relay packages. However, none of these applications requires technologies inherently different than that discussed above.

Weather sensor payloads have also been proposed.[127] This concept involves distributing micro-air vehicles across an area of interest with each possessing specialized sensors that would measure one or more specific parameters such as pressure, temperature, winds, humidity, etc…. Weather MAVs could begin their measurements while airborne or after landing, and continue reporting until energy for measurement and communications was no longer available.

Weather payloads appear particularly well suited for use of miniaturized transducer and micro-electromechanical system technologies. Indeed, it appears feasible to fly a weather MAV within the next few years, though its communications range will initially be limited. One reason for such optimism comes from the strides being made in the "Smart Dust" program whose goal is to "demonstrate that a complete sensor/communication system can be integrated into a cubic millimeter package." This work, funded by DARPA, has demonstrated a cubic inch weather package (temperature, humidity, pressure, light intensity, and magnetic field sensors) with a laser transmitter that provided one week's continuous operation and the ability to report its measurements over a twenty-one kilometer distance. While continued work is required to achieve even greater levels of miniaturization, research into "distributed algorithms" is also necessary to achieve "sensor fusion," that is, a melding of the all the data collected over an array into a useful summary.[128]

# Chapter 4

## Micro-Air Vehicle Support to USAF Functions and Likely Employment Contexts

In Air Force Doctrine Document 1 (AFDD 1), the functions of "Aerospace Power" are listed and described.[129] Micro-air vehicles would appear to support many, but not all of these functions and in the listing below, those holding promise are indicated by an asterisk (*).

- Counterair (including Offensive* and Defensive Counterair)
- Counterspace (including Offensive and Defensive Counterspace)
- Counterland (including Interdiction* and Close Air Support*)
- Countersea
- Strategic Attack*
- Offensive* and Defensive Counterinformation*
- Command and Control*
- Airlift/Spacelift
- Air Refueling
- Special Operations Employment*
- Intelligence,* Surveillance,* and Reconnaissance*
- Combat Search and Rescue*
- Navigation & Positioning
- Weather Services

Each asterisked item above will be defined and discussed in turn to investigate how MAVs could play a potential future role in Air Force functions across the spectrum of military operations. (The definition of each term presented here is as given in AFDD 1.) But before doing so, it is necessary to address a number of MAV limitations that could have significant effects on how well these functions are performed. These limitations should be kept in mind in any discussion of potential MAV applications.

## MAV Operational Limitations

The most obvious limitations to micro-air vehicle capabilities will be in range, autonomy, precision, endurance, damage potential, and from weather. Ways to mitigate these limitations will have to be found if MAVs are to achieve their full promise.

### Range

The limited range of Micro-air vehicles requires these vehicles to be delivered to the vicinity of their desired operating locations. To this end a number of alternatives have been proposed. MAVs could be dispensed by manned aircraft, larger UAVs (to include cruise missiles), or munitions. This concept is similar to the new Low Cost Autonomous Attack System by a tactical munitions dispenser.[130] Another alternative is to package MAVs for delivery via artillery rounds such as 120-millimeter mortar tubes or 155-millimeter howitzers in much the same way that the Army's Tactical Missile System delivers Brilliant Anti-Tank rounds over large distances.[131]

Micro-air vehicle ranges will also be constrained by inherent transmission and reception limitations. Small antenna and miniaturized avionics will necessitate MAVs having to remain close to their launch controllers and/or intended recipients of video or other data. Enemy jamming could prove problematic given their power advantage. One way around this constraint would be to use MAVs in swarms wherein communication ranges are decreased through use of point-to-point relay. Alternatively, a "mother ship" concept could be employed where an airborne relay loiters above a MAV operating area to serve as a signal booster.

### Autonomy

To the extent that micro-air vehicles are autonomous, they will have greater ability to carry out their missions without supporting elements such as human flight controllers. However some missions, such as military operations in urban terrain, will only be accomplished with limited effectiveness until capabilities such as autonomous obstacle avoidance can be incorporated.

## Precision

Lack of positional precision in micro-air vehicle location will constrain their use in targeting, strike, intelligence, surveillance, reconnaissance, and combat search and rescue. For example, target geo-location uncertainties are a strong driver in weapons selection. Battle damage assessments will be made more difficult should it be unclear which among several similar-looking targets in close proximity, a MAV is imaging. A lack of precision in search and rescue might cause rescue crews to encounter threats that might otherwise be avoided with precise downed aircrew location data.

## Endurance

Longer endurance enhances most Air Force functions. Longer operation translates into greater mission flexibility and less frequent need to replace expended MAVs. It also means fewer systems will have to be purchased which saves costs. This is why progress in energy generation and storage capabilities for MAVs is so important.

## Damage Potential

Micro-air vehicles are small. Thus, the effectiveness of any mini-munitions they are capable of delivering will be directly dependent on being extremely accurate in delivery and incorporating a sufficiently energetic blast. Potentially an area for system engineering trade-offs, advances in precision navigation and munitions technologies will enhance the damage potential of MAVs. However, for the near- to mid-term, it would be unrealistic to expect MAVs to be capable of anything greater than a very localized destructive effect.

## Weather

As discussed earlier, micro-air vehicles are sensitive to disturbances in the atmosphere. Aerodynamic control will be difficult under conditions of moderate to high winds and precipitation; thus, image stabilization for intelligence, surveillance, and reconnaissance variants will be a challenge. The upper limit for MAV operations in winds may be no more than thirty miles per hour. This limitation may be particularly restrictive in urban settings where buildings are known to facilitate the production of local gusts and downdrafts.[132]

## Aerospace Power Functions Applicable to MAVs

### Offensive Counterair (OCA)

> OCA consists of operations to destroy, neutralize, disrupt, or limit enemy air and missile power as close to its source as possible and at a time and place of [one's] choosing. OCA operations include the suppression of enemy air defense targets, such as aircraft and surface-to-air missiles or local defense systems, and their supporting [command and control].

Micro-air vehicles could support offensive counterair in a number of ways. The vignette presented at the start of Chapter 1 in which MAVs were used to damage enemy fighters through foreign object damage is one such way. MAVs could also be used as target beacons for precision strikes against enemy aircraft, surface-to-air missiles, and command and control assets. MAVs outfitted with mini-explosives could be used to damage these targets to put them temporarily out of action. MAV stealth might be a particularly strong asset in helping locate enemy radars that otherwise would refrain from emitting for fear of attack from hunter-killer platforms.

### Interdiction

> Interdiction consists of operations to divert, disrupt, delay, or destroy the enemy's surface military potential before it can be used effectively against friendly forces. . . . Interdiction attacks enemy [command and control] systems, personnel, materiel, logistics, and their supporting systems to weaken and disrupt the enemy's efforts.

Micro-air vehicles could support interdiction in much the same way as they would offensive counterair. The nature and size of the target set, is however, more varied and in some respects more vulnerable.

## Close Air Support (CAS)

"CAS consists of air operations against hostile targets in close proximity to friendly forces." Micro-air vehicles in support of close air support would most likely find application enhancing combat identification through use of identification friend or foe or target tagging. They might also be used in target designation for precision-guided munitions. If equipped for imaging, MAVs might also perform a forward air controller type mission in support of the close air support function.

## Strategic Attack

> Strategic attack is defined as those operations intended to directly achieve strategic effects by striking at the enemy's [centers of gravity (COG)]. These operations are designed to achieve their objectives without first having to necessarily engage the adversary's fielded military forces in extended operations at the operational and tactical levels of war. COGs are those characteristics, capabilities, or localities from which a force derives its freedom of action, physical strength, or will to fight.

If the enemy's fielded forces are a center of gravity, then the nature of micro-air vehicle support to strategic attack is subsumed by the other aerospace power functions described herein. If, however, an enemy's centers of gravity are rooted more in the enemy's heartland (such as his electric power grid, transportation infrastructure, leadership, etc…), then MAV contributions go beyond that characteristic the above functions. MAVs may jam communications nodes, disrupting key utilities and industries, attack soft targets, and thus demoralize the enemy and reduce his will to fight. This last application might be accomplished simply through the frustration caused by having to deal with swarming MAVs that seem to be everywhere at all times making life difficult if not outright dangerous. A populace might feel no less helpless than the poor soldiers in the trenches of World War I who faced the constant onslaught of artillery fire.

Naturally, the deeper the center of gravity is behind enemy lines, the greater the need for long-range micro-air vehicle delivery means and for autonomous operation. If requirements extend to reconnoitering and/or conducting harassment operations inside leadership buildings and other interior locations, the MAVs to conduct these missions will need to be more sophisticated with advanced navigation and power systems.

## Offensive Counterinformation (OCI)

> OCI includes actions taken to control the information environment . . . [with t]he purpose [of] disabl[ing] selected enemy information operations. OCI operations are designed to destroy, degrade, or limit enemy information capabilities . . . Examples of OCI include jamming radars and corrupting data acquisition, transformation, storage, or transmissions of an adversary's information; psychological operations; deception; and physical or cyber attack.

The same (or similar) micro-air vehicles that can jam radar systems as described above, can deceive radar systems rather than jam them outright. MAVs could also conduct deception by supporting feints and diversionary attacks as well as broadcasting bogus friendly signals. Executing cyber warfare or information system attacks via MAVs will be possible to the extent that an enemy's cyber and information systems are accessible through communications infrastructure or industrially implanted "trap doors." Should MAVs ever advance to the point that they can land on transmission lines (copper or glass) and tap into them, they will be able to extend their offensive counterinformation operations beyond the realm of the radio frequency spectrum.

## Command and Control ($C^2$)

> $C^2$ includes the battlespace management process of planning, directing, coordinating, and controlling forces and operations. $C^2$ involves the integration of the systems of procedures, organizational structures, personnel, equipment, facilities, information, and communications designed to enable a commander to exercise command and control across the range of military operations.

The most obvious ways in which micro-air vehicles could support the command and control function are by enabling communications and providing own force surveillance. It is unlikely that MAVs will supplant more robust systems in which the USAF has invested over the years to support its current communications and force tracking infrastructure. However, MAVs could find a niche supporting command and control in unique situations such as over-the-horizon communications as part of a force protection scheme in a newly secured operating zone or imaging friendly operations to ensure they are proceeding according to commander's intent.

## Special Operations Employment

> Special operations employment is the use of airpower operations (denied territory mobility, surgical firepower, and special tactics) to conduct the following special operations functions: unconventional warfare, direct action, special reconnaissance, counterterrorism, foreign internal defense, psychological operations, and counter-proliferation. To execute special operations, Air Force special operations forces (AFSOF) are normally organized and employed in small formations capable of both independent and supporting operations, with the purpose of enabling timely and tailored responses across the range of military operations.
>
> Uniquely distinctive from normal conventional operations, AFSOF may accomplish tasks at the strategic, operational, or tactical levels of war or other contingency operations through the conduct of low-visibility, covert, or clandestine military actions. AFSOF are usually conducted in enemy-controlled or politically sensitive territories and may complement or support general-purpose force operations."

This extensive quote from AFDD 1 was necessary to bring out two things. First, it is the function most amenable to micro-air vehicle capabilities given their current developmental impetus on supporting small ground force operations (as intelligence, surveillance, reconnaissance, communications, offensive counterinformation, targeting, and deception assets) at least to the extent the special operations employment function involves Air Force personnel on the ground in enemy territory. Second, special operations employment is the function most likely to emphasize the MAV's qualities of low-visibility, redundancy, persistence and covertness.

## Intelligence, Surveillance, and Reconnaissance (ISR)

> Intelligence provides clear, brief, relevant, and timely analysis on foreign capabilities and intentions for planning and conducting military operations. . . . [I]ntelligence gives commanders the best available estimate of enemy capabilities, COGs, and courses of action.
>
> Surveillance is the function of systematically observing air, space, surface, or subsurface areas, places, persons, or things, by visual, aural, electronic, photographic, or other means. Surveillance is a continuing process, not oriented to a specific 'target.'

> Reconnaissance complements surveillance in obtaining, by visual observation or other detection methods, specific information about the activities and resources of an enemy or potential enemy; or in securing data concerning the meteorological, hydrographic, or geographic characteristics of a particular area. Reconnaissance generally has a time constraint associated with the tasking.

The value micro-air vehicles may have for the intelligence, surveillance, and reconnaissance function has already been made apparent. MAVs could contribute across this spectrum by ascertaining ground and electronic order of battle to supporting the intelligence activity of targeteering. These functions would be accomplished using data gathered by MAV imagers, communications intercepts, and signals intelligence analyses. MAVs may also be an innovative tool to conduct post-strike battle damage assessments. MAVs could be fitted to ride piggyback on a precision-guided munition. After launch into the target area, the munition and MAV would separate before weapon impact with the latter loitering to provide images of the weapon's effect. Advantages to such a scheme include lowered combat risk (by obviating the need for post-strike battle damage assessment by manned reconnaissance), better and more timely battle damage assessments especially as regards weapons effectiveness and possible need for re-attack, as well as cost savings in operations and logistics.

**Combat Search and Rescue (CSAR)**

CSAR consists of those air operations conducted to recover distressed personnel during wartime or military operations other than war. The most likely concept of operation involving the combat search and rescue function has micro-air vehicles signaling rescue forces on the whereabouts of distressed personnel. Other possibilities include MAVs providing "overhead" imagery to enhance downed aircrew and rescue party situational awareness, serving as communications relays, and assisting in SEAD operations during an entire rescue operation from ingress, through extraction to egress of the rescue team. Should MAV range capabilities become sufficient, MAVs could perform as "homing pigeons" to lead combat search and rescue teams back to the exact location a downed aircrew launched the MAV, even providing encapsulated messages to preclude communications intercept.[133] When it is difficult to isolate the exact current location of distressed personnel, blanketing a region with

MAVs might be a particularly efficient way to support wide area search activities.

## MAV Employment Contexts

As has been shown, micro-air vehicles can be used in many different ways to support a wide variety of Air Force functions. Thus, it is reasonable to expect that they would have utility across the spectrum of military operations from peacetime to combat involving nuclear, biological, and chemical weapons. This section will explore MAV support to Air Force functions within the various contexts making up the spectrum of conflict beginning with military operations short of war working through increasing levels of conflict.

### Military Operations Other Than War (MOOTW).

"Military operations other than war" is a "catch-all" term used to describe a number of different activities military forces can be engaged in short of general war. It includes border and area patrol, humanitarian operations, peace operations, support during domestic crises, non-combatant evacuation operations, and anti-terrorism.

**Border and Area Patrol.** Border patrol operations are generally a peacetime operation. Its purpose is generally to support activities such as homeland defense, illegal immigration control, and to stop drug smuggling. Here, the crucial functions are intelligence, surveillance, and reconnaissance. Military involvement typically occurs in cooperation with other agencies. In this case, micro-air vehicles may not be a more cost-effective solution than larger UAV or aerostat alternatives. Further, Air Force involvement is may not be appropriate.

If, however, the purpose of the patrols is in the context of counter-proliferation of weapons of mass destruction, Air Force micro-air vehicles equipped to search for evidence of such weapons could have a role. This role would depend, of course, on such factors as the geographical circumstances and political environment. MAVs could augment national overhead surveillance assets to keep suspect complexes under continuous scrutiny and to sniff for traces of agents associated with the manufacture and storage of these weapons.

**Humanitarian Operations.** Humanitarian operations extend from airlift of medical supplies and foodstuffs to people who have experienced a natural disaster to managing refugee relief camps. Many times such operations must be conducted in remote locales where public infrastructure facilities have been severely stressed or are non-existent.

Micro-air vehicles could prove useful in such contexts as a means to survey the extent of disasters or to provide communication links to replace lost commercial nodes. They could also locate trapped personnel using aerial surveillance and serve as homing beacons to guide rescue personnel. In this regard they might be the only safe alternative for searching for survivors inside burning buildings or amidst rubble from earthquakes or terrorist bombings. Air Force involvement would probably be limited to provision of such assets at the commencement of humanitarian missions until full up emergency relief teams arrive on scene with their own.

**Peace Operations.** Peace operations are generally divided into peace keeping and peace enforcement. Because peace keeping rests upon the mutual interests of the conflicting parties to avoid bloodshed, the probability of armed conflict is lower than in the case of peace enforcement where the parties to conflict may wish to keep fighting. Accordingly, peace keeping forces tend to be more lightly armed and their rules of engagement more conservative. Peace enforcers, on the other hand, need to be ready to demonstrate more resolve to keep conflict from flaring up.

In such contexts the most likely role for micro-air vehicles is again as surveillance platforms. In some ways their stealth may detract from the demonstration of presence that enhances the peace operation. The surveillance role would not be restricted to imaging as signals intelligence would also be of value to monitor communications levels. Should peace degenerate into combat, MAVs could be used by isolated forces in much the same way as described earlier for combat search and rescue operations.

In all likelihood, micro-air vehicles will be organic to the ground-based force. However, Air Force involvement may be necessary for wide area operations too large to be continuously monitored by a limited ground force.

**Domestic Crises.** For the purposes of this paper, domestic crises refers specifically to situations of imminent danger as in riots, stand-offs between groups threatening violence and law enforcement personnel, and natural or man-made disasters in progress. In riot situations micro-air vehicles could prove particularly adept at providing reconnaissance in urban settings where tall buildings block line-of-sight. The psychological impact of MAVs should not be underestimated as the mere observation of the presence of MAVs might serve notice to the rioting masses (or leadership if there is one) that they are being monitored continuously. This could also act to complicate attempts by those wishing to manipulate rioting crowds to their own ends. Images taken by MAVs could aid in post-riot law enforcement efforts to prosecute criminal actions. MAVs could be used to provide pinpoint delivery of crowd control agents such as tear gas thereby reducing the chaos that sometimes ensues over a wide area when these measures are employed. In 'Waco-style' stand-offs, MAVs could be used to deliver knockout agents to subdue hostage takers before they realize what is going on. While severe weather would constrain MAV operations, they could still prove their value reconnoitering the extent of floods, chemical spills, noxious agent clouds, and the like. Here, the chemical and biological sensor payloads will come into play depending on the nature of the disaster. As with the border patrol role, it is not clear that active DoD units will be primary responders.

**Non-Combatant Evacuation Operations (NEO).** Non-combatant evacuation operations can be described as military missions on foreign soil to extract non-military personnel from a dangerous situation. Embassy evacuations are the most common example. Micro-air vehicles could prove useful in a supporting role by providing intelligence and reconnaissance, intercepting and/or jamming adversary communications, and signaling rescue forces when the non-combatants are distanced from planned pick-up points. Air Force use of MAV assets could be envisioned for any of these scenarios.

**Anti-Terrorism.** Anti-terrorism is another activity that takes on a multi-agency flavor especially when focused on the domestic scene. Micro-air vehicles have the potential to enhance anti-terrorist operations especially as covert intelligence, surveillance, and reconnaissance assets that could enhance domestic and military authorities' knowledge of the threat they face in a crisis. MAVs capable of negotiating their way into a building during a hostage situation and able to maintain a covert presence for on-going reconnaissance greatly increase the odds in favor of anti-terrorist forces. MAVs fitted with nuclear, biological, and chemical weapon sniffers would aid immeasurably in understanding the extent to which terrorist use of such weapons has contaminated an area. MAV contributions in the anti-terrorism context will probably not come through Air Force channels on the domestic front, even though they may reside within the arsenal of the newly formed Joint Task Force-Civil Support or in conjunction with operations in Homeland Security. The purpose of this task force is to coordinate military support in terrorist situations involving use of weapons of mass destruction.[134] Nevertheless, it may be appropriate for Air Force provision of MAVs if the source of the terrorism is in another country and requires MAV long-range delivery.

**Limited Raids**

Limited raids fall in between military operations other than war and acknowledged war in the spectrum of conflict. These are conducted by nation states against state or non-state actors using standard military or special operations forces. Categorically, they involve a single or small number of engagements and are conducted over a time interval spanning minutes to several days.

In all important respects, limited raids look like conventional military operations in content and tenor. They differ from more general warfare in that no *a priori* "state of war" exists between the combatants within the international legal understanding of the phrase, although raids could be used by the attacked party as justification for declaring war. Limited raids are typically used to "send a message," to "show resolve," or as a form of retaliation. The may also be used within the context of enforcement of international sanctions or military occupational duties. Operation DESERT FOX conducted by the U.S. against Iraq in 1998 is an example of a limited raid.

Air Force micro-air vehicles could make contributions in support of limited raids by virtually all of the means mentioned previously: pre-strike reconnaissance, targeting, and post-strike battle damage assessment; electronic warfare to include signals intelligence and communications intercept/jamming; communications relay; target area weather monitoring; combat search and rescue in those cases where aircrew survive shoot down; offensive counterair operations including SEAD; and offensive counterinformation to include deception and psychological operations. The MAVs could be used for strategic attack if the raid were to have that purpose. MAVs might prove particularly attractive for use in this context in that they are expendable and do not put friendly personnel at risk; two considerations that are usually significant factors in the decision to launch a limited raid. Due to their stealth, MAVs also facilitate surprise, which is an important element if limited raids are to achieve maximum effect.

**Insurgent Warfare**

Insurgent warfare has the following characteristics:

- It almost always involves protracted struggles
- It relies on an underground infrastructure for concealment and intelligence and siphons support from the target population
- It uses military actions as a complement to the political struggle, not as the dominant means to attain success
- It employs guerilla tactics[135]

Given the capabilities posited earlier for micro-air vehicles and the description of insurgent warfare outlined above, it is a simple extrapolation to conceive of how such weapons could prove extremely amenable to insurgent forces. What may be less obvious, but no less true, is that MAVs – along with other specialized weapons and tactics – could support an option for conduct of insurgent type warfare by U.S. forces.

Much is made in the literature about how the U.S. must prepare itself for future contingencies in which enemy forces may employ asymmetric strategies as a means to overcome U.S. conventional superiority. Very rarely do you see proponents of the notion that the U.S. should itself adopt such asymmetries to enhance its combat power. Micro-air vehicles hold this attraction. More explicitly, they make possible the idea of employing combat power in a manner that resembles an asymmetric strategy like insurgent warfare at least with respect to the use of guerilla tactics.

Guerrilla warfare is usually perceived as the means used by a weak entity to fight a strong one. This has dictated certain tactics such as heavy leverage of the element of surprise, operations in small units or cells, rapid massing of locally superior forces on isolated enemy units, actions to cause harassment, demoralization, and embarrassment of enemy forces, and eschewing the taking and holding of terrain.[136]

When one considers the probable types of warfare that the U.S. may be faced with in the future, one possibility that stands out as highly likely is what has been termed "dirty war."[137] If faced with such a future where failed states and non-state actors combine to produce complex and "dirty" conflict, the U.S. should use strategies that avoid heavy involvement of ground forces, that minimize exposure of personnel and materiel to attack, and that employ tactics which work well against a diffuse and fleeting enemy. Strategies of this nature would require new concepts of operations and complementary technologies to make them successful. Given their characteristics of stealth, flexibility, potential ubiquity through low-cost, mass manufacture and employment, micro-air vehicles could fit quite nicely within strategies that take on the character of insurgent warfare. Through stealth and versatility, they could provide wide area intelligence, conduct surprise hit-and-run attacks, and be easily operated by limited numbers of indigenous personnel sympathetic to the U.S. cause as the Mujahadeen did using Stinger missiles against the Soviets in Afghanistan. Depending on the goals of the campaign, successful operations along these lines might not require the capture of terrain, would create frustration and embarrassment among enemy forces while limiting the exposure of U.S. personnel to attack. Such a capability would be extremely useful in operations like ENDURING FREEDOM. This would serve to create the impression of long-term commitment and invincibility.

Of course, in the more traditional sense, micro-air vehicles could prove an ideal weapon to export to insurgencies in other countries that are fighting for interests consonant with those of the U.S. Again, the example of the Stinger in Afghanistan provides a model for emulation. In this context the potential for technological secrets to fall into the hands of enemies would be less of a concern for MAVs as compared with other weapons like the Stinger. This accrues from the fact that the real edge comes not from the technological capabilities resident on the weapon itself as it does from their manufacture. Furthermore, new technologies that come under the title of "anti-tamper" are now available to mitigate the threat of exploitation.[138]

## Conventional Warfare

Conventional warfare refers to engagements fought and campaigns pursued by regular forces under conditions mutually acknowledged as a state of war. The vast majority of considerations for micro-air vehicle support within this context have already been examined in the section on USAF Aerospace Power functions. Only one more observation in this context will be made having to do with operations in urban, mountainous, and forested terrains.

The force structure the U.S. has developed to date is best suited for operations in open terrain as is found in the deserts of the Middle East or the plains of central Europe. Operations that must be conducted in terrain involving extensive urban dwellings, rugged mountains, or forested regions (as exist in the Balkans) greatly complicate securing the goals of dominant battlespace awareness and precision attack. Developing and procuring weapon systems that overcome such obstacles is fundamental to achieving the vision for our future force enunciated in documents like *Joint Vision 2020*.

It should be evident by now that micro-air vehicles can potentially contribute in no small way towards helping reduce the fog and friction of war that are exponentially increased for operations in these settings. By providing the ability to sense in heretofore denied areas, by extending presence into virtually anywhere on the battlefield, and by holding an adversary continuously at risk from lethal or non-lethal effects from the air, MAVs magnify the effects of our force assets that otherwise would be greatly diminished.

**Warfare Involving Weapons of Mass Destruction (WMD)**

It has already been illustrated how MAVs equipped with nuclear, biological, and chemical sensors could aid in battlefield detection of these agents and assist in operations to avoid or contain contaminated areas. Further, MAVs could also be used to determine the extent of destruction and develop consequence mitigation plans. Additionally, MAV use in counter-proliferation efforts has also been described. Air Force participation in such efforts would appear to be appropriate. Beyond these, however, once conflict escalates to massive WMD use, other uses for MAVs would appear to be of limited consequence.

# Chapter 5

## Summary and Concluding Thoughts

Micro Air Vehicles are a class of UAVs whose time is near. A confluence of key events is about to occur that will enable these versatile aircraft to have military effects disproportionate to their diminutive size. The supporting technologies are progressing rapidly to the point that simple, short-duration missions will soon be possible. With time, more varied and enduring applications. At the same time, the need for weapons that help achieve the Joint Chiefs of Staff vision for dominant maneuver, precision engagement, full dimensional protection, and focused logistics will be more pressing than ever. The military utility of MAVs in this context can only grow as they come closer to realizing their potential.

At the start, micro-air vehicles could find application by providing localized imaging reconnaissance. Then as other key technologies mature, uses may expand to electronic warfare, nuclear, biological, and chemical agent warning, and battle damage assessment. Later still, we could see MAVs autonomously flying through air shafts reconnoitering deeply buried bunkers and reporting back to enable proper configuration of penetrating weapons. MAVs might then proliferate throughout the force structure becoming as much an "arrow in the quiver" of the foot soldier as another round on the hard point of a fighter's wing.

As micro-air vehicles become credible weapon systems widely available and reliable, they will be used at virtually all levels of conflict, from peace operations to battlefields on which weapons of mass destruction may be unleashed. While the Air Force may not be the operator of MAVs in all of these contexts, it will be the appropriate one in a great many of them.

Perhaps the most revolutionary application of micro-air vehicles would be their use within the context of "swarms." Whether swarming is accomplished by a great number of vehicles that are in no way integrated with each other or by groups that share sensor data, centralized command and control, distributed processing, and/or aggregated lethality, such an employment concept will present incredible difficulties for any defensive scheme. Imagine being tasked with fending off attacks of swarms of MAVs as they engage from literally every direction around one's position with stealth and autonomic single-mindedness. The defender will face incredible challenges in detection, targeting, and engagement multiplied many times over. Swarming MAVs will give the offensive side a distinct advantage not easily countered and will represent the exquisite marriage of *quality* with *quantity*.

While utility in the operational performance dimension argues for the pursuit of micro-air vehicles, there are other reasons as well. These include low cost of development and acquisition as well as of operations and maintenance. Since many applications will entail a "wooden round" (i.e., single use) concept, the logistics trail will be minimal. The ability of MAVs to support traditional missions as well as their potential to enable implementation of new military strategies make them ideal agents to assist transitions to alternate force structures and/or concepts of operation. There are likely to be spin-offs for commercial and space uses as well. The micro-air vehicle is hardly a system concept that will find itself restricted to the alternatives presented here or to the military realm alone.

For certain, the potential of micro-air vehicles is not unbounded and key shortcomings will have to be mitigated for these aircraft to have the minimal utility necessary to make them viable candidates to perform Air Force missions. Among the challenges yet to be overcome are achieving reasonable range capabilities in distance traveled and radio frequency transmission radius, prolonging endurance both in the air and post-flight for unattended ground operation, enhancing navigational precision, and acquiring true autonomy. While these challenges may seem daunting now, it does not seem unreasonable to look ahead in 20 years to foresee a time when they may be well in hand.

If the Air Force is to have a share in a future involving micro-air vehicles, now is the time it must step up to the plate and embrace them as its own. A recent article in *Joint Forces Quarterly* makes this argument quite pointedly:

> The military systems of 2020 and 2030 will be based on the science of the year 2000 just as the high-tech weapons of today are the results of investments made by our predecessors in the 1960s and 1970s. . . .
>
> The 20 to 30 years needed for basic scientific discovery to evolve into a fielded system means that now is when we must understand the concepts of far future war and the capabilities we will want. . . .
>
> Great breakthroughs occur at the interface between scientific disciplines and organizations. . . .
>
> At present the services only influence product development in the latter stages of the R&D cycle. Industry experience, however, has shown that if the customer and designers share in all product development decisions from the initial design, the degree of innovation is much higher, the product acceptance rate is much greater, and the pace of technological change is much faster.[139]

The micro-air vehicle is a concept "at the interface between scientific disciplines and organizations." It has reached the point in its development life cycle that operators (i.e., "the customer") can have a decided effect on its progression. The window of opportunity is now presenting itself. Now is the time to open the shutters.

In 1991 the USAF commenced Operation DESERT STORM with massive, synergistic, and devastating attacks on the Iraqi Integrated Air Defense System and proceeded over the course of days to render it useless. In 1999 the USAF again went to war, but this time over Yugoslavia in Operation ALLIED FORCE, and the going was a bit more difficult. While success was achieved at suppressing the Serbians' air defenses, the threat they posed in this regard was far from emasculated at war's end. This enemy had learned some lessons and applied asymmetric strategies such as replacing air defense communication links with cellular technologies. Is the next enemy going to be even better? How will the USAF craft a strategy to defeat the next integrated air defense system it faces and the thinking enemy behind it? To remain successful, the USAF will have to continue advancing itself, adding new capabilities to its bag of tricks, and adopting counter-strategies of its own. Micro-air vehicles could be a partial answer to this challenge. These aircraft require a high degree of systems integration, which is a relative strength of the U.S. industrial establishment. If pursued aggressively, MAVs could be in the hands of

U.S. warfighters well ahead of potential adversaries who would need to make substantial efforts to copy and/or counter them. Thus, they could prove a substantial asymmetric advantage for the U.S. to enjoy in the intervening time between introduction and imitation.

If this paper has appeared to place too much faith in technological solutions, then let it be tempered by the following sage advice. In developing our strategies for the future, we have to be careful not to place too much trust in nor depend solely on technology as the end or be all. As the studied strategist, Colin S. Gray, cautions,

> New technology, even when properly integrated into weapons and systems with well-trained and highly motivated people, cannot erase the difficulties that impede strategic excellence. . . . Progress in modern strategic performance has not been achieved exclusively through science and technology.[140]

Developing, procuring, and integrating micro-air vehicles into our fielded forces must be accompanied by the evolution of appropriate tactics, the development of an experience base gained through experimentation and realistic training, and the creation of responsive organizations to operate them professionally. Only then will MAVs reach their true potential.

If all of these pieces – technology, operational constructs, experience, and organization – can be brought together holistically, then the USAF will have gained another advantage against almost any opponent. The enemies of today have learned the hard way that U.S. aerospace power is massive, flexible, and overwhelming. It inspires awe. This hard-won respect magnifies its influence and enhances its prestige as an instrument of national policy. Micro-air vehicles add a new dimension to this instrument, one that may be characterized by stealth, seeming ubiquity, and persistence. Pursuit of MAVs can only add to what Eliot Cohen has described as the “mystique of U.S. air power . . . a mystique that is in the American interest to retain.”[141]

*Notes*

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