Pesky Critters

by

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CHAPTER 7
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I. Vision

> *In every successful transformation effort that I have seen, the guiding coalition develops a picture of the future that is relatively easy to communicate and appeals to customers, stockholders, and employees.*
>
> -- John Kotter[1]

In the year 2015 North Korea invades South Korea in an attempt to unify the divided country. North Korea had learned many lessons in the over 60 years from the last campaign to bring their peoples together. They realized the United States would be a difficult adversary. To counter America's conventional might, the North Koreans built significant underground facilities. The United States' Achilles' heel is its inability to prosecute hard and deeply buried targets. This sanctuary would protect them from the extensive conventional bombardment sure to follow.

On the first day of the war, however, American Joint Strike Fighters drop cluster bomb unit dispensers filled with a unique surprise. The dispensers separate from the aircraft and decelerate by a retardation parachute before the bomb body opens. Within each dispenser are 100 house-fly-sized unmanned aerial vehicles. Once attaining the preset altitude and airspeed, the cluster bomb unit distributes the miniature air vehicles throughout the battlefield. These devices are the latest technological innovation utilized by the Americans to counter the asymmetric threat. These devices mimic the performance of a real housefly and follow a pre-programmed path to the entrance to the underground North Korean complex. They have several different capabilities to include chemical/biological sensing, surveillance, and a hunter-killer capability able to eliminate the key North Korean leadership. The chemical/biological sensors seek hidden weapons of mass destruction and production facilities. They can continually sample the air to identify specific toxins by molecular composition. If threats are discovered, the flying sensor escapes the complex and notifies the friendly forces of the type of toxin and its location. Special operations forces later infiltrate the facility to neutralize the threat.

The reconnaissance platform's mission is to eavesdrop and record leadership conversations for later analysis. Utilizing a micro-electromechanical microphone, the unmanned vehicle has the sensitivity to record discussions while its shape and size make it the ideal stealthy reconnaissance platform. When was the last time anyone paid increased attention to a fly buzzing about a room? The sensing robots expand throughout the facility monitoring the location and conversations. After gathering sufficient data, these vehicles exit the bunker and broadcast the clandestine data to dedicated networked sensors.

The hunter-killer pursues specific individuals and eliminates them. These devices have the unique deoxyribonucleic acid (DNA) signature for individual leadership in their memory and examine the environment for a match. Once the proper candidate is isolated, the fly inserts a probe into the victim, injecting a toxic substance or altering the victim's own genetic material with a virulent composition, causing quick incapacitation. The victim notices the "sting" from the robot but considers it a pest and thinks nothing of the consequences.[2] A day or two would pass before the targeted leader is not a further factor in the warfighting. These miniscule vehicles offer a unique, stealthy capability for a government. From the exterior, the robots appear to be common houseflies. They mimic the performance of the housefly in nearly every aspect except for the internal composition. Their innocuous existence offers implementers military advantages. While the development of a hunter-killer weapon may breach legal boundaries, its potential is illustrative of the possible alternative applications, many of which, such as the intelligence and surveillance approaches, are perfectly legal.

The above scenario may seem implausible—something dreamed within the mind of a science fiction writer—but the capabilities are closer to reality than one might imagine. The design, manufacture, and use of an unmanned aerial vehicle the size of a common housefly is feasible and worth exploring. This paper examines the current state of unmanned aerial vehicles and the guidance for their future development. By looking at the current state of technology investment, it demonstrates the viability of a true micro-robot of these proportions. The discussion then centers on the usage and limitations of this revolutionary system. Finally, the essay examines the strategic implications of this innovative weapon.

II. The Current State of Unmanned Aerial Vehicles

> *Yet if any technology transformed war, it was that of nuclear weapons. Will any technology similarly transform war in the next 25 years? Micromachines and hybrid organic-electronic computers are candidates for that role.*
>
> -- Thomas C. Hone and Norman Friedman[3]

Unmanned aerial vehicles (UAVs) clearly demonstrated military utility in the last decade, offering the possibility of low cost systems reducing the concern of survivability.[4] So far, warfighters have mostly relegated these platforms to intelligence, surveillance, and reconnaissance. With the high cost of existing sensors, unmanned vehicles are no longer the throwaway systems they once promised. Further advances in technology portend the ability to reduce unit cost through miniaturization.

Background

Unmanned aerial vehicles are not new. Even before manned flight, scientists and engineers researched the mechanics, uses, and missions for unmanned vehicles. Actually, Samuel Langley designed and demonstrated the first unmanned system over the Potomac River in 1896.[5] Prior to World War I, visionaries such as Lawrence Sperry, Charles Kettering, and Glenn Curtiss, investigated flying bomb designs capable of striking targets 75 miles away.[6] The V-1 buzz bomb was probably the best-known example of an unmanned system utilized in World War II, terrorizing the British populace in 1944-1945.[7] During the Vietnam War the BQM-34 "Firebee," the size of a small fighter with a jet engine and swept wings, epitomized the unmanned aerial vehicle. The Firebee conducted a variety of missions including strike, reconnaissance, and electronic attack.[8] During the Gulf War the BQM-74 was employed to impersonate the flight profiles of fighter aircraft as a decoy to energize the Iraqi air defense system. The quest to develop unmanned systems has been present since the dawn of flight.

Unmanned vehicles have shown remarkable results in our latest conflicts. The Predator, a medium altitude system cruising at 70 knots and equipped with electro-optical and infrared cameras, has allowed real-time monitoring of the battlespace.[9] The data is beamed throughout the theater, either to the air operations center through the time critical targeting cell, or to an aircraft, such as an AC-130, to prosecute the target.[10] Global Hawk provided long-loiter, continuous surveillance during Operation Iraqi Freedom (OIF). These publicized operations tend to reinforce the belief unmanned systems are recent products of the research world.

Present and Future

The 2002 Department of Defense (DOD) Unmanned Aerial Vehicle Roadmap and the 2003 United States Air Force Scientific Advisory Board (USAF SAB) are the official capstone studies concerning the required and future technology of unmanned aerial vehicles. They espouse continued development and integration of these systems to conduct the "dull, dirty, and dangerous" missions.[11] Both documents advocate continued fielding of intelligence, reconnaissance, and surveillance as well as combat platforms. Unfortunately, neither study identifies new, revolutionary missions for unmanned vehicles, although the documents discuss increased opportunities for miniature or "micro" unmanned vehicles. These tiny aircraft, less than six inches long, offer a wider range of options, not limited to intelligence, reconnaissance, and surveillance but also suited for biological/chemical weapon detection.

Current concepts of employment use existing platforms that are large in scale. The Predator is 27 feet long and has a wingspan of 48.7 feet.[12] The Global Hawk is almost as large as the U-2, the aircraft it may replace in the future. This grand scale is not just an Air Force phenomenon; the Army's Hummingbird unmanned rotary craft is the size of existing manned helicopters. These systems fill the "dull, dirty, and dangerous" missions sets by taking the pilot out of the system but leave the platform at relatively the same size, complexity, and price

Must all unmanned aerial vehicles be as large as manned systems? Small, or micro, systems are a burgeoning area for future warfighting concepts. The Marine Corps has a requirement for a small, unmanned system to provide squads with a view of nearby threats. Their solution, Dragon Eye, is a miniature, backpack-sized, propeller-driven system incorporating a camera providing a company, platoon, or squad organic intelligence, surveillance, and reconnaissance out to five nautical miles.[13] Still, very little research and development investment has occurred with respect to small, unmanned systems. The DOD UAV roadmap identifies a gap in small vehicle research and missions. In Figure 7.1 this gap, labeled "SMALL" UAV GAP, appears under the lower, pink-colored portion of the diagonal arc. While few documented military requirements exist for micro-UAVs, the potential advantages of these systems are great.

Therefore, the next 25 years should see a significant increase in development of micro-systems.[14]

Micro-unmanned aerial vehicles offer significant advantages. Small platforms are very responsive to changes in the tactical environment. Due to their reduction in size and complexity and the corresponding lack of a requirement for redundancy, they are significantly cheaper than larger systems. Finally, the logistics tail to support a set of small systems is also smaller.[15] Due to their diminutive dimensions, small vehicles can move with forces. A ground unit can carry their own “eyes and ears” with them to peer over the next hill and examine the obstacles. Such small systems eliminate the time delay in ground operations. Opposite the expensive, complex, logistically intensive, and large high-flyers the smaller systems can deploy to the front lines and provide instantaneous updates down to the squad level. These systems are equivalent to a pair of flying binoculars for the commander.[16]

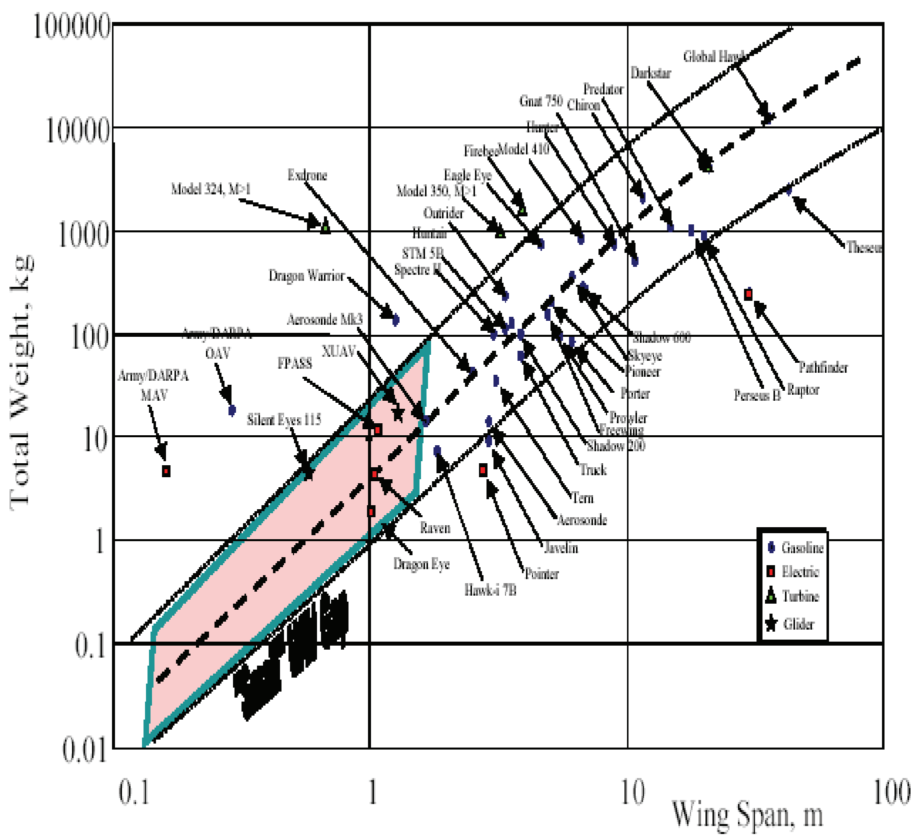

Figure 7.1 UAV Weight vs. Wing Span[17]

Smaller platforms may lead to lower per unit costs. A paradox exists in unmanned systems between the needs of redundancy and affordability. One goal of the UAV roadmap is to devise metrics for controlling system expenditures.[18] The Predator system was developed with the philosophy of being able to replace a lost vehicle cheaply. Due to lack of redundancy, its overall system costs were relatively small compared to a manned aircraft. The sensor suite alone comprises almost 50 percent of its total value. Designers found themselves adding redundancy into this system to lessen the monetary impact of losing a vehicle. A vicious cycle occurred while trying to increase reliability without spirally increasing costs. Due to the limited size and restrictive available space for components, small systems could offer significant cost reductions because there is less temptation to make them too complex.

As previously stated, the DOD roadmap and the Air Force study mention the need for small, miniature unmanned systems. However, the missions for these platforms are limited to tactical intelligence, surveillance, and reconnaissance in support to a field commander. In some cases, the unmanned systems are planned to provide perimeter security at a weapon storage site, airfield, port, or urban area. The vision seems too narrow. Clearly, they can provide more than just tactical information to the commander. Their value is being small enough to supply operational and strategic data by entering high value command and control facilities unnoticed. Unfortunately, Air Force senior leadership appear at times to view unmanned vehicles as just aircraft without a pilot in them. The visions of the Air Force Chief of Staff and the commander of Air Combat Command (ACC) are limited to large-scale platforms conducting reconnaissance and strike missions.[19] ACC is driving a requirement for unmanned systems to be able to fly in tight formations similar to their manned cousins and to be able to refuel.[20] Absent is the advocacy for miniaturization. Rather than just replacing the biological life form in the cockpit, future UAVs can possess increased capabilities bound only by man’s imagination. While it is true that future systems will reduce the danger to humans, military leaders must envision new missions and scales for unmanned systems. Yes, unmanned systems will replace the “dull, dirty, and dangerous” missions that exist today, but the vehicles are also platforms for new concepts outside the status quo.

III. Technology

> *Biomimicry is a new way of viewing and valuing nature. It introduces an era based not on what we can **extract** from the natural world, but on what we can **learn** from it.*
>
> --Janine M. Benyus, Biomimicry[21]

> *Insects are the most successful group of macroscopic organisms on Earth, and they were the first to take to the air.*
>
> ---Dr. Michael Dickinson, UC Berkeley[22]

The synergy of quantum physics, nanotechnology, and the new science of biomimicry portend the bedrock of the machinery needed to produce the "housefly" unmanned vehicle. Clearly, several technological miracles must occur to ensure its development. Encouragingly, several organizations are experimenting with possible solutions. Several national and military laboratories are investigating micro-electromechanical (MEMS) technologies—an outgrowth from the semiconductor industry, which currently enables the etching of miniature gears and levers. Some are one-third the diameter of a human hair. While the maturity of this technology is not yet capable for small-insect sized machines, by 2020 micro-electromechanical devices will be prevalent throughout everyday equipment.[23] In the future, using micro-electromechanical technology, one may well be able to construct small machines and engines the size of an insect or smaller. Very small devices of this size are already used as impact sensors for automobile air bags.

Scientists have turned to nature as a solution for some of today's technological problems. A new science, called biomimicry, attempts to discover how natural occurrences can be imitated into systems. The initial, pathfinding initiative in this approach was to find environment-friendly, manufactured devices. An example is using spider silk to manufacture strong filament as a possible replacement for Kevlar. Another effort uses the duplication of oyster shells as a hardened shell protecting equipment.

To build a fly-like unmanned vehicle, several key technological advancements are required. Among these is a better understanding of the aerodynamic effects of flying insects, miniaturized systems to enable command and control, sensors, smaller propulsion sources, and miniaturized communications. Each technology area would enable the previous, hypothesized capability to become a reality. All of the technology areas are interrelated due to the system's diminutive size.

Aerodynamics

The aerodynamic environment for small-scale systems is quite different from conventional aircraft. Several universities have conducted research on the aerodynamic effects in the low Reynolds number environment. Reynolds number, a mathematical term defining the ratio of two fluid forces—inertial and viscous—is one of the most useful parameters in fluid dynamics.[24] It is represented by the equation: $\mathbf{Re = l \times v \times \rho/\mu}$

- 1 is the length of the vehicle
- v is its velocity
- ρ is the fluid's density
- μ is the fluid's viscosity—thickness

A conventional aircraft operates at Reynolds numbers of approximately one million to 100 million (Figure 7.2). Conversely, an insect transits in fluids with Reynolds numbers about 100 to 1,000 and actually smaller than 100 for the tiniest of insects.[25] For large aircraft, the correspondingly large Reynolds number allows designers to build small-scale models and test them in a wind tunnel replicating the aerodynamic forces exerted on a full-scale system.

The Universities of Florida, California at Berkeley, Notre Dame, and the Georgia Institute of Technology have published widely on the mechanics and ability of insect flight. These articles include work on micro air vehicle airfoil performance at low Reynolds numbers and flapping/flexible wings and adaptive airfoil aerodynamics.[26] At UC Berkeley, biologist Dr. Michael Dickinson has modeled the aerodynamic forces and the fluid flow around insect wings by using a viscous mineral oil tank. His 25-centimeter robot wings flap at a rate of once every five seconds, similar to a 2.5-millimeter fruit fly wing flapping at 200 times a second in air.[27] Through these experiments the riddle of how insects are able to fly is being answered, thereby bringing the reality of a robot-flying insect closer to demonstration.

Command and Control

The proper level of autonomy for UAVs has been constantly debated. Leadership is hesitant to allow unmanned, killing machines to roam the environment freely. Having the human make the final decision is the validating point for ethical use of such weapon systems. Revolutions in computing power enable future machines to think for themselves. Computers can emulate the human brain computational ability by 2019.[28] The amount of automation to reach the capability in the scenario should come in steps. Clearly, the objective is to have the machines searching freely for the exact target.

Ideally, the missions envisioned for the micro-vehicle necessitate an autonomous guidance system. Guiding the robot from an off-station source would require a communication source throughout the flight profile. Such connectivity is not always possible in an urban or indoor environment. Steering signals could not reach the vehicle while flying underground or navigating around obstacles such as stairways, rooms, or doors. This need for autonomy drives requirements for a robust computer, an inertial sensing device, and control algorithms. Additionally, these systems require extremely low power for operation.

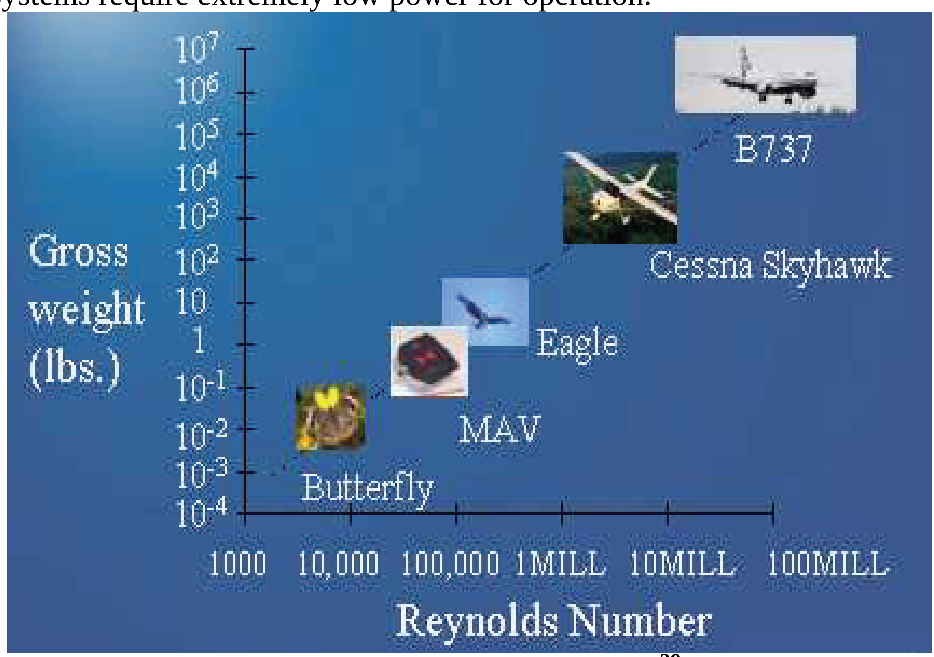

Figure 7.2 Reynolds Number[29]

Computational capability, storage, and processing speed follow Moore's Law by doubling every 12-18 months.[30] Therefore, by 2019 a $4,000 computing device will be able to perform 20 quadrillion calculations per second.[31] By that time, a standard computer chip will have approximately the same computational ability as the human brain. While the proposed robotic fly is not large enough to house a computer chip of this size, a chip one-thousandth this size would fit and have sufficient processing capability. Performing over 200 billion calculations per second, such a device could control propulsion, calculate its location, record data, provide steering and stability guidance, and sense the locale.

Another option may be DNA molecule computers. These analytical devices, based on the material of which one's own genes are composed, may rival the capability of inorganic-built systems. In 1994 Dr. Leonard Adelman conceived of the possibility of creating an organic computer. He was able to calculate flight routes between seven cities using these molecules in a test tube.[32] While this manner of demonstration was far from meeting future expectations, the test did ably show the possibilities. "A teardrop-sized DNA computer, using the DNA logic gates, will be more powerful than the world's most powerful supercomputer. More than 10 trillion DNA molecules can fit into an area no larger than 1 cubic centimeter (0.06 cubic inches). With this small amount of DNA, a computer would be able to hold 10 terabytes of data, and perform 10 trillion calculations at a time."[33]
To power the biochemical computer, a molecule called ATP is added for fuel. In 2004 the Israelis developed a method to power the computational device that uses enzymes within the DNA to provide the energy. Again, their efforts are just in the initial stages, but they predict a computer with the performance of 330 trillion operations per second. If they are successful at meeting these goals, they will develop a device more than 100,000 times more powerful than the fastest personal computer.[34] Finally, the Defense Advanced Research Projects Agency, through their bio-computational systems effort, is developing DNA computing and storage.[35]

The MEMS revolution is leading the way to developing small-scale inertial reference systems for navigation, guidance, and control. MEMS accelerometers are common in automobiles today, pivotal for sensing impact and triggering the deployment of safety air bags (Figure 7.3). The most successful types are capacitive transducers resulting in sensor simplicity, low power consumption, and stability over temperature variations. For example, Analog Devices makes a three square-millimeter chip that contains a two-axis accelerometer requiring less than two microamperes of power (Figure 7.4).[36] For example, a typical household circuit carries 20 amperes covering several plugs in a room. Similarly, universities are developing MEMS geophones and gyroscopes to sense angular rotation. A combination of accelerometers, geophones, and gyroscopes can yield an accurate inertial reference unit small enough for the micro-unmanned air vehicle.

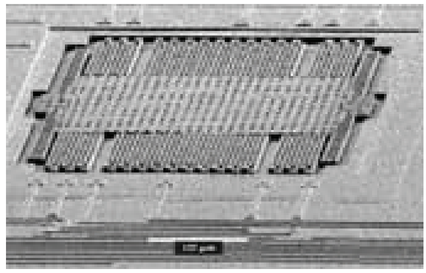

Figure 7.3 Typical Airbag Sensor[37]

Figure 7.4 Analog Devices MEMS Accelerometer[38]

The Defense Advanced Research Projects Agency (DARPA) is also investigating miniature Global Positioning System receivers. The effort, under the nano-mechanical array signal processing designation, has the goal of developing antennae arrays 0.8 square-centimeters with a power consumption of three milliwatts. The effort will use resonant structures for signal processing, allowing miniature devices to receive satellite timing information. This data is of value when the micro-robot is flying in an open environment before entering a building or bunker complex. The data will initialize the inertial reference system for subsequent flight.[39]

Sensors

Presently, imaging sensors are too cumbersome for the proposed "housefly" unmanned vehicle. Research agencies are working toward miniaturized sensors using MEMS technology and copying nature. Biomimicry will open the door to a multitude of options. With 20 years of additional research, the ability to locate specific individuals by smell, touch, or DNA is within the realm of possibility.

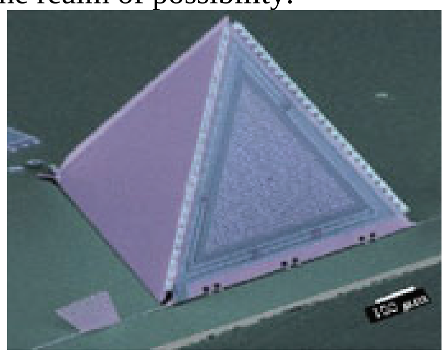

Figure 7.5 MEMS Microphone[40]

The initial success for miniaturized sensors is in acoustics. DARPA's microsystems technology office has contracted over 15 efforts with academia and industry to expand today's current capabilities. They have demonstrated directional and omni-directional microphones, less than 10 square millimeters in area, with sensitivities on par with the best commercial microphone at four orders of magnitude less cost (Figure 7.5).[41] Through this funding, Draper Laboratory built a MEMS microphone more sensitive than commercially available hearing aid microphones.[42] Additionally, the State University of New York at Binghamton has modeled the anatomy of the housefly's ears and manufactured a MEMS duplicate. This sensor is 0.5 square millimeters in size, providing a low-cost sensor for hearing aid applications.[43] Technical applications utilizing micro-electromechanical systems and biomimicry enable development and refinement of mature miniature acoustic sensors.

While the acoustic sensors seem technically mature, miniature chemical and biological sensors are several years away. Both the Army and DARPA are interested in funding the development of chemical and biological agent detectors. These sensors either measure the electrical response between a metal and the chemical or they detect a signal from a biological component's reaction to a toxin.[44] The biological warfare defense detection program is attempting to develop a biochip that will detect anthrax with very low false alarm rates. By manufacturing a nucleic-acid-base array, researchers were able to develop a pox biochip in 2002. In 2004 researchers developed a single chip containing all DNA sequences enabling the identification of biological agents. The next goal is to add sequences with brucellosis and yersinia pestis (plague) onto the chip.[45]

Scientists at NASA's Ames Research Center have developed an ultra-sensitive electronic DNA sensor using carbon nanotubes. These nanotubes are carbons sheets that are rolled up into tubes from 30 to 50 nanometers in diameter.[46] The nanotubes are loaded onto arrays of chromium electrodes on a silicon wafer at a density on the order of 100 million to 3 billion items per square centimeter.[47] The device is sensitive enough to identify specific DNA in samples of 3.5 million molecules and may identify it in samples as small as a few thousand molecules. In fact, it can precisely identify a biological contaminant with a sample of only one-one thousandth of a drop of water.[48] Conceivably, these sensors could identify a specific individual or a race of individuals by sampling the air in a room.

The Air Force Research Laboratory's (AFRL's) Material Directorate is studying how nature senses its surroundings. The directorate has identified the protein from the bacterium salmonella and has replicated the heat-sensing capability in a 4x4 array in about 0.25 square inches.[49] The directorate's sensor could fit on a micro-vehicle the size of a small breadbox now.[50] The benefit of this type of sensor is its minute size. Since the sensor uses a protein for detection medium, significant cooling is not required. Currently, man-made sensors are large, expensive, and require cryogenic cooling for operation. Sensors based on nature may offer a remarkable alternative for efficiency. The Air Force Office of Scientific Research funnels around $1 million of research annually into biomimetic infrared sensors.[51] One promising initiative involves duplicating the process snakes use to locate prey at night. Scientists have isolated a protein in the pit cells that is sensitive to different wavelengths of infrared energy. Despite their diminutive size, these sensors are over ten times more sensitive than man-made equivalents.[52]

The necessity to fly in an urban or indoor environment drives interest in developing miniature optical sensors to enable the robot to "see" where it is in relation to obstacles. Clearly, existing optical sensors are too large for this proposed system. Again, the approach utilizing biomimicry offers researchers the possibility of building a sensors meeting the requisite dimensional restraints. Insects are able to "see" using a technique called optical flow. "Optic flow is essentially the apparent visual motion experienced by an insect (or anything that "sees") as it travels through the environment. Objects that are close will tend to appear to move faster than objects that are far away, and objects with which the insect are on a collision course will tend to appear as if they are rapidly increasing in size."[53] Researchers have been able to duplicate the principle of optic flow in remotely operated vehicles. The Australian National University was able to show terrain following and altitude control and hovering using a two-meter fixed wing vehicle and a two-meter rotorcraft, respectively.[54] The sensor array was oriented in the downward direction enabling altitude calculations. Additionally, other researchers were able to demonstrate altitude control, terrain following, and obstacle avoidance using a ten-gram optical flow sensor. While the vehicles and sensors for these successful demonstrations are not suitable for the micro-robot, the research is promising.[55]

Dr. Geof Barrows is leading the optical research effort in the U.S. Using a 4.5-gram sensor, his team at Centeye, Inc. has demonstrated take-off and landing on a slow, fixed-wing aircraft. They are presently attempting flight down a tunnel. The current sensor consumes about 35 milliamperes at 5 volts or 170 milliwatts. The team believes that a sensor weighing ten milligrams with a power usage in the range of 10 microwatts to 1 milliwatt is feasible in the future. Their research has uncovered that the more maneuverable the unmanned vehicle, the closer it can get to an obstacle before eliciting an optical flow response. Therefore, the smaller vehicle performs better in avoiding obstacles.[56] Finally, sensor systems will need an operating system for data routing and control. Researchers at the University of California at Berkeley have developed an operating system for miniature sensors.[57] This open source computer code, TinyOS, consists of fewer than 8 kilobytes of memory—less than a small email.[58] The operating system is used to help integrate hundreds of temperature sensors monitor bird migrations, communicate the results, and listen for incoming messages.[59]

Propulsion/Power

Any measure of sensing or autonomy is not valuable unless the vehicle can move around the battlespace. Besides propulsion, the power generation from the propulsion is also necessary. Propulsion options include micro-turbine engines, off-board power systems, and the most exotic—flapping wings similar to the manner insects fly. Each of these has its advantages and disadvantages. The systems must be small enough to meet size constraints while operating from a limited fuel supply.

Propulsion

DARPA is supporting efforts in micro-turbine engine designs, and the Massachusetts Institute of Technology has developed a silicon micro-jet powered by propane with a fuel consumption of 25 grams per hour. They are integrating the engine into a micro-air vehicle to demonstrate flight for two hours at a speed of 55 to 110 kilometers per hour.[60] The drawback of using scaled-down, traditional engine designs is the increase in turbine speeds due to miniaturization. These high speeds lead to greater noise and vibration, which are not advantageous to remaining stealthy.[61] Additionally, their design speeds are not profitable for indoor applications, as the vehicle would travel too quickly to be able to maneuver around stairs or closed doors. When encountering an obstacle it would have limited options and crash.

Other possibilities for propulsion include using off-board power sources, such as microwave and lasers. This technology is beneficial because the platform would not have to carry its fuel with it during the mission. The body of the vehicle would act as the antenna receiving the energy and converting it to propulsion.[62] This power source would enable the vehicle to be small indeed. Unfortunately, the microwave or laser source would require very high power and would need to be nearly collocated to provide enough efficient energy.[63]

Biomimicry is providing the most intriguing source of examination to this point. Scientists and engineers are investigating duplicating insect flight as the standard for future unmanned vehicles. Since man's initial attempts at breaking the bounds of earth, humans have looked to nature as a possible solution. The Georgia Institute of Technology is attempting to mimic the wings and flight of a flying insect.[64] When operating indoors, slower flight is better. The vehicle must be able to maneuver through hallways, rooms, and tight spaces, which requires either a rotorcraft or flapping wing design. While the rotor is relatively simple to turn, it is inefficient due to the varying angular rotation throughout the length of the blade.[65] Propellers, or rotor systems, below three inches in diameter are inherently inefficient—approximately 50 percent less than a larger sized propeller due to the close proximity of the tip to the hub.[66] Finally, a rotorcraft has the disadvantage of creating a significant acoustic signature. The frequency of the flapping wing design is much lower and thus offers a noteworthy advantage in stealth.[67]

Besides solving the complex aerodynamic equations to prove this type of flight is possible, the researchers needed to develop a method to drive the wings. Dr. Robert Michelson's Georgia Institute of Technology team utilizes a reciprocating chemical muscle to provide energy. His team took advantage of the fact that more energy density is achieved through a chemical reaction than through electrical energy storage. For example, a drop of gasoline has more energy potential than a comparable sized battery.[68] At this time, electrical storage density is unable to produce missions with long durations.

The reciprocating chemical muscle allows the mechanical wings to beat based on a chemical energy source.[69] The muscle utilizes a non-combustive chemical reaction and the resulting gas discharge to expand a spring. The muscle converts chemical potential energy directly into kinetic energy with high efficiency.[70] Advantageous side effects include the generation of small amounts of electricity based on the beating wings and the ability to steer the vehicle through differential flapping.[71] The micro-vehicle could fly from point-to-point and rest while collecting data from its sensors using the power generated from flying. By utilizing a series of hop flights, the platform could traverse a long distance to the target.

A team at UC Berkeley is also working on a micro-mechanical flying insect (Figure 7.6). Their concept is to use solar energy to drive three miniature motors for each wing providing the up and down, back and forth, and rotation motions. The goal is to manufacture a stainless-steel micro-robotic fly weighing just over 40 milligrams that is 10 to 25 millimeters in width.[72] The vehicle body will be made from thin stainless steel and the wings from Mylar.[73] Leveraging the scaling factors due to the Reynolds number, the team has built 25-centimeter Plexiglas wings and submerged them in mineral oil. The thick solution with the large wings equates to small wings in ambient air.[74] The researchers have been successful at reaching 90 percent of the force required for liftoff within the above size limitations.[75]

Using the rotorcraft approach, the Seiko Epson Corporation demonstrated flight with an 8.9-gram micro-vehicle. The unmanned system "levitated" while attached to a 3.5-volt power supply. The vehicle uses two contra-rotating propellers powered by four miniature ultrasonic motors. The goal is to have the robot take pictures from untethered flight.[76]

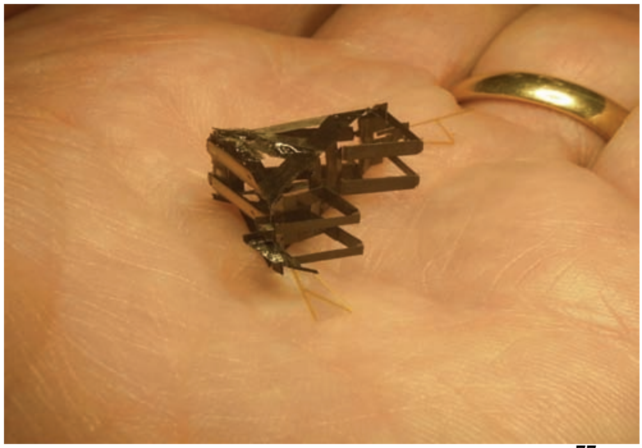

Figure 7.6 UC Berkeley's Robofly[77]

Power Generation

Packaging a power source small enough to fit within a limited volume but potent enough to run the sensors, computers, and communication systems is a challenge. The main issue is the available energy density—putting stored energy in a small package that does not weigh too much.[78] Power requirements for a micro UAV are relatively low. Dr. Kris Pister, UC Berkeley, calculates that just a few nanoJoules of energy are needed to conduct sensor operations, simple processing, and communication.[79] Key technologies in the power realm are micro-engines, DNA motors, batteries, and fuel cells.

MIT's micro-turbine engine is a single-spool, one-gram, MEMs turbojet with a rotational speed of 2.4 million revolutions per minute (Figure 7.7).[80] This engine produces a power output of 50 watts, comparable to a lithium battery. Yet, it has one-twentieth the weight and almost one-fourteenth the volume of the battery. The motor has an energy density fifteen times larger.[81] While the power outputs are adequate to meet the requirements, this engine is too large for the proposed fly-sized vehicle.

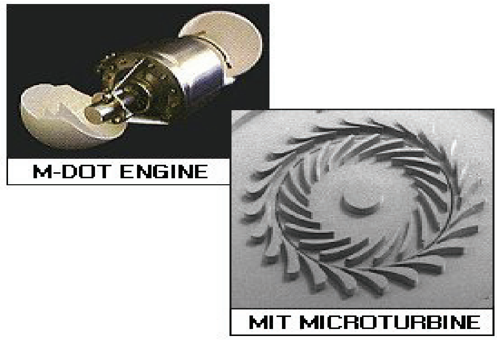

Figure 7.7 Massachusetts Institute of Technology Microturbine[82]

Bell Laboratory is investigating DNA motors, a separate power generation technology not provided from the propulsion source. DNA, due to its molecular size, is the proper scale for the micro-machines described in the scenarios. Bell's studies focus on mixing three single strands of DNA in a chamber. One strand bonds itself to half of another strand, and the third latches onto the remaining half. By adding a DNA fuel substance, the open ends will bond together. Additional DNA will uncouple the last bond opening the strands for more partners. By using DNA with electrical molecules, the process of bonding and disbonding can result in electrical charge.[83] Additional research is required to determine whether this power generation method is sufficient to meet the needs.

The most promising technology that meets the packaging and power requirements is fuel cells. A fuel cell is an electrochemical device similar to a battery that combines a gaseous fuel with oxygen to produce electricity and heat. Water is a byproduct of the reaction.[84] DARPA has contracted Case Western University to investigate fuel cell capabilities. Researchers have developed a 0.2 square centimeter fuel cell prototype producing 100 microwatts of continuous power—over 30 hours—with a peak ability of 20 microwatts over a fifteen-millisecond pulse.[85] The fuel cell systems have a power density of 15 milliwatts per square centimeter, with a goal of 40 milliwatts per square centimeter.[86] The aim of the program is to develop a four-square centimeter fuel cell delivering ten milliwatts.[87] Presently, fuel cell technology appears to be the most appropriate for future miniature scale unmanned vehicles.

Communication

The final technology concerns communication. Present communication systems are too bulky and require significant amounts of power when compared to micro-vehicles. Even the use of the reciprocating chemical muscle and the resultant power generation would not provide sufficient amounts of energy required to communicate over vast distances. Several options exist for communication outside of classical means. These alternatives include radio frequency MEMs, lasers, and biomimicry.

DARPA is funding research into radio frequency MEMs. Breakthroughs have occurred in building miniature switches that are key to radio design. Contractors have developed 200 to 1,000 micron switches using less than a milliwatts of power.[88] These efforts are the initial steps in fabricating a very small-scale radio system. The Xemics Corporation has demonstrated a transceiver chip with frequency coverage from 30 kilohertz to 915 megahertz.[89] With a decent antenna, a range of 100 meters at 10 kilobits per second should be feasible with one milliwatt transmitted. By incorporating directional antennas, the range could increase to one kilometer increasing the transmitted power to 10 milliwatts. Multipath issues could occur in an urban or indoor application.[90]

Again focusing on biomimicry, AFRL is studying bioluminescence. The scientists have isolated the material responsible for lighting organisms in the deep ocean. Some of the luminescence is outside of the visible spectrum requiring detection by infrared or ultraviolet detectors. For example, imagine a firefly visible in the infrared region only. One would not be able to see the firefly with the naked eye but through external filters. If this luminescence could be altered at will, the micro-vehicle could turn on and off the “lights” with a pattern. In effect, the platform could transmit data through a code of timing the “lights.” By viewing the battlespace with the proper spectrum filters, communication could occur. Communication is the key attribute for the intelligence, surveillance, and reconnaissance scenario.

IV. Limitations

It must be considered that nothing is more difficult to transact, nor more dubious of success, nor more dangerous to manage, than to make oneself chief to introduce new orders. Because the introducer has for enemies all those whom the old orders benefit, and has for lukewarm defenders all those who might benefit by the new order --Niccolo Machiavelli[91]

The previous section showed the maturity of the technologies responsible for the fly-sized UAV. While scientific research and investment is attempting to overcome some of the engineering riddles, limitations do exist including the technological maturity, sponsorship, and the natural environment. This section concludes with an alternative approach to reaching the endstate of an insect-like vehicle. This stepping-stone will help mitigate some of the risk inherent in the proposed miniature vehicle.

Technical Maturity

As discussed previously, the technical maturity is not present today to field the system. Three major initiatives need examination before any miniature unmanned aerial vehicle can be practical. These include non-scaling items, stored energy, and propulsion.[92] Non-scaling items relate to external factors over which one has little control. For example, the communication antennas may not provide the gain or directionality required when shrunk to fit within the confines of the proposed degree.[93] The necessary components of the communication system and visual sensors may not allow miniaturization.

The energy density of the power source is critical to building a mobile sensor at this scale.[94] For sufficient mission duration, sensor activity, and range, current battery technology does not enable long endurance missions. The expectation is that fuel cells may contribute. For now, chemical or fossil fuels will have to provide the source of energy. The third area requiring significant development is in propulsion, whether for flying forward, hovering, or crawling. As previously discussed, mimicking biological flight is optimal indoors.[95] The robotic sensor must fly in a confined environment and be able to transition to crawling and back to flight as required. The requirement to crawl is drawn by the fact that the vehicle may encounter closed doors and must be able to crawl under them.

Resolving these limitations will take a systems engineering approach. Due to the limited packaging space available in the miniature system, a high degree of integration is required.[96] Only by looking at all of the technical issues as a whole and making the necessary trade-offs between them can a scientist design an optimal sensor system. The type of power system, whether a fuel cell or fossil fuel, may drive the possible types of a propulsion system. Likewise, the amount of power density within the system will determine to energy budget for sensors and communication systems.

The University of California at Berkeley's micro-mechanical flying insect project is developing the integrated system. Currently, they are manufacturing a 3-centimeter by 3-centimeter version with a mass of 0.1 gram. The device shows the capability to provide lift greater than weight. They anticipate the required flight power to be 5-10 milliwatts, and electric power, including mechanical and electrical power will need to be 20-30 milliwatts from a battery. They are integrating various sensors, including an optical flow sensor weighing less than 10 milligrams and using less than two milliwatts of power. The insect uses piezo-electric actuators as motors to power the wings, providing 500 watts per kilogram. With a lithium battery source, a flight time of 10 minutes is anticipated.[97]

Sponsorship

The concept of operations for a micro-UAV is outside the Air Force leadership's long-term vision, hampering development. To bring this promising scenario to fruition, an organization must adopt the requirement. Ideally, a DOD or joint office could initiate the integration effort. The Army and the Marine Corps have units responsible for chemical and biological weapons detection, and U.S. Special Operations Command is the supported commander for the war on terrorism. The proposed vehicle could facilitate covert intelligence collection on terrorist organizations without having to expose a human.

Because the vehicle is a flying machine, the Air Force should be the lead service for the development, testing, fielding, and sustainment, with either Air Force Special Operations Command or 8th Air Force being a candidate organization. Air Force Special Operations Command is chartered to conduct non-conventional operations, and 8th Air Force is responsible for intelligence, surveillance, and reconnaissance missions. Either approach could help consolidate the various research and funding efforts. Research is occurring throughout many universities and laboratories examining the multitude of technological challenges. A central voice would help prioritize the effort, thereby ensuring limited resources are spent on promising solutions vice the broad spectrum investigated today.

The candidate offices could also provide significant intellectual work to refining the concept of operations. The definition of possible operational uses of the system would further focus the research effort. From the concept of operations, the organization could develop the tactics, techniques, and procedures for the specific hardware. The organization could guarantee the development of an acquisition strategy clearing the way for a definite capability. If this unmanned vehicle is to exist by the 2020 timeframe, the identification of this supporter must occur within the next five years.

Nature

Besides the technological challenges and the limited deliberation concerning concept of operations, the fly-sized vehicle will encounter ordinary pressures. Several natural predators to the common housefly would also be threatening to the envisioned miniature, flying robot. These threats include wildlife such as birds, frogs, and vegetation. These biological systems may treat the sensor aircraft as if it were a true fly. Similarly, the proposed unmanned aerial vehicle is susceptible to sticky surfaces—for example, fly paper. The anticipated sensor does not have the required power to liberate itself from these types of bonds. The diminutive size would require optimization for packaging of its components. Previously, this paper identified the limited power density available in this system. Designing solutions to each of these inhibitors is impractical. By keeping the unit price to a minimum, less than $20 thousand, the loss of a vehicle is acceptable.[98] The robotic fly is envisioned to be a truly disposable system. The vision is for a fleet of over 100,000 vehicles with enough flexibility for attrition. Therefore, the total production cost would be approximately $2 billion.

This throwaway philosophy will also reduce maintenance costs. The current policy is to perform depot level maintenance on a recurring basis. This repair work entails breaking down the system to sub-components and performing inspections and, if necessary, refurbishment. The low cost micro-scale of an insect vehicle does not require periodic inspections. A military could keep this sensor system in storage and conduct a built-in-test just prior to use. If the robot did not pass the test, discarding might be the best option. In the worst case, a non-functioning system could be cannibalized for spare parts.

Another natural barrier for the vehicle is weather. With its diminutive size and a forward speed of about 25 miles per hour, both wind and precipitation limit flight. During strong winds, the robot would have to either fly near the ground or crawl. Ideally, the ultimate environment for the micro-unmanned vehicle is indoors. Normally, the surroundings interior to a building, underground facility, or cave complex do not exhibit the breezes or precipitation limiting flight.

Near-term Approach

What is the plan for bringing the vision past the realm of science fiction? Clearly, researchers must resolve the technical issues. A possible alternative is to reach for a near-term approach between the DOD roadmap's micro-UAV and the fly-sized vehicle. A vehicle the size of a dragonfly is the middle ground. Currently, the military acquisition workforce is embracing spiral development. Under this concept, a system is fielded with multiple iterations consisting of several increasing capabilities. The spiral development approach is one way of providing equipment to the warfighter in a timelier manner.

Legacy acquisition systems have taken an increasingly longer time to fill a user's requirement. For example, the F/A-22 program began in the early 1980s, and more than twenty years later, the first operational fighter aircraft are just coming off the production line. This program was supposedly aided by a prototype phase in the early 1990s attempting to resolve engineering issues. Spiral development would shorten this extended development timeline substantially. By utilizing this concept, the acquisition community could deliver ever-increasing capability every five years. Instead of waiting for technological solutions that may or may not occur, the warfighter could exercise an 80 percent solution more quickly.

The intermediate-sized "dragonfly" approach would be that interim solution giving the operator a near-term capability. Table 7.1 shows the differences in scale between a dragonfly and the common housefly, with the dragonfly being approximately two orders of magnitude larger. This increased size would lessen many of the technological limitations described above. Finally, the dragonfly is approximately half the size of the smallest "bird-like" vehicles prescribed in the Department of Defense roadmap. The scale seems to offer an appropriate middle ground.

	Weight (grams)	**Length** (mm)	**Wing Span** (mm)	**Speed** (mph)
Dragonfly	--	70-100[99]	100-190[100]	--
Housefly[101]	0.04	5-7	14	25-35

Table 7.1 Dragonfly and Housefly Comparison

A recent Fox News television special on the Central Intelligence Agency's tools of spy craft displayed a dragonfly-mimicking unmanned vehicle. The agency developed the system over 30 years ago as an effort to eavesdrop on Soviet Union activities. They decided to shelve the project due to the limited performance of the vehicle in windy conditions.[102] Computer and guidance technology have significantly increased through the intervening years. Possibly the problems of the past are rectifiable with the latest improvements.

V. Conclusions

> *Transformation is impossible unless hundreds or thousands of people are willing to help, often to the point of making short-term sacrifices.*[103]
>
> -- John Kotter

Clearly, the miniature flying robot sensor offers a nation the ability to deny an adversary a safe haven. During his testimony before the Senate Appropriations Committee concerning the 2004 Presidential budget, Secretary Donald Rumsfeld identified six goals of the future defense transformation:

- Defend the United States homeland and bases of operations overseas
- Protect and provide for military units throughout distant theaters
- Deny enemy sanctuary
- Improve space capabilities and assure space access
- Continue to embrace information technology enabling the military to fight jointly
- Protect the infosphere from outside attack

To deny enemy sanctuary, Secretary Rumsfeld requested over $49 billion over the future years defense plan.[104] He called for continued investment in a persistent intelligence capability and cited the military's performance in OIF as highlights of our capabilities today.

The fly-sized vehicle would definitely meet the Secretary's goal of denying sanctuary for our adversary. The United States has a robust intelligence, surveillance, and reconnaissance architecture with the current air-breathing and space assets. While the existing network is very capable, our enemies have still found ways to keep their intentions hidden. During the Vietnam War, for instance, the North Vietnamese and the Viet Cong resorted to building tunnel complexes to hide from American intelligence eyes. These complexes afforded them a haven to rest, train, and protect their forces. To counter this threat, the United States used Army personnel as rat patrols to enter the caves and investigate. The proposed concept could lessen risk in such a scenario. Soldiers could release the sensor at the tunnel opening. The system could then fly through the complex recording conversations, the tunnel design, and the number of personnel and their locations. From this information, friendly military commanders could determine the appropriate method for neutralizing the asymmetric advantage.

Another example of sanctuary is al Qaeda's use of caves in Afghanistan and Pakistan. The rugged terrain and the various nooks and crannies provided these terrorists a refuge from U.S. overhead reconnaissance. The American response was to use thermobaric explosives—material that denies oxygen in a confined environment—in an attempt to negate their advantage. The use of a small, unmanned system could provide useful data instead of dead bodies. The micro-UAV could use its DNA sensor to determine the facility's inhabitants. Additionally, it could record conversations for future exploitation, information that could reveal the location of future terrorist attacks or the cell infrastructure.

As described above, the proposed system has significant intelligence benefits over today's existing systems. The United States has a very robust intelligence, surveillance, and reconnaissance aptitude, resident in overhead satellites, high flying manned aircraft, such as the U-2, and unmanned systems like the Predator and Global Hawk. The downside is our susceptibility to prediction. Due to the declassification of some of these systems and the spread of information across the Internet, our adversaries are able to determine the time overhead sensors will collect data.

Human intelligence is the most critical portion for uncovering terrorist groups. Terrorists groups know our surveillance capabilities. They have adapted by hiding their exercises from our satellites, using fiber optic communication links, and coding their messages when utilizing cell phones. The optimal manner to intercept terrorist attacks is to infiltrate their organizations, learn their plans, and neutralize the actors.[105] Normally, the Directorate of Operations within the Central Intelligence Agency is tasked to exploit human intelligence. Unfortunately, the directorate has had difficulty expanding in this area. The small, unmanned platform could be an adequate alternative to training personnel for dangerous, terrorist organization penetration. The robot could record conversations and plans for later deciphering. The system could mitigate the risk associated from using humans for the same information. These systems could reduce the impact of years of human intelligence funding shortfalls. A fly with a microphone recorder is ubiquitous enough not to draw attention.

The hunter/killer version of the organism contains the deepest implications for a country planning to incorporate the technology. Using the robot as described in the beginning of this paper may violate international law. Realistically, users of the miniature capability would likely develop additional varieties beyond just an intelligence source. Similar to the Hellfire missile modification of the Predator vehicle, champions of the small-scale unmanned vehicle would search for lethal packaging, possibly in the form of a genetic-altering weapon. Or, theoretically, a designer could package a tiny amount of explosives and make the aerial sensor into a kinetic device. By first identifying the key individuals, several platforms could swarm onto the victim prior to detonation. The combined effect of multiple explosions would be akin to killer bees attacking a human incapacitating the target.

Some zealots for new technology have over-sold their concepts by saying their widget can replace the need for uniformed military personnel. Early airpower advocates, such as Douhet and Mitchell, entertained the notion that airpower could replace fielded forces. The fact that airpower could utilize another dimension and bypass standing ground formations was the basis for the prophecy. In reality airpower did not replace ground forces, but it became just as important. Similarly, the miniature vehicle will not replace existing squadrons of aircraft or the need for companies of troops. The minute system is a niche design filling a void in intelligence capability. The robot will form the third leg of a triad of surveillance systems including space and persistent aircraft. It would be another valuable tool in the kit bag of a future joint warrior faced with an uncertain and volatile adversary.

The goal of building a miniature vehicle by 2020 or 2030 is achievable. The current state of research is providing a firm foundation.

The Central Intelligence Agency recently displayed a dragonfly-sized and mimicked unmanned vehicle that flew thirty years ago. While they discovered maintaining flight in gusty wind conditions to be difficult, they were able to package a sensor in a small environment. The advances in computer power and control logic may help reduce these problems. The postulated system would deny our adversaries the sanctuary they so desperately seek.

Notes

[1] John P. Kotter, *What Leaders Really Do* (Cambridge: Harvard Business Review Press, 1999), 81.

[2] Daryl J. Hauck, "Pandora's Box Opened Wide: Micro Unmanned Air Vehicles Carrying Genetic Weapons," (Maxwell AFB AL: Air War College, 2004), 20-27.

[3] Hans Binnendijk, ed., *Transforming America's Military* (Washington D.C.: National Defense University, 2002), 41.

[4] Ray O. Johnson and Malcolm R. O'Neil, "AF Scientific Advisory Board Report on: Unmanned Vehicles in Perspective: Effects, Capabilities, and Technologies," June 2003, 4-5.

[5] Johnson and O'Neil, 3-6.

[6] Kenneth P.Werrell, *Evolution of the Cruise Missile* (Maxwell AFB AL: Air University Press, September 1985), 8-14.

[7] Werrell, 41-62.

[8] Lt Col Richard M. Clark, *Uninhabited Combat Aerial Vehicles: Airpower by the People, for the People, but not with the People,* CADRE Paper No. 8 (Maxwell AFB AL: Air University Press, August 2000), 20-27.

[9] "RQ-1 Predator Unmanned Aerial Vehicle," *Air Force Fact Sheet*, May 2002. On-line. Internet, 21 August 2003. Available from http://www.af.mil/news/factsheets/RQ_1_Predator_Unmanned_Aerial.html, n.p.

[10] Anil R. Pustam, "Unmanned Aerial Vehicles: Trends and Prospects," *Military Technology* 26, no. 11 (2002), 44.

[11] Department of Defense, *Unmanned Aerial Vehicles Roadmap: 2002-2027* (Office of the Secretary of Defense, December 2002), iv.

[12] AF Predator Fact Sheet, n.p.

[13] Department of Defense, 10.

[14] Department of Defense, 127-133.

[15] Department of Defense, 128.

[16] Ibid.

[17] Department of Defense, 129.

[18] Department of Defense, v.

[19] Ibid, 72.

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

[21] Janine M. Benyus, *Biomimicry: Innovation Inspired by Nature* (New York: William Morrow and Company, 1997), i. Emphasis included from the original.

[22] Michael Dickinson, "Solving the Mystery of Insect Flight," *Scientific American,* June 2001, On-line 22 November 2003. Available from http://www.sciam.com/article.cfm?chanID=sa006&articleID=000EE5B1-DCA8-1C6F-84A9809., n.p.

[23] Michio Kaku, V*isions: How Science will Revolutionize the 21st Century* (New York: Anchor Books, 1997), 270.

[24] John D. Anderson, Jr., *Fundamentals of Aerodynamics* (New York: McGraw-Hill Book Company, 1984), 25.

[25] Dickinson, n.p.

[26] "Micro Air Vehicles." On-line. Internet, 25 January 2004. Available from http://www.aero.ufl.edu/~bfc/html/body_related_info.htm., n.p.

[27] Dickinson, n.p.

[28] Ray Kurzweil, *The Age of Spiritual Machines: When Computers Exceed Human Intelligence* (New York: Penguin Books, 1999), 203.

[29] "Micro Aerial Vehicle Research," University of Notre Dame, On-line 13 December 2003. Available from http://www.nd.edu/~mav/research.htm., n.p.

[30] Kurzweill, 21.

[31] Ibid.

[32] Kevin Bonsur, "How DNA Computers Will Work," *How Stuff Works*, On-line 2 December 2003. Available from http://computer.howstuffworks.com/dna-computer.htm., n.p.

[33] Ibid.

[34] Ibid.

[35] "Fact File: A Compendium of DARPA Programs," Defense Advanced Research Projects Agency, August 2003, 51.

[36] Ibid.

[37] David Bishop et al., "The Little Machines That are Making it Big," *Physics Today*, October 2001, On-line 22 November 2003. Available from http://www.physicstoday.org/pt/vol-54/iss-10/p38.html., n.p.

[38] "MEMs Technology," *Analog Devices,* On-line 24 February 2004. Available from http://www.analog.com/Analog_Root/productPage/productHome/0,2121,generic%3DADXL320%, n.p.

[39] Dr. Daniel J. Radack, "Nano Mechanical Array Signal Process (NMASP): Overview," Defense Advanced Research Projects Agency, On-line 13 September 2003. Available from http://www.darpa.mil/mto/nmasp/overview/index.html., n.p.

[40] David Bishop et al., n.p.

[41] DARPA Compendium, 69.

[42] J. Bernstein, "MEMS Air Acoustics Research," *Air Acoustics,* August 1999, On-line 22 November 2003. Available from http://www.darpa.mil/MTO/sono/presentations/draper_bernstein.pdf., n.p.

[43] Ronald N. Miles, "Biomimetic Acoustic Sensors," On-line 22 November 2003. Available from http://www.darpa.mil/MTO/sono/natureinspired.html., n.p.

[44] Michael Walsh, "Nano- and MEMS Technologies for Chemical Biosensors," Defense Advanced Research Projects Agency, On-line 21 October 2003. Available from http://www.atp.nist.gov/atp/focus/98wp-nan.htm., n.p.

[45] DARPA Compendium, 1.

[46] Eric Smalley, "Chip Senses Trace DNA," *Technology Research News*, 30 July – 6 August 2003, On-line 4 December 2003. Available from http://www.trnmag.com/Stories/2003/073003/Chip_senses_trace_DNA_073003.html.

[47] Ibid.

[48] Ibid.

[49] Lawrence L. Brott et al., "The Creation of a Hybrid Protein/Conductive Polymer Thermosensor," Materials and Manufacturing Directorate, Air Force Research Laboratory, 6 February 2003.

[50] Discussions with Dr. Morley Stone, Air Force Research Laboratory Materials Directorate.

[51] Kelly Hearn, "Snake Proteins May Make Good Sensors," United Press International, 28 February 2001, On-line 7 December 2003. Available from http://www.globalsecurity.org/org/news/2001/010228-ir.htm., n.p.

[52] Lee Dye, "Double Vision: How Snake Eyes Could Lead to Smarter Missiles and Stop Cancer," ABC News, 9 January 2002, On-line 7 December 2003. Available from http://more.abcnews.go.com/sections/scitech/DyeHard/dyehard020109.html., n.p.

[53] G.L. Barrows, *Future Visual Microsensors for Mini/Micro-UAV Applications,* 2002 Conference on Cellular Neural Networks and Applications, Frankfurt, Germany, On-line 22 February 2004. Available from http://www.centeye.com/pages/resources/downloads.html., n.p.

[54] Ibid

[55] Ibid

[56] Discussions with Dr. Geof Barrows. Email on 22 February 2004.

[57] Heather Green, "Tech Wave 2: The Sensor Revolution," *Business Week*, 25 August 2003, On-line 22 November 2003. Available from http://www.businessweek.com/magazine/content/03_34/b3846622.htm., n.p.

[58] Ibid.

[59] "Feature: Thanks to advances in nanotechnology, RF and RF MEMS, researchers say a cloud of miniature self-organizing sensors could monitor chemical spills or tell you your milk is sour," *Hoovers Online,* 24 October 2003, On-line 22 November 2003. Available from http://hoovers.com/free/news/detail.xhtml?ArticleID=NR200310243400.1.5_25f900643b1., n.p.

[60] G.V. Goebel, "Miniature UAVs," 1 January 2003, On-line 13 September 2003. Available from www.vectorsite.net/twuave.html., n.p.

[61] Ibid.

[62] Dale Kuska, "Micro-UAVs Possible in Near Future," American Forces Press Service, January 1998, On-line, 2 December 2003. Available from http://www.fas.org/irp/news/1998/9801072.html., n.p.

[63] Alan Vick et al., "Aerospace Operations in Urban Environments: Exploring New Concepts," Rand, 2000, On-line, 4 February 2004. Available from http://www.rand.org/publications/MR/MR1187/MR1187.appb.pdf., n.p.

[64] "Microspies: A Web Anthology," *Air & Space Magazine,* On-line 6 December 2003. Available from http://www.airspacemag.com/asm/mag/supp/am00/uSPY.html., n.p.

[65] Robert C. Michelson and Steven Reece, "Update on Flapping Wing Micro Air Vehicle Research: Ongoing work to Develop a Flapping Wing, Crawling Entomopter," 13th Bristol International RPV/UAV Systems Conference Proceedings, Bristol England, 30 March 1998-1 April 1998, On-line 2 December 2003. Available from http://advil.gatech.edu/RCM/RCM/Entomopter/paperlist.html., n.p.

[66] Michael S. Francis and James M. McMichael, "Micro Air Vehicles – Toward a New Dimension in Flight," Defense Airborne Reconnaissance Office, 7 August 1997. Available from http://www.darpa.mil/tto/mav/mav_auvsi.html., n.p.

[67] Michelson and Reece, n.p.

[68] Ibid.

[69] "Entomopter Project," Georgia Tech Research Institute, On-line 28 August 2003. Available from http://avdil.gtri.gatech.edu/RCM/RCM/Entomopter/EntomopterProjectbody.html., n.p.

[70] Robert Michelson et al., "A Reciprocating Chemical Muscle (RCM) for Micro Air Vehicle Entomopter Flight," 1997. Proceedings of the Association for Unmanned Vehicle Systems, International, June 1997. On-line 29 September 2003. Available from http://avdil.gtri.gatech.edu/RCM/RCM/Entomopter/paperlist.html., n.p.

[71] Ibid.

[72] Kevin Bonsor, "How Spy Flies Will Work," On-line 22 November 2003. Available from http://people.howstuffworks.com/spy-fly.htm/printable., n.p.

[73] "Spy Fly: Tiny, winged robot to mimic nature's fighter jets," On-line 6 December 2003. Available from http://www.robotbooks.com/spy-fly-robot.htm., n.p.

[74] Robert Sanders, "Robofly Solves Mystery of Insect Flight According to New Report by UC Berkeley Biologists," University of California, Berkeley News Release, 15 June 1999, On-line 22 November 2003. Available from http://www.berkeley.edu/news/media/releases/99legacy/6-15-1999.html., n.p.

[75] Bonsor, "How Spy Flies…"

[76] Yoshiko Hara, "Epson Develops Micro Flying Robot, sort of," *EE Times,* 21 November 2003, On-line 22 November 2003. Available from http://www.eetimes.com/story/OEG20031121S0053., n.p.

[77] "Ron Fearing's Home Page," University of California at Berkeley, 7 July 2000, On-line 24 February 2004. Available from http://robotics.eecs.berkeley.edu/~ronf/., n.p.

[78] Conversation with Dr. Robert Michelson.

[79] Kris Pister, On-line 22 November 2003. Available from http://robotics.eecs.berkeley.edu/~pister/SmartDust/in2010., n.p.

[80] Mark Hewish, "Smaller, lighter, cheaper: Micro-machines will revolutionize the way the military senses and exploits its environment," *Jane's International Defense Review* 34, May 2001, 28.

[81] Hewish, 29.

[82] Goebel, n.p.

[83] "Researchers from Lucent Technologies' Bell Labs and University of Oxford create first DNA motors," Lucent Technologies, Bell Labs Innovations, 9 August 2000, On-line 13 September 2003. Available from http://www.lucent.com/press/0800/000809.bla.html., n.p.

[84] Lea McLees, "Powering the Future: Fuel Cell Research Center's Knowledge and Innovations to Promote Sustainable Energy Sources," Georgia Tech Research News, 1 August 2000, On-line 22 November 2003. Available from http://gtresearchnews.gatech.edu/newsrelease/FUELCELL.html., n.p.

[85] Robert Savinell, "Micro Power Generation," DARPA Project Summaries, On-line 22 November 2003. Available from http://www.darpa.mil/mto/mpg/summaries/2003_1/cwru.html., n.p.

[86] Discussions with Dr. Robert Savinell. Email on 23 February 2004.

[87] Savinell, n.p.

[88] Discussions with Dr. Mike Megargee, team member of DARPA's RF MEMS Improvement program. Email on 6 February 2004.

[89] "XE1200 Series Transceivers," *Xemics*, On-line 26 February 2004. Available from http://xemics.com/internet/products/series.jsp?productID=9., n.p.

[90] Conversation with Dr. Ron Fearing. Email on 25 February 2004.

[91] Niccolo Machiavelli, *The Prince*, ed. and trans. by Angelo M. Codevilla (New Haven: Yale University Press, 1997), Chapter 6, 22.

[92] Michelson and Reece, n.p.

[93] Ibid.

[94] Conversation with Dr. Robert Michelson.

[95] Michelson and Reece, n.p.

[96] T. Spoerry and Dr. K. C. Wong, "Design and Development of a Micro Air Vehicle Concept: Project Bidule," School of Aerospace, Mechanical, and Mechatronic Engineering, University of Sydney. On-line 22 November 2003. Available from http://www.aeromech.usyd.edu.au/wwwuav/papers/Paper_mAV_Bidule.pdf., n.p.

[97] Discussions with Dr. Ron Fearing. Email on 22 February 2004.

[98] Dr. Ron Fearing, University of California at Berkeley, calculates the Robofly will cost approximately $2,000 per item. The author has conservatively added another order of magnitude based on historical defense acquisition system performance. The cost includes manufacturing only and does not take into account any maintenance or overhaul costs. Email with Dr. Fearing 24 February 2004.

[99] "Aeshna multicolor female Specimen #76 top view," Digital Dragonfly Museum, On-line 23 February 2004. Available from http://stephenville.tamu.edu/~fmitchel/dragonfly/Aeshindae/am1ta.htm., n.p. Calculated from photograph.

[100] Ross H. Arnett, Jr., *American Insects: A Handbook of the Insects of America North of Mexico* (New York: Van Nostrand Reinhold Company, 1985), 92.

[101]Available from http://www.valentbiosciences.com/environmental_science_division/houseflies.asp.

[102] Fox News broadcast, 8 February 2004.

[103] Kotter, 83.

[104] Senate Appropriations Committee, "Prepared Statement for the Senate Appropriations Defense Subcommittee: 2004 Defense Budget Review." Available from http://www.defenselink.mil/speeches/2003/sp20030514-secdef0202.html., n.p.

[105] Richard K. Betts, "Fixing Intelligence," *Foreign Affairs* 81, no. 1 (January/February 2002), 44.