Micro Air Vehicles for Optical Surveillance

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■ We present a study of micro air vehicles (MAVs) with wingspans of 7.4 to 15 cm. Potential applications for MAVs, both military and civilian, are numerous. For most military applications, MAVs would be controlled by local users, operating covertly, to supply real-time data. This article focuses on a military surveillance application that uses either visible or mid-wavelength infrared imaging sensors. We present concepts for these sensors as well as for a miniature Ka-band communications link. MAV flight control would require miniature motion sensors and control surface actuators based on technology under development by the micro electromechanical systems community. As designed, the MAV would fly in a low Reynolds-number regime at airspeeds of 10 to 15 m/sec. Propulsion would be provided by a combination of an electric motor with either an advanced lithium battery or fuel cell, or by a miniature internal-combustion engine, which is a more efficient option. Because of the close coupling between vehicle elements, system integration would be a significant challenge, requiring tight packaging and multifunction components to meet mass limitations. We conclude that MAVs are feasible, given about two to three years of technology development in key areas including sensors, propulsion, aerodynamics, and packaging. They would be affordable if manufactured in quantity by using microfabrication techniques.

In the last decade, researchers have developed increasingly sophisticated unmanned air vehicles (UAV) for military applications. In the Persian Gulf War, for example, UAVs served in surveillance missions and as decoys to distract enemy air defenses. Increased demands for intelligence are spawning the development of a smaller next-generation UAV called the micro air vehicle, or MAV. Small enough to fit in the palm of your hand, an MAV would have an operating range of several kilometers and transmit detailed pictures back to a portable base station, as shown in Figure 1. Several MAVs and their base station could be carried by a single person—an impossible scenario with the much larger UAVs, which have wingspans of 2 to 35 m.

On the basis of recent advancements in key technologies of propulsion, flight control, communications, and sensors, we believe that MAVs with wingspans of 7.4 to 15 cm, or 3 to 6 in, could be developed in two to three years. These MAVs would be ten times smaller than the smallest UAV currently flying for defense applications, the Self-Navigating Drone Expandable/Recoverable, or SENDER, from the Naval Research Laboratory. Figure 2 compares the size of two proposed MAVs with four existing UAVs, including SENDER.

Potential capabilities for MAVs range from a fixed-wing surveillance MAV that uses a data link and line-of-sight control to an advanced MAV that hovers and navigates independently and carries multiple sensors. Because of their small size and low power, such MAVs would be quite covert. In addition, exploiting microfabrication technology would make possible the production in large quantities of MAVs at low unit cost.

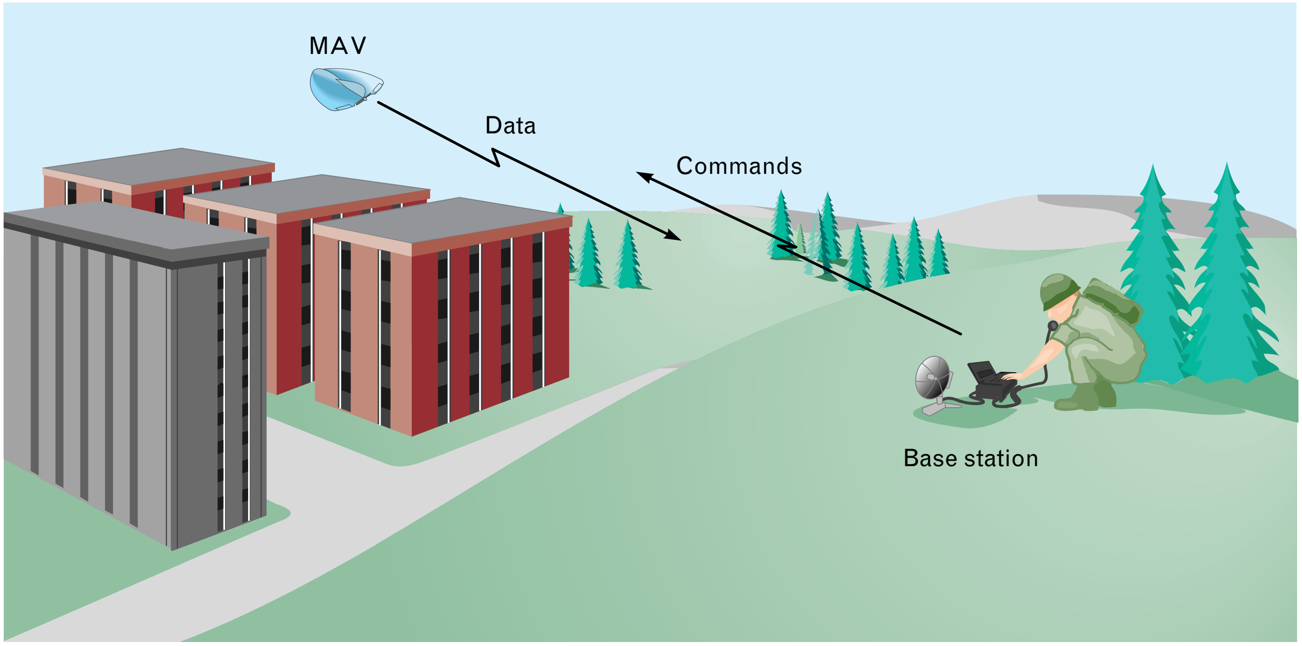


FIGURE 1. Micro air vehicle (MAV) used for reconnaissance. A soldier carrying the MAV and a portable base station could remotely monitor the MAV under hostile conditions. Sensor data could be transferred in real time or stored on board the MAV.

In December 1992, RAND [1] reported on a study conducted for the Defense Advanced Research Projects Agency (DARPA) that considered the use of a wide range of microdevices for defense applications. They projected that flying vehicles with a 1-cm wingspan and with payloads less than 1 g were feasible in ten years. We were motivated by the RAND study to look at MAVs in more detail.

Creating MAVs offers us the challenge of integrating several technologies under development at Lincoln Laboratory into a single vehicle. We began in 1994 by considering all the key MAV subsystems, including sensors, and their integration into a practical vehicle. Figure 3 shows payload mass versus wingspan for several UAVs, with predicted MAV payloads falling within the trends extrapolated from UAVs. Our initial efforts focused on determining the smallest vehicles possible within two to three years that would be built with extensions of existing technologies. These technologies included microelectronics fabrication of focal-plane arrays and radio frequency (RF) components; the relatively new field of micro electromechanical systems (MEMS); and high-performance propulsion systems.

Our initial design concept resulted in a model of a 7.4-cm wingspan MAV, shown in Figure 4. Most of the model's 10.5-g mass comes from a propulsion system comprising an advanced lithium battery and an electric drive motor. The vehicle would be equipped with a 21-GHz data link and a high-definition visible camera (1-g mass) that uses a silicon charge-coupled device (CCD) array of 1000 × 1000 pixels. We are continuing the process of evaluating subsystem technologies and are now beginning to design a 15-cm, fixed-wing MAV.

Making the Most of MAVs

The MAV has a variety of potential uses in military operations, including local reconnaissance, fire control, and detection of intruders. Law enforcement organizations could use MAVs for hostage rescue, border patrol, traffic surveillance, and riot control. For most of these applications, a swarm of MAVs could provide wide-area coverage.

Much of the appeal of the MAV for covert operations comes from its small size. To determine how "invisible" the MAV would be on the battlefield, we examined the various means of detection available to potential adversaries. To the human eye, an MAV in flight would resemble a small bird. MAV radar signatures would be similar to those of small birds and are thus likely to be lost in clutter. Furthermore, the projected MAV airspeed of 10 to 15 m/sec is below the minimum detectable velocity for most radars. Infrared search-and-track units would be able to detect an MAV only at short ranges because of its low power. For an electrically powered MAV, the acoustic signature would be dominated by the aerodynamic noise of the propeller, and would be audible only at close range. An MAV powered by an internal-combustion engine with a muffler could achieve similar acoustic performance.

Although emissions from the MAV omnidirectional communications downlink could be detected by an adversary, a broadband-radar warning receiver will have limited detection capability because of the low power emissions of the MAV. An electronic support-measures receiver, on the other hand, can intercept the communications downlink if the receiver employs a narrowbeam search antenna and the downlink frequency is known. There are several ways to limit detection, however. One strategy is to use spread-spectrum techniques; another approach is to operate the MAV autonomously, storing data on board until a later time when conditions are favorable for transmission.

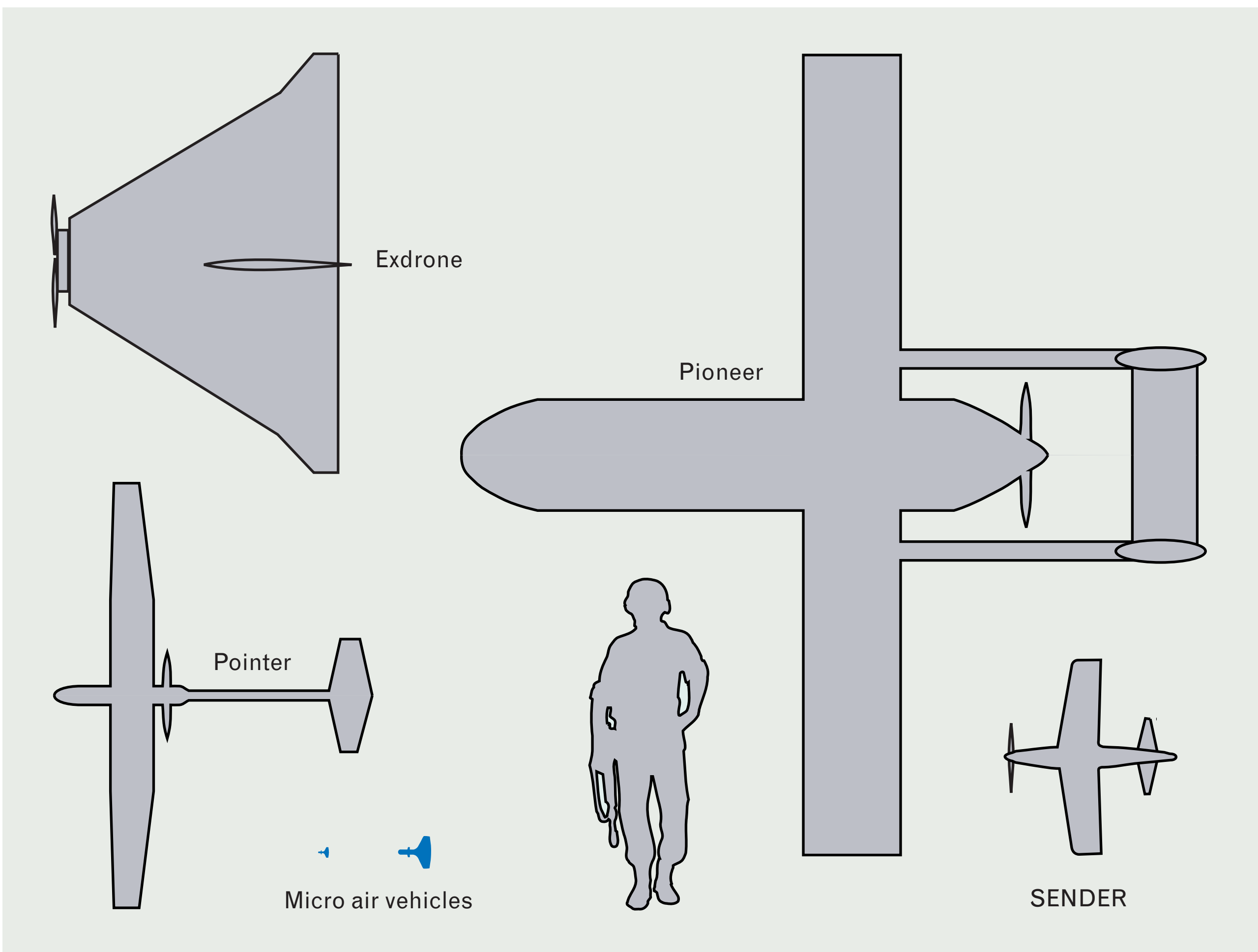


FIGURE 2. Size comparison of existing unmanned air vehicles (UAVs) and proposed MAVs. The profile of a soldier, for scale, represents six feet. The smallest known UAV for defense applications currently flying is the Naval Research Laboratory Self-Navigating Drone Expandable/Recoverable (SENDER), which has a 1.2-m wingspan. The proposed MAVs have wingspans of 7.4 cm and 15 cm, or 3 and 6 in.

Design capabilities for MAVs are tightly coupled to their missions, most of which could be carried out by using fixed-wing aircraft that can circle areas of interest. The vehicle must fly 10 to 15 m/sec—fast enough to overcome head winds—and have an endurance of 20 to 60 min to provide adequate range and mission time. For information-gathering missions, simple acoustic, seismic, or magnetic sensors can detect the presence of personnel, vehicles, and structures. Additional sensors can permit the MAV to detect chemical, biological, and nuclear contaminants in the atmosphere. Nonimaging sensors can detect light sources or measure local temperature. Visible and infrared imaging systems can provide useful data for surveillance applications.

The simplest design is an MAV that can remain within the line of sight of a small base station that tracks the vehicle, maintains the communications link, and performs navigation calculations. A vehicle that flies behind buildings or hills—beyond the line of sight—must depend on some other approach to communications and needs an independent means of navigation. One configuration that meets these requirements stores data on board with later readout when the vehicle returns to line of sight. Another configuration includes an overhead communications relay. Without a line of sight for navigation, alternative navigation approaches such as dead reckoning, inertial navigation, and the Global Positioning System (GPS) might be tapped, with the latter two depending on the availability of small components.

Intelligence gathering around or within buildings requires a hovering vehicle with a sophisticated navigation system. Alternatively, the MAV might be able to perch, or fasten itself to a fixed object, or turn into a crawler for local sensing. Combined hovering-flying vehicle possibilities include conventional main rotor-tail rotor helicopters, coaxial rotors, propulsion-driven rotors, ducted fans, and tail-sitter airplanes. For some applications, the vehicle would need to be fully autonomous and able to respond to the data received by onboard sensors.

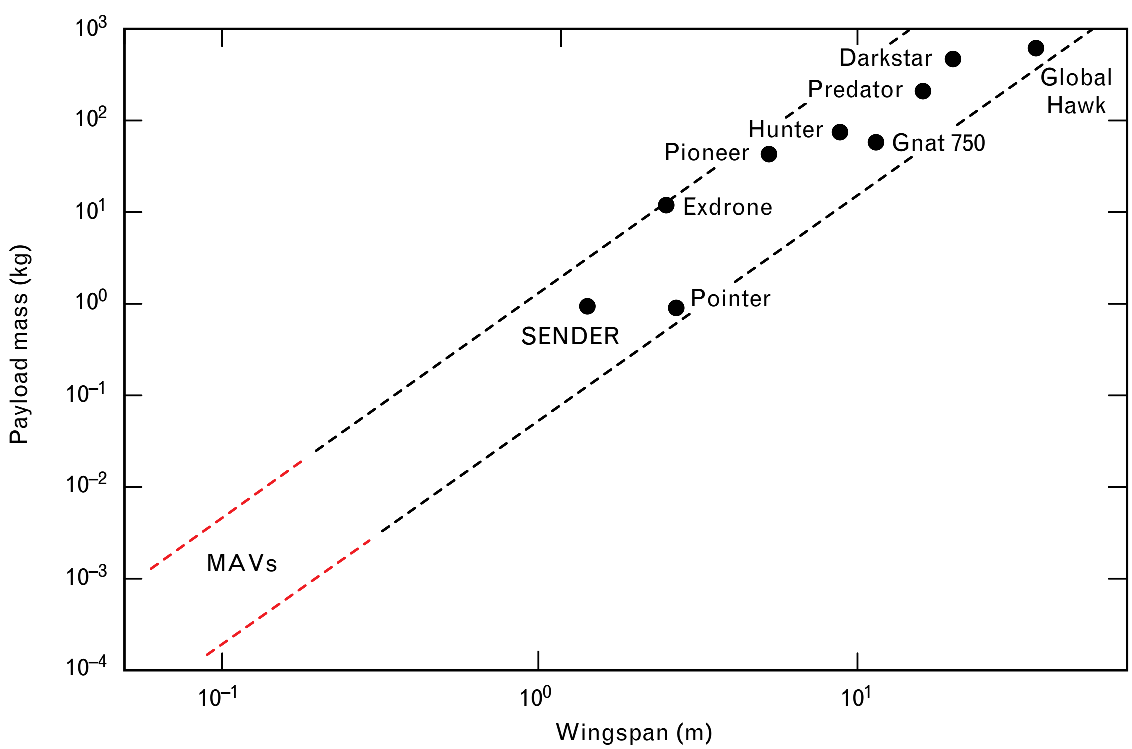


FIGURE 3. Payload versus wingspan for existing UAVs and proposed MAVs. Predicted capabilities for MAVs fall within the trends extrapolated from larger vehicles. Note that the MAVs proposed in this article are an order of magnitude smaller than existing UAVs.

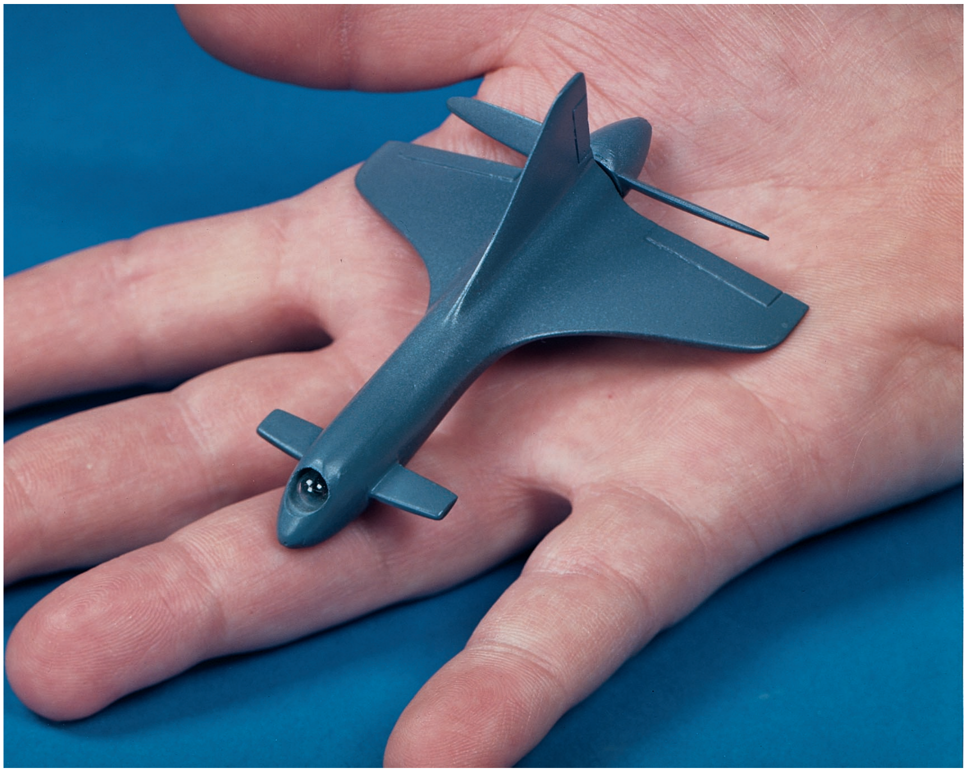


FIGURE 4. Model of Lincoln Laboratory concept of the smallest possible MAV (7.4-cm wingspan) with a visible imager for reconnaissance missions. This bottom view of the model shows the downlooking camera port in the nose.

Baseline Surveillance Application

The remainder of this article presents a baseline 15-cm fixed-wing MAV concept and discusses vehicle subsystems and the status of the technology needed to implement them. Baseline variations that provide additional performance, such as increased range, are also presented. To establish performance requirements, we chose a surveillance mission. A high-resolution, visible charge-coupled device (CCD) camera is the baseline sensor. We also discuss a larger and heavier mid-wavelength (3 to 5 μm) infrared (MWIR) camera that would increase the airframe size.

We assumed that a single MAV operates within clear line of sight of a controlling base station at ranges up to five kilometers. The base station tracks the position of the MAV, performs navigation calculations, and receives data from the MAV sensor. We also considered variations on this approach, including the possibility of GPS navigation. Table 1 summarizes additional requirements chosen for the baseline MAV.

To detect people, the MAV requires a low operating altitude of about one hundred meters. Note that even with a narrowbeam receive antenna at the ground station, multipath effects could degrade link performance significantly and the low operating altitude might not be maintained beyond a communications range of about one kilometer. Longer ranges would require higher altitudes to keep the MAV within line of sight and minimize multipath effects.

Aerodynamics and Vehicle Configuration

The aerodynamic design of MAVs offers unique challenges because of the relatively low Reynolds-number flight regime in which they fly. The Reynolds number is a nondimensional similarity parameter that relates inertial forces to viscous forces, and is proportional to the flight speed times a characteristic length, such as the wing chord. MAVs would operate at low Reynolds numbers of 20,000 to 50,000. Little research has been conducted on aircraft in the low-Reynolds-number regime, and both analytical and experimental research is required to develop the MAV. We do know that in this regime viscous forces are more significant than those experienced by conventional aircraft in flight, and the MAV would experience increased drag, reduced lift-to-drag ratios, and reduced propeller efficiency. Wing boundary-layer airflow would be laminar rather than turbulent, as found in conventional aircraft, and boundary-layer separation effects must be taken into account.

To compensate for these factors, we are examining drag minimization, which reduces the propulsion requirements, and specialized airfoil design. Despite the aerodynamic penalties of small size, an advantage accrues because as the size of the vehicle decreases, the volume, and therefore the mass, decreases more rapidly than the wing area required to generate lift.

Figure 5 illustrates some of these aerodynamic effects. Curves of constant wing aspect ratio—wingspan squared divided by wing area—are also included in the figure. The lift coefficient C_L for minimum drag is plotted as a function of the parasitic drag coefficient C_{D0}. Lift and drag are calculated by multiplying their respective coefficients by the dynamic pressure and wing area. The quantity C_{D0} accounts for all the drag on the vehicle except the induced drag, which is the drag associated with generating lift. Figure 5 shows that the values of C_{D0} for MAVs are considerably higher than for other aircraft because of the Reynolds-number effect. We can expect to get C_L values of about 0.6 to 0.8.

The lift-to-drag ratio is an important measure of the propulsive power required to fly, and equals the ratio of C_L to $C_{D_{total}}$, where $C_{D_{total}}$ equals the parasitic drag plus the induced drag. The lift-to-drag ratio for MAVs is only 5 to 8, while SENDER and conventional jet transports have a value of about 15, and sailplanes have larger values of 30 to 50. Because the MAV wingspan is constrained, a low aspect ratio of about 3 would be needed to provide enough wing area to lift the vehicle. Similar aerodynamic considerations affect the performance of the propeller, and MAV propeller efficiencies would be about 50 to 60%, compared with 80% or greater for conventional aircraft.

To determine the configurations that best satisfy the demands of aerodynamic efficiency, flight control, and vehicle-subsystem packaging, we are considering a variety of vehicle types and platforms. In addition to the canard configuration shown in Figure 4, the possibilities for fixed-wing MAVs include conventional wing tail and flying wings, both illustrated in Figure 6, as well as multiple-wing combinations. The conventional wing-tail configuration has effective control surfaces and predictable stability. It should have a relatively good lift-to-drag ratio, although the interference drag at the wing-fuselage juncture could

Table 1. Baseline MAV Performance Goals

Airspeed	10 to 15 m/sec
Endurance	20 to 60 min
Downlink rate	2 Mb/sec
Communications range	5 km
Navigation method	Ground-station tracking (line of sight)
Visible sensor	1000 × 1000-pixel CCD; 40° × 40° field of view

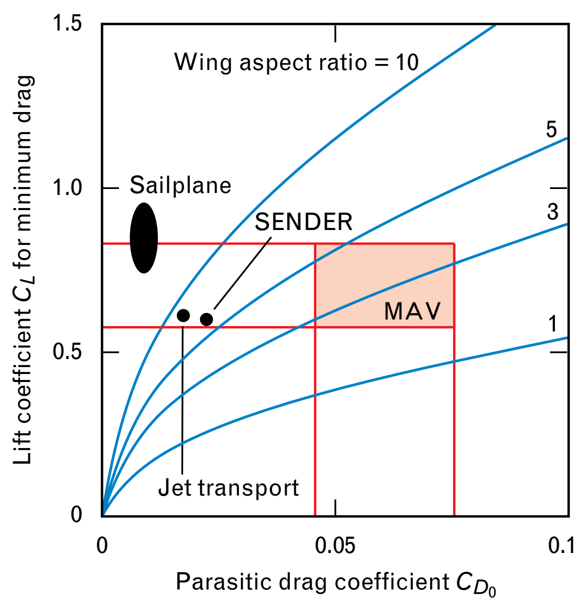


FIGURE 5. Comparison of lift and drag parameters for conventional aircraft, SENDER, sailplanes, and MAVs. Because of its small size and airspeed, the MAV experiences higher drag coefficients than other aircraft.

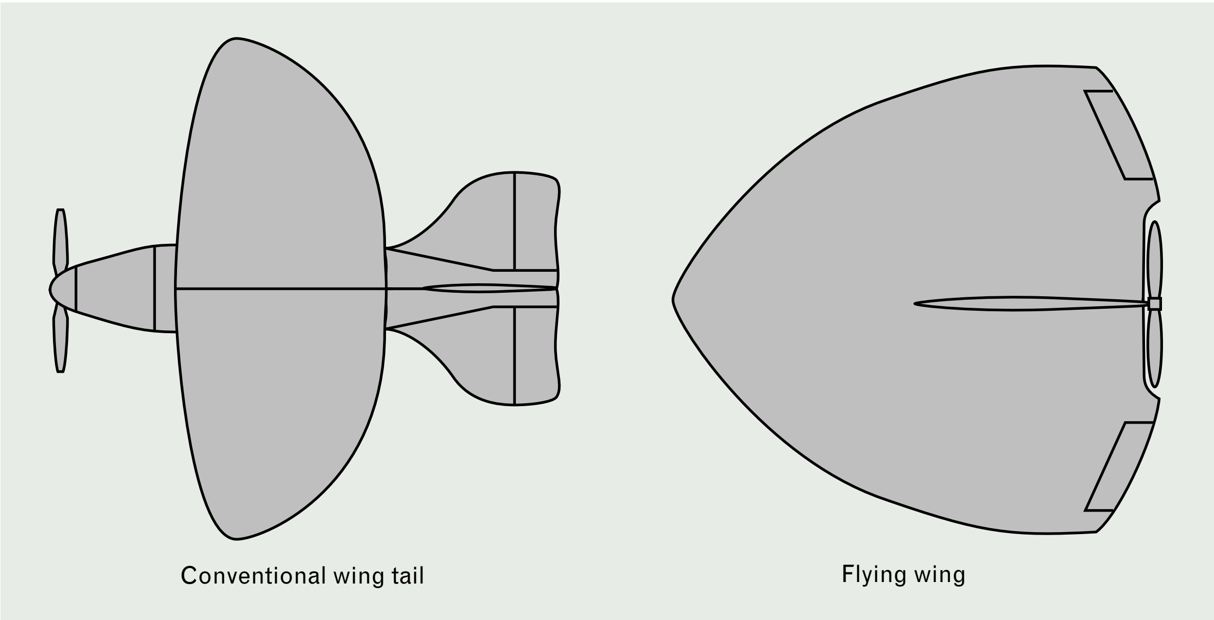


FIGURE 6. Promising MAV aerodynamic configurations. The conventional wing-tail configuration has effective control surfaces, predictable stability, and relatively good lift-to-drag ratio. However, interference drag at the wing-fuselage juncture could be high. The flying wing would have a larger angle-of-attack range than the conventional design; this range is advantageous in turbulent conditions. The flying wing could, however, be more difficult to stabilize in flight because of its lower lift-to-drag ratio.

be high. The flying wing would probably have a lower lift-to-drag ratio, but its angle-of-attack range would be larger, which is advantageous in turbulent conditions that cause large angle-of-attack variations. A disadvantage is that the flying wing could be more difficult to stabilize in flight.

Propulsion

Having explored the predicted lift-to-drag ratio and propeller efficiency for the MAV, we now consider the power required to fly one. Figure 7 shows the flight power (airspeed times thrust), shaft power, and electric power needed for a range of MAV sizes, with the requirements for our baseline 15-cm wingspan highlighted. For conservative choices of lift-to-drag ratio and C_L, the baseline flight power is 1.25 W. For a propeller efficiency of 50%, the baseline shaft power is 2.5 W. If we use an electric motor with 60% efficiency, the baseline electrical power is 4.2 W. These values, however, provide only enough power for level flight, and they must be doubled so that the MAV can turn, climb, and fly in gusty air.

To produce this power, we considered a variety of efficient and lightweight propulsion systems, including electric motors powered by batteries or fuel cells, internal-combustion engines, turbines, compressed gas, and power plants using flywheels or capacitors for energy storage. The majority of these systems proved inadequate. Compressed gas is not likely to provide enough endurance, and flywheels and capacitors require significant development to be practical. Microsize turbines under development at MIT could offer robust performance and be used to generate thrust or electrical power; however, they require more than three years of development [2]. Fuel cells, particularly those combining atmospheric oxygen with hydrogen generated by using chemical hydride or methanol oxidation [3, 4], have promise, but none have been built in the MAV-size range. Consequently, we focused on the most promising near-term candidates for power—battery-driven electric propulsion and internal-combustion engines.

Battery-driven electric propulsion has three advantages: it avoids the need for consumable fuel, is more reliable than internal-combustion engines, and is quiet. Small electric motors with adequate power

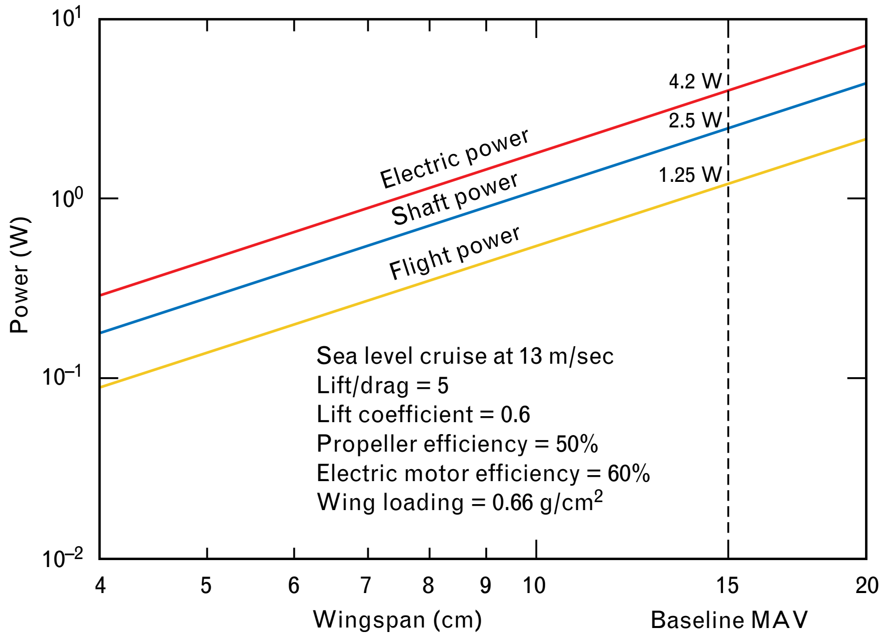


FIGURE 7. Required propulsion power for a range of MAV sizes and a particular choice of aerodynamic parameters. The lines indicate the power required to drive an electric motor, to drive a propeller shaft, and to fly.

densities are now available. New magnetic materials under development will also improve performance.

Electric propulsion, however, poses several obstacles. Currently available batteries in the required small sizes are not designed for the high discharge rates needed for MAV propulsion. Rather, they are intended for powering electronics at low discharge rates over long periods. Lithium chemistries offer adequate energy, but the case that contains the reaction contributes to battery mass. It should be possible to reduce the case mass significantly while still safely containing the battery chemicals. With one or two years' development, a smaller battery should be able to produce power densities of about 350 mW/g and energy densities of about 800 J/g that would provide a one-hour endurance for our 15-cm fixed-wing baseline vehicle. A hovering MAV would require significantly higher power densities, which batteries will be unlikely to achieve for some time.

Internal-combustion engines offer the possibility of greater power and energy densities that would be adequate for hoverers and improve the performance of fixed-wing MAVs. However, internal-combustion engines must be muffled for covert operations. Figure 8 compares total propulsion-system mass (including fuel for a one-hour mission) for internal-combustion propulsion, and for electric propulsion based on the projections in the previous paragraph. We assumed that our baseline MAV maneuvers 20% of the time; thus the average shaft power requirement is 3 W. An internal-combustion engine of the required size for the baseline MAV is projected to offer a significant power advantage. The smallest available model-airplane engines, shown for comparison, use less energetic fuels than the hydrocarbon fuels that could be burned by an MAV engine. We predict the development of miniature engines using energetic fuels in about one to two years.

As with any aircraft development, we would undertake an iterative design process to determine the vehicle gross mass and the distribution of mass among subsystems. For our 15-cm baseline MAV, aerodynamic performance and propulsion requirements are the biggest factors in this process, severely constraining the mass available to other subsystems. Table 2 shows a preliminary mass distribution for the baseline MAV. The mass allotments for the payload and the flight-control subsystems and their electrical

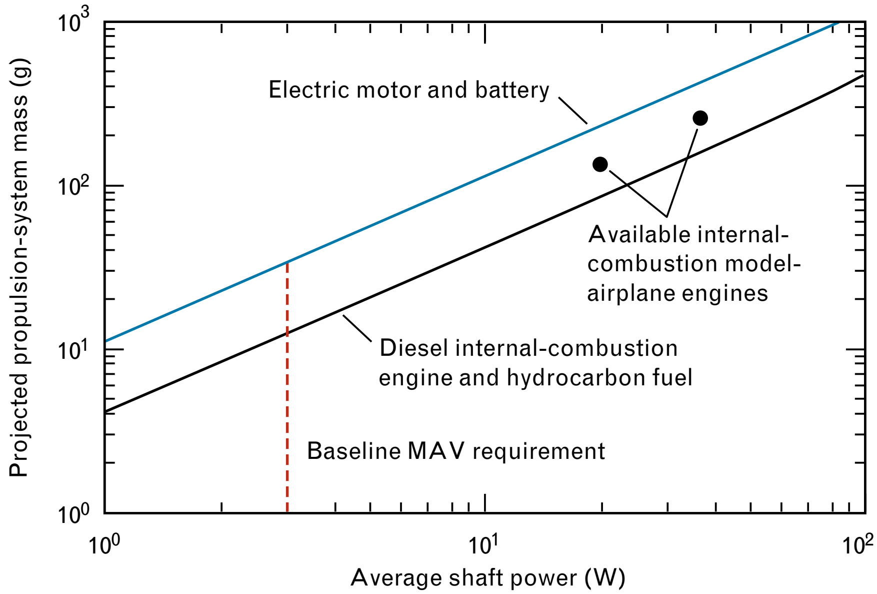


FIGURE 8. Mass projections for propulsion system for a one-hour mission. Internal-combustion engines that use energetic fuels would offer significant advantages over the best projections for battery-motor combinations. The smallest model-airplane engines are too large for the MAV.

power sources are extremely small. This distribution results in significant design challenges that are discussed in the following sections on flight control, communications and navigation, and optical sensors.

Table 2. Baseline MAV Mass Distribution

Component	*Mass (g)*
Airframe	6
Propulsion	36
Flight control	2
Payload	
Communications	3
Visible sensor	2
Total mass	49

Flight Control

Aerodynamic and propulsion factors limit the MAV to narrow ranges of airspeed and angle of attack, rendering the vehicle more vulnerable to gust upset. Flight control allows the MAV to fly at low airspeed in the presence of wind gusts and turbulence, stabilizes the vehicle with the aid of appropriate sensors, and provides aerodynamic controls. Figure 9 illustrates the elements in the MAV flight-control system. Because the MAV airframe dynamic modes, such as Dutch roll and the short-period longitudinal mode, will occur at higher frequencies compared with larger vehicles, the MAV will need some means of augmenting the natural stability of the airframe. In addition, the MAV should have the capability to fly itself to preprogrammed waypoints selected by the operator.

Microsize pressure gauges and accelerometers are currently available [5–7] and miniature magnetic compasses may also be feasible soon. Most useful for this application, however, are rate sensors. Microchip angular-rate sensors are now being produced [8, 9], and will be useful for MAVs as soon as they are mated to miniaturized readout electronics. Drift rates from these sensors will be adequate for vehicle stabilization applications.

The ability to generate aerodynamic forces and moments is also required to stabilize and maneuver the MAV. These controls could be achieved with con-

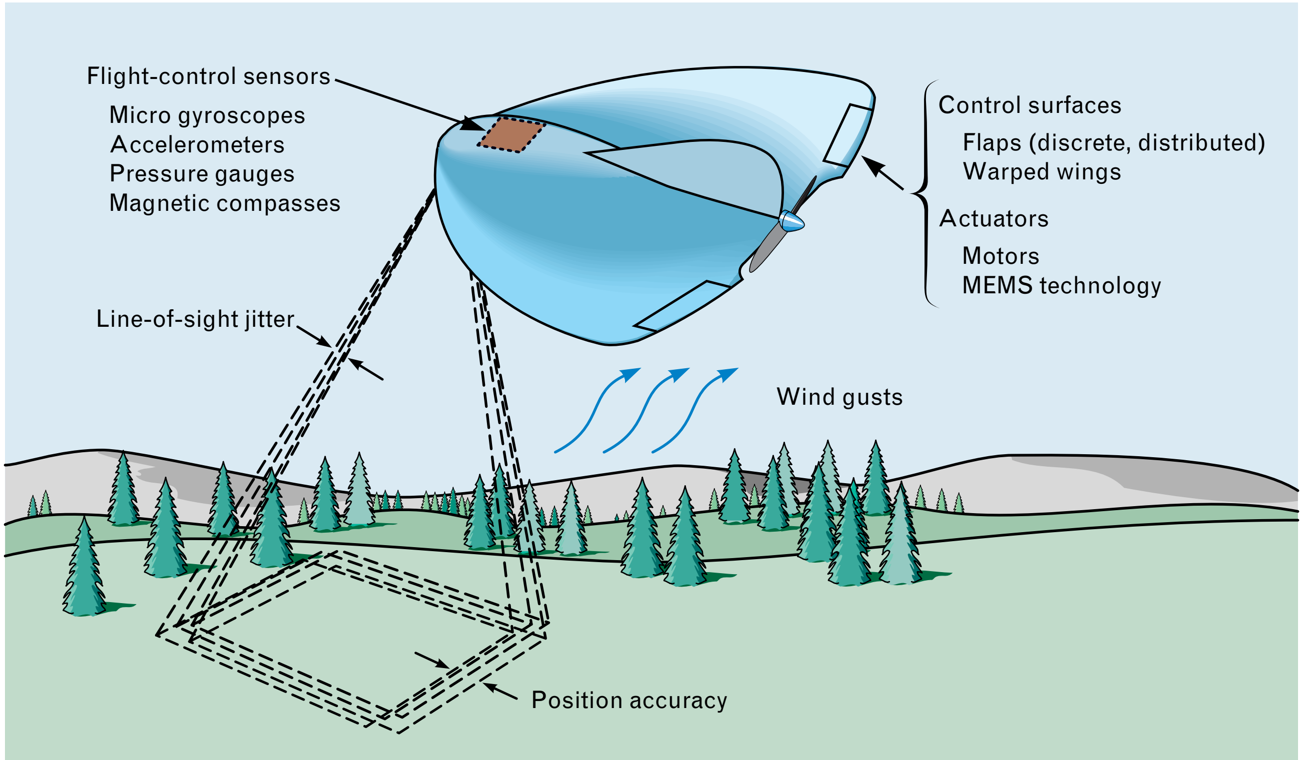


FIGURE 9. MAV flight-control system. Flight control requires sensors that measure motion (roll, pitch, and yaw) of the MAV, and aerodynamic control inputs that stabilize and maneuver the MAV in wind gusts and turbulence.

ventional discrete hinged surfaces such as ailerons and elevators; distributed micro-actuated control surfaces; or wings that change shape or warp. All methods require micromechanical actuators. Because of recent advances in MEMS, a number of different actuator candidates should be available in the next one to two years [10–19]. Examples include integrated force arrays, which generate electrostatic attraction force, and several approaches using piezoelectric crystals. These actuators can generate linear forces or be used in the construction of rotary machines that produce torque. They have the advantage of employing fabrication approaches that lend themselves to high production rates. Tiny conventional electromagnetic actuators, such as those used in watches, may also be tapped for some first-generation MAVs [20].

The flight-control sensors and actuators must be integrated into the flight-control system by using a digital processor with the necessary signal interfaces. A custom microcontroller chip that also serves as the central processor for the communications and optical-sensor subsystem will accomplish this function.

Communications and Navigation

For nonautonomous operation the communications system must provide flight- and payload-control commands to the MAV and receive data transmitted from onboard sensors. For our baseline MAV, the communications system also tracks the position of the MAV from the ground.

Using the Ka-band for communications provides a good compromise of antenna size, antenna beamwidth, and propagation losses. The 21-GHz band was chosen because of its availability and the existence of circuit technologies for satellite communications in that band. A half-dipole antenna at this frequency is only 0.7 cm long, readily fitting within the vertical stabilizer of the vehicle and providing omnidirectional coverage. With current gallium arsenide (GaAs) monolithic microwave integrated circuits (MMIC) technology, we can build an onboard transceiver with 25 mW of transmit power. This transceiver requires 200 mW from the vehicle, and a mass of about 2 g. Development of this transceiver would require a custom stripped-down architecture within MMIC capabilities. The onboard receiver portion of the transceiver would require most of these design resources, even though its data rate is low. Simple oscillators, power amplifiers, and phase or frequency modulators would be straightforward for transmitter design in the range of several megabytes per second.

For a minimum system with an operating range of 1 km, a ground station equipped with a 13-cm dish antenna could accommodate a video downlink at 2 Mb/sec and a command uplink at 1 kb/sec. The dish antenna at the ground site is mounted on a drive that allows it to track the azimuth and elevation of the vehicle. Range is derived with the two-way link. The azimuth, elevation, and range information is used to determine the vehicle location to within about 7 m in three dimensions. The navigation calculations and video display are performed on a laptop computer.

Range capability could be increased by using a larger dish antenna or increasing the onboard power consumption, which is only a small portion of the total power for the baseline system. The data rate could be improved by using proportionally more power. Another power-usage adjustment involves adding low probability of detection or anti-jam capabilities. For communication ranges out to about 10 km, the net result of these adjustments is a system consisting of a ground station (with a dish antenna proportionally larger for the longer distance) and several MAVs that could be carried in a knapsack.

This simple line-of-sight communications system limits operation to a minimum elevation angle of about 6° above the horizon—an MAV altitude of about 100 m at 1 km—and can be blocked by terrain, trees, or buildings. One alternative would be to use an overhead communications relay that would allow the MAV to fly close to the ground or at least below the direct line of sight. Such a relay function could be accomplished with a second flying vehicle such as a UAV. An MAV is not a good candidate for the relay vehicle unless the carrier frequency is much lower, and the relay craft is close to the mission MAV.

Autonomous operation is desirable when the line of sight to the base station cannot be preserved. In this mode, an air vehicle climbs periodically to transmit data to the user. Autonomous operation requires a means of navigation independent of the base station when the MAV is out of sight. GPS is an obvious choice, but further development is required to reduce the size, mass, and power requirements of a GPS receiver. GPS works by receiving a simultaneous number of satellite transmissions and, through some fairly sophisticated signal processing, by deducing the receiver's position in three dimensions. A GPS antenna operates at L-band, where the characteristic antenna dimension is larger than the MAV unless relatively heavy dielectric materials are used in its design. Also, current GPS receiver power consumption is too large for MAVs. Efficient receivers plus the required signal processing can take hundreds to thousands of milliwatts with present designs, although improvements in these areas are expected in a few years.

We considered two additional navigation schemes: dead reckoning and inertial navigation. Dead reckoning is not a good candidate because it requires fairly accurate knowledge of the winds aloft in order to calculate absolute position. Inertial navigation, which uses microrate sensors and accelerometers plus careful filtering algorithms to deduce absolute position, has potential. Tiny inertial navigation sensors are under development, but achieving drift rates suitable for position determination is probably still several years away. Another possibility, if compatible with the mission, is to navigate with prepositioned beacons within the line of sight of the vehicle.

Optical Sensors

Without optical sensors, an MAV would be just a pocket-sized, high-tech model airplane, unsuitable for surveillance operations. Like all MAV components, these sensors must meet small mass and power requirements: sensor mass must be under 2 g and power consumption under 100 mW. These parameters are one to several orders of magnitude smaller than for any commercial cameras available today. In addition, surveillance missions require high-resolution sensors with the ability to see in the complete range of outdoor light levels, from noonday sunlight to overcast starlight. These optical sensors must have high resolution (approximately 1000 × 1000 pixels) for recognition of human figures at the mission altitude of 100 m. Other operational requirements are driven by two important environmental factors: movement of the aircraft, which could cause image blur, and relatively high operating temperature. To meet these requirements, Lincoln Laboratory has considered visible and infrared sensors.

Visible sensors use an object's reflected radiation to produce an image. The visible imager is sensitive to the visible spectrum (400 nm to 700 nm) and the near-infrared spectrum (700 nm to 1000 nm). The latter range is typically utilized in night-vision goggles. Although imaging capability at night is desirable for the MAV, current night-vision technology that uses high-voltage image intensifiers is too heavy to implement, has a limited dynamic range, and does not work well in daylight conditions. Current research efforts at Lincoln Laboratory focus on a supersensitive silicon imager that will be capable of responding to the full range of desired light levels.

Infrared sensors use an object's emitted radiation and, to a lesser degree, its reflected light to produce an image. Because the emitted radiation depends on an object's temperature and emissivity, and not solar illumination, infrared sensors are sensitive during night conditions. One disadvantage to this technology is that sensitive infrared imagers operate at cryogenic temperatures and require a cooling unit that increases the MAV size and mass. Another disadvantage is that an infrared image requires more interpretation than a visible-band image. Warmer objects are prominent, but some terrains have low temperature contrast, which makes placing an object into context with its surroundings difficult. Researchers are addressing this problem by combining infrared and visible information to produce more easily interpreted images.

Visible Sensor

A visible silicon imager built with current technology for the baseline MAV can address noonday sunlight to partial moon illumination, which is most of the desired light-level range. Operation of the camera down to overcast-starlight night conditions is not feasible with current visible CCD technology because of the large f-number and small lens-size optics for the MAV. Consequently, infrared imaging or a visible imager with larger optics would have to be used for these extremely low light-level conditions.

Several important environmental factors influence the design of the optical sensor. The first of these is aircraft movement, which has two components: forward movement of approximately 15 m/sec, and movement caused by turbulence. The degree of movement determines the maximum exposure time before image resolution is degraded. The high operational temperature of the device (ambient air temperature reaches up to 115°F) contributes to the generation of dark current in the visible imager. Dark current can increase noise in the image in addition to the read noise. Although cooling the visible sensor would enhance performance, the cooling unit would also exceed the MAV mass and power requirements. For a given temperature, there is a trade-off between limiting the time to read out the device, therefore limiting the dark current, and conversely maximizing the time to read the device, and therefore limiting the bandwidth necessary for the output amplifier, thus also limiting the thermal read noise. The impact of temperature on the imaging device also affects our decision to attempt to integrate all control and readout electronics on one imaging chip.

Candidates for the visible imager include three types of CCD devices: a full-frame CCD with frame store (CCD-1), the same device but with the additional feature of a built-in electronic shutter (CCD-2) [21], and an interline transfer CCD with diode-array light-sensitive elements (CCD-3). CMOS imager devices (active pixel arrays) are also candidates [22–23]. Table 3 summarizes the important properties of the four candidate architectures. The properties are listed approximately in decreasing order of importance for the MAV application.

All the CCD devices can be made with the required resolution. The large pixel size of the CMOS device, however, would require a large lens and unacceptably increase the size and weight of the entire camera. The CMOS imager does have the advantages of standard integrated-circuit fabrication techniques and low operating power requirements. The two back-illuminated CCD candidates have the best quantum efficiency, share the lowest read noise, and therefore are the most sensitive detectors for night application. CCD-1 has the largest packet size among the CCDs; therefore, it is best equipped for a large

Table 3. Candidate Device Architectures for MAVs

	CCD-1: Full Frame, No Shutter	*CCD-2: Full Frame with Shutter*	*CCD-3: Interline Transfer with Frame Store*	*CMOS Active Pixel*
Resolution	1000×1000 pixels	1000×1000 pixels	1000×1000 pixels	1000×1000 pixels
Pixel size	5×5 μm	5×5 μm	5×5 μm	$<20 \times <20$ μm
Quantum efficiency	>85%	>85%	20% + lenslet array	20–25% *
Read noise	<10 e^- at 1 MHz	<10 e^- at 1 MHz	<10 e^- at 1 MHz	14 e^- at 0.1 MHz
Packet size	40,000 e^-	30,000 e^-	15,000 e^-	64,000 e^- *
Dark current	100 pA/cm^2	300 pA/cm^2	50 pA/cm^2	500 pA/cm^2
Shutter	Move to frame store	Electronic	Electronic	Electronic
Frame store	Yes	Yes	Yes	No
Noiseless binning	Yes	Yes	Yes	No
Voltage levels	11 V	21 V	5 V	5 V
Signal output	Analog-to-digital or charge-to-digital converter	Analog-to-digital or charge-to-digital converter	Analog-to-digital or charge-to-digital converter	Analog-to-digital converter

* Extrapolated or estimated from Reference 22.

dynamic range and can handle large amounts of dark charge. Because of its relatively simple fabrication process, it is also low in dark current.

The shutter property was originally thought to be important because of the short image exposure times (1 to 8 msec) dictated by MAV motion. The shutter mechanism for the CCD-1 device is the rapid movement of charge into a frame-store array. However, this action takes 1 msec, which equals the shortest shutter time expected and indicates the potential for image smear. (Shutter time is less than 1 μsec for the other imager candidates.) A simulation was carried out to assess whether the frame-shift shutter method caused unacceptable image degradation. The conclusion is that this method caused only minor degradation to an average aerial image, and therefore is not an important limitation.

For the MAV, a remote frame store is needed to compensate for the light leakage associated with electronic shutters. In normal applications the exposure time is comparable to the time needed to read out the image. For the MAV imager, however, the readout time is approximately 1 sec, a factor of about 1000 larger than the exposure time. This longer readout time puts severe requirements on the shutter leakage and is the reason that all three CCD candidates are equipped with a frame-store region that is remote from the imaging region. However, the CMOS device is not readily able to be equipped with a remote frame-store region, and therefore image corruption by shutter leakage is a risk in this device.

The pixel-readout binning function is planned for use in low-light-level conditions, to improve the signal-to-noise ratio and therefore the resolution at low light levels. The CMOS device is not equipped to bin photocharge in a noiseless way, because charge is converted to voltage (and therefore read noise is added) at every pixel site.

The last two entries in Table 3 deal with required operating voltage levels and signal output. Any MAV of reasonable complexity and sophistication requires an internal regulated power supply. Therefore, the existence of larger operational voltages for CCD-1 and CCD-2 is not an important penalty. The output of all four candidates is planned to be produced with conventional CMOS amplifiers and analog-to-digital converters. A new device, a direct charge-to-voltage converter [24], is currently being investigated as an alternative. This device could perform the signal conversion function at a lower power than conventional techniques. However, it would operate only on charge signals, which precludes the CMOS device. The converter does require integration directly on the CCD chip, but CCD and CMOS integrated fabrication processes with sufficient capability have already been demonstrated.

As mentioned above, our strategy for designing MAV imaging sensors is to reduce the pixel size of the focal-plane array, thus minimizing the size of the optics, and to incorporate additional functions, such as charge-to-digital conversion and clocking, on the same chip as the focal-plane array. Figure 10 shows a concept that incorporates this approach. The visible sensor is based on a silicon CCD focal plane with a 1000×1000 array of 5-μm pixels. The optics would be built with microfabrication techniques, resulting in overall camera dimensions of about one cubic centimeter, or the size of a dime. The mass of the complete camera is under 1 g, and power requirements are under 25 mW.

The 1000×1000 pixel array provides image resolutions equivalent to high-definition television. The sample image shown in the figure is derived from a photograph taken at an altitude, aspect angle, and width of field of view representative of conditions seen by an MAV CCD sensor. The photograph was digitized to form an image representative of the number of pixels (in the horizontal dimension) and 4-bit gray scale envisioned for the CCD sensor. The resulting image provides sufficient detail to recognize the presence of vehicles and personnel on the ground.

The image contains 4 Mb of data that must be stored or transmitted to the MAV operator. An update rate of 0.5 frame/sec should be adequate for flight speeds of 10 to 15 m/sec, which would require a communications link capability of 2 Mb/sec (assuming no image compression). Frame rates could be increased with a more capable communications system.

Infrared Sensor

A candidate infrared-camera design has been developed with off-the-shelf technologies. Figure 11 shows a 3-to-5-μm-band infrared camera based on a platinum silicide (PtSi) CCD focal-plane array with 512×485 pixels. Other infrared imager technologies with higher quantum efficiencies such as indium antimonide (InSb) and mercury cadmium telluride (HgCdTe) were considered, but the PtSi arrays have the smallest possible pixel sizes and lowest noise. The longer wavelength range necessitates larger and more complex optics than the visible camera, and 3 g of liquid nitrogen is required to cool the CCD for about one hour. (Liquid nitrogen could be generated in the field with a portable mechanical refrigerator.) The complete camera mass is under 16 g with power under 150 mW from using small pixels and combining functions on the CCD chip. While this camera mass greatly exceeds the payload mass limit of Table 2, second-generation MAVs with advanced propulsion systems could be capable of carrying such a sensor for extremely dark night-vision missions.

The infrared image in Figure 11, while only 256 pixels wide, indicates the image quality from this infrared sensor. The view spans a parking lot and roads; automobiles and a pedestrian can be easily identified. A 2-Mb/sec communications link accommodates a rate of 2 frames/sec for the full 512×485-pixel array.

The two cameras described here are within the current state of the art for imaging sensors. The small pixel size has been demonstrated, as has the combining of processing functions on CCD arrays. The remaining step is the investment of resources to design and fabricate the custom CCD and CMOS camera chips needed for this application.

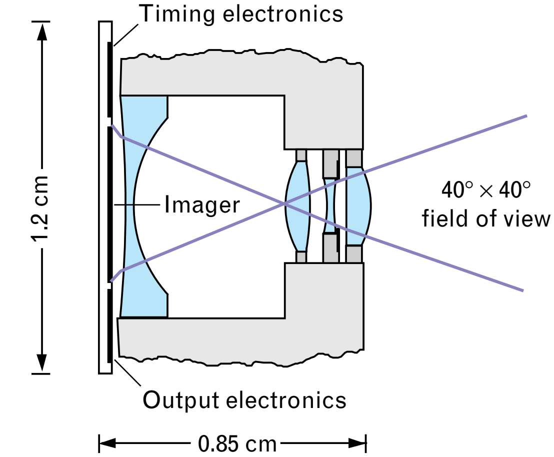
Systems Integration

Systems integration for the MAV to meet low mass and volume requirements and to permit low-cost mass production requires close interaction among multiple disciplines. Because conventional aircraft integration technology does not apply at the MAV scale, new approaches must be developed.

Systems integration affects the selection of components and the design of the vehicle. For example, bat-

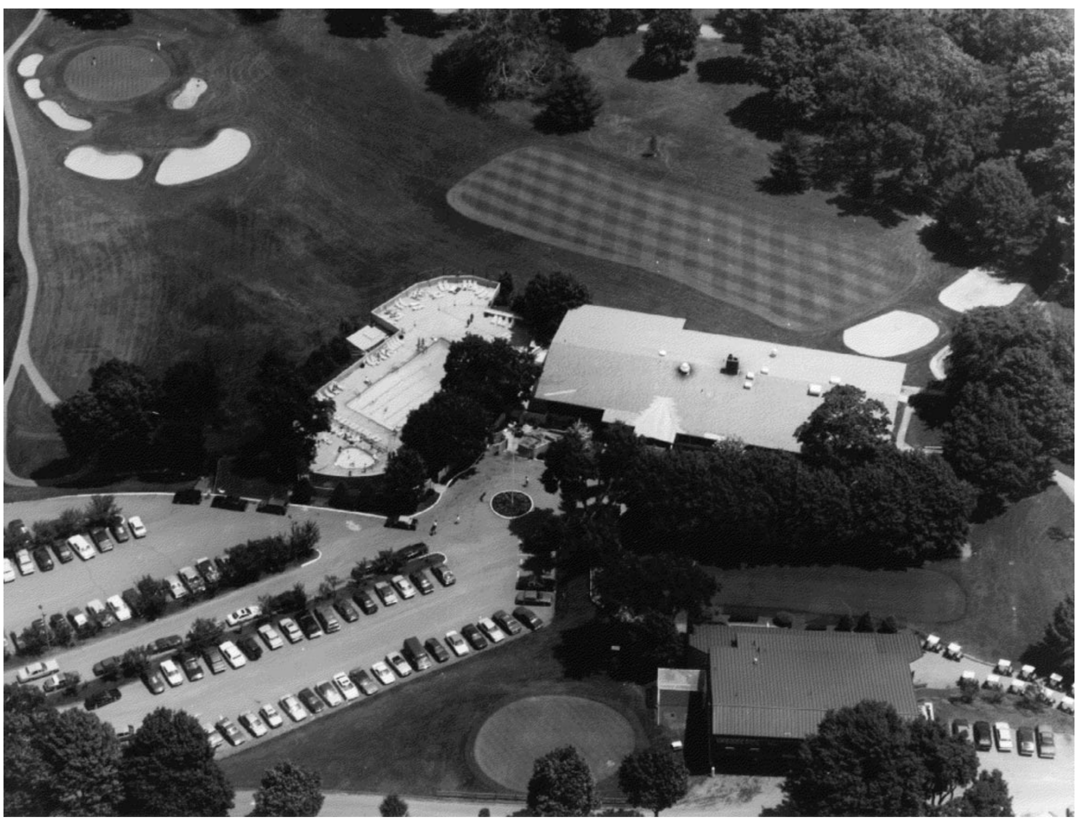
Visible-light camera

Aperture	0.26 cm
Angular resolution	0.7 mrad (7 cm at 100-m range)
Pixel count	1000 × 1000
Frame rate	0.5 frame/sec
Mass	<1 g
Power	<25 mW



(a)

Simulated visible-light camera image



100-m altitude, 45° aspect

(b)

FIGURE 10. Visible sensor for the MAV. (a) Advanced silicon CCD technology permits the packaging of a 1000 × 1000-pixel imager and associated output electronics in a single chip, resulting in a camera the size of a cubic centimeter and weighing less than 1 g. (b) With resolution comparable to that of high-definition TV, the simulated image shows an example of the detail that could be obtained from the visible-light camera mounted in an MAV.

teries need to serve multiple functions, such as contributing to the vehicle structure. Electronic functions have to be combined, which can entail using a single custom application-specific integrated circuit for the entire vehicle. Mass can be reduced by thinning electronic circuitry and using interconnections printed onto the vehicle shell in place of interconnecting wiring. The close proximity of vehicle subsystems also provides challenges such as control of heat dissipation, vibration from internal-combustion engines, and electromagnetic interference from electric motors.

Conclusions

An MAV could provide significant new capabilities to a wide range of users. Several MAVs and a base station could be transported and operated by a single individual, providing real-time data directly to the local user. The MAV promises to be particularly useful for covert operations. A variety of vehicle configurations and sensors could be used for many possible missions. We conclude that about two to three years of aggressive development in the appropriate technologies will produce a working MAV with an imaging sensor. Propulsion is the most significant challenge. Other key technologies include aerodynamics, flight control, communications, sensor development, and subsystem integration.

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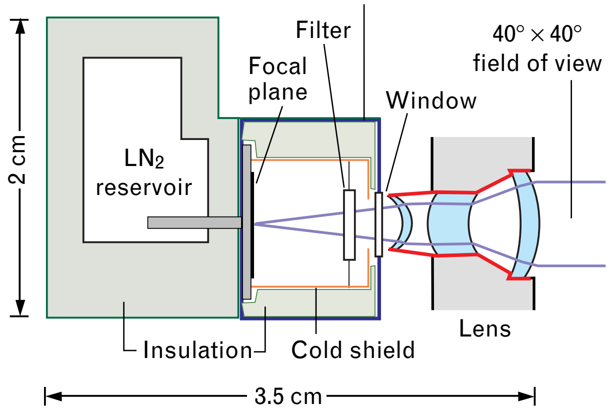
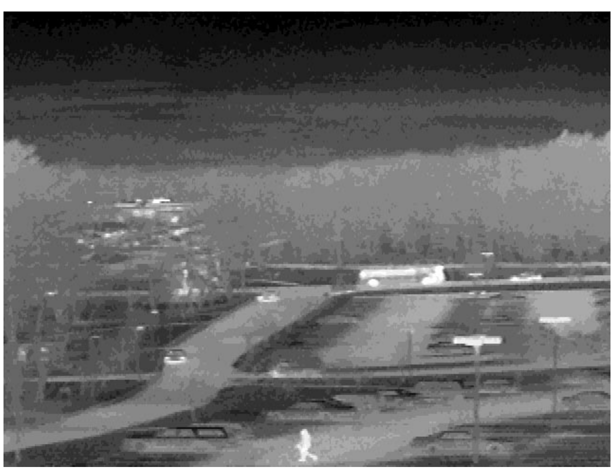
Day/night camera



Aperture	0.77 cm
Angular resolution	1.3 mrad (13 cm at 100-m range)
Pixel count	512 × 485
Frame rate	2 frames/sec
Mass	<15.5 g
Power	<150 mW

(a)

Sample day/night camera image



(b)

FIGURE 11. Mid-wavelength infrared (3 to 5 μm) camera for day and night conditions. (a) The camera, based on platinum silicide (PtSi) CCD technology, is larger than the visible camera of Figure 10 because of requirements for larger optics and liquid nitrogen cooling of the focal plane. (b) A sample image of a parking lot taken at a range of 200 m shows a pedestrian and automobiles.

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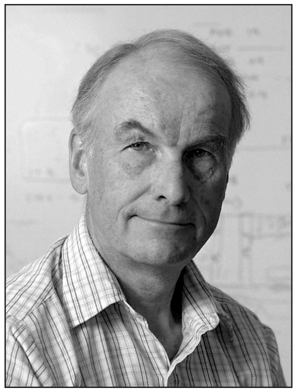

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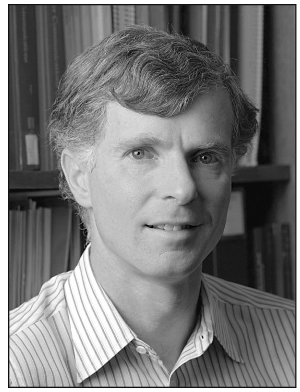

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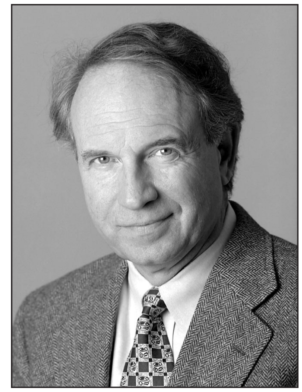

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