Design of Micro Air Vehicles and Flight Test Validation

Dr. Stephen J. Morris
President, MLB Company

Dr. Michael Holden
Chief Scientist, MLB Company

137 Lundy Lane
Palo Alto, CA 94306
www.spyplanes.com

ABSTRACT

Mission capable Micro Air Vehicles (MAVs) must be convenient to operate, have a small system size and weight, be able to operate in high winds, and deliver high quality image data. The design of these aircraft requires an integrated technique which accounts for overall mission performance of the MAV system. This paper presents a multidisciplinary optimization design study of MAVs and the flight test results of a family of aircraft based on the optimization results. The analysis shows that low Reynolds number aerodynamic performance plays a minor role in mission capability and that flight control, sensing, communication, and propulsion are the areas that have the strongest impact on mission performance. Configurations for fixed wing and VTOL designs are presented that show simple solutions to low Reynolds Number aerodynamic issues. Flight test results of these aircraft demonstrate the importance of designing the MAV as an imaging platform at the earliest stages of design.

SYMBOLS

C_{do}	zero lift parasite drag coefficient
C_{d2}	lift dependent parasite drag coefficient
C_d	total drag coefficient
f	fuselage flat-plate area (ft^2)
sref	reference wing area (ft^2)
C_{dp}	parasite drag coefficient
C_L	lift coefficient
AR	wing aspect ratio
e	induced span efficiency factor
D	total drag (lb)
ρ	air density (slug/ft^3)
v	true airspeed (ft/sec)
L	total lift (lb)
C_{lmax}	maximum lift coefficient
W_{af}	airframe weight (lb)
GTOW	gross take-off weight (lb)
bref	reference span (ft)
t_c	airfoil thickness/chord
K_i	empirical constant for structural weight model
pinst	installed power (hp)
ff	fuel flow (lb/hr)
Wprop	propulsion weight (lb)
sfc	specific fuel consumption (lb/hp-hr)
spw	specific power (hp/lb)
pdens	power density limit (hp/lb)
η_p	propellor efficiency

INTRODUCTION

There has been recent interest in unmanned air vehicles with a largest linear dimension no greater than 6 inches. Micro air vehicles (MAVs) are intended to operate in close proximity to a point of interest without being detected and should provide surveillance teams with critical information in a rapid-deployment urban-environment mission scenario. Small vehicle size is intended to lower the total system cost when compared to larger military UAVs and will also allow these aircraft to be man-portable. A typical MAV mission consists of flying 1km to a point of interest, loitering in close proximity for 1/2 hour, and then returning. The aircraft must be able to fly in turbulent winds up to 25 mph, perform tight turns near buildings, and climb repeatedly to 350 feet altitude. The MAV must be stable enough to serve as an airborne video platform and must be easy enough to operate that soldiers may deploy it with minimal training.

Currently, there are no MAV designs which meet these criteria and many technical issues must be resolved before a successful MAV can be produced. This paper addresses the issues of how propulsion, configuration, and flight control issues influence the mission capability of MAV’s. We present results from numerical optimizations and simulations, along with data gathered from flight tests of MAVs. MLB has developed complete MAV systems and participated in military exercises with our aircraft.

In this paper we assume that the micro-aircraft can be treated as an airborne platform with a payload of sensing devices, so that the design of the MAV is decoupled from its payload. A numerical optimization procedure is used to find the smallest aircraft that meets the mission performance constraints given the assumed propulsion, aerodynamic, structural, and payload models. Parameters in the mission constraints and the system models are varied to study the relative sensitivity of vehicle size to these changes.

Results of the optimization studies show that the vehicle size is highly sensitive to the required turning radius because vehicles that must turn tightly require lower wing loading which implies greater size for a fixed total mass. Sensitivity studies show that maintaining a high lift coefficient strongly affects vehicle size and that the influence of parasite drag on size is small. A comparison of designs using an advanced lithium battery versus an internal combustion engine (ICE) show that the weight of the electric powered design suffers due to the low power density of the lithium battery when compared to the ICE. A feasible MAV with ICE power, 1 ounce payload weight, and a 20 ft. minimum turn radius is recommended based upon this analysis.

Based on the results of the MDO analysis, MLB developed an ICE powered MAV named the Trochoid and has demonstrated flight performance that matches the predicted results. The Trochoid aircraft has been flown with a simple stability augmentation system, live video downlink, and a dispensing system for deploying miniature sensors. Our experience with the 20 cm size Trochoid has shown that the MAV system size, including the ground station, is not adversely affected by considering larger aircraft and that mission capability vastly improves with increasing aircraft size. Based on this conclusion, we developed 60 and 100 cm versions of our Bat MAV and successfully deployed 60 cm surveillance MAV’s in a military exercise. The most advanced version of these aircraft is capable of fully autonomous GPS guided flight, carries an inertially stabilized camera system, and has the same system “footprint” as a 15 cm MAV.

Our study concludes with several observations on the influence of vehicle size on mission capability. Our experience has shown that with present technologies the maximum capability of an MAV system is realized with aircraft in the 50 to 100 cm size.

MDO SYNTHESIS OF A FIXED-WING MICRO AIR VEHICLE

Method

Preliminary design of a MAV involves finding the necessary gross take-off weight (GTOW) and wing size needed to complete the specified mission. For the case of MAV's, this study becomes an optimization problem where the smallest size vehicle that completes the mission is the desired solution. Figure 1 is a flowchart of the multidisciplinary optimization (MDO) method that is implemented on a computer to find the smallest MAV. The optimizer solves for the six design variables:

Design Variables	symbol	units
wing area	sref	(sq.ft.)
wingspan	bref	(ft)
cruise C_L	C_{Lc}	none
loiter C_L	C_{Ll}	none
gross take-off weight	GTOW	(lb)
installed power	pinst	(HP)

which satisfy six mission constraints:

Constraints	type	Nominal value
Duration	=	0.5 (hr)
Operational radius	=	3500.0 (ft)
Minimum turn radius	<=	10.0(ft)
Minimum climb angle	>=	15.0 (deg)
Maximum altitude	=	350.0 (ft)
Number of climbs	=	3

while minimizing the largest linear wing dimension which is defined as the diagonal of an assumed rectangular planform wing:

size=sqrt(wingspan^2 + (wing area / wingspan)^2) (ft)

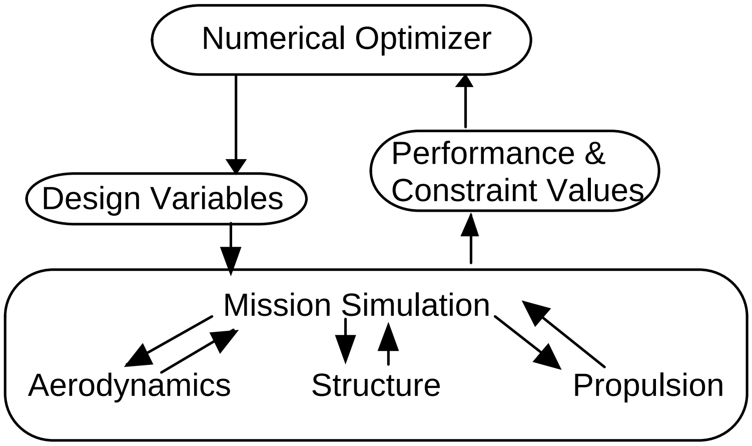

Figure 1. MDO method flowchart.

The mission simulation assumes the following events in sequence (see figure 2):

1) Climb to 350 ft
2) High speed dash (40 mph IAS) to target (headwind=25 mph)
3) Loiter at target
4) Maneuver over target (turn at minimum radius) during loiter
5) Descend and climb over target
6) Climb to 350 ft
7) High-speed dash (40 mph IAS) to launch point (tail wind 25 mph)

The mission performance is calculated by sequentially simulating each of the described flight phases. If any of the constraints are violated the performance is penalized by an appropriately weighted penalty function. At each step of the mission simulation numerical models for aerodynamic forces, propulsion system, and structural weight are used to calculate the MAV's performance.

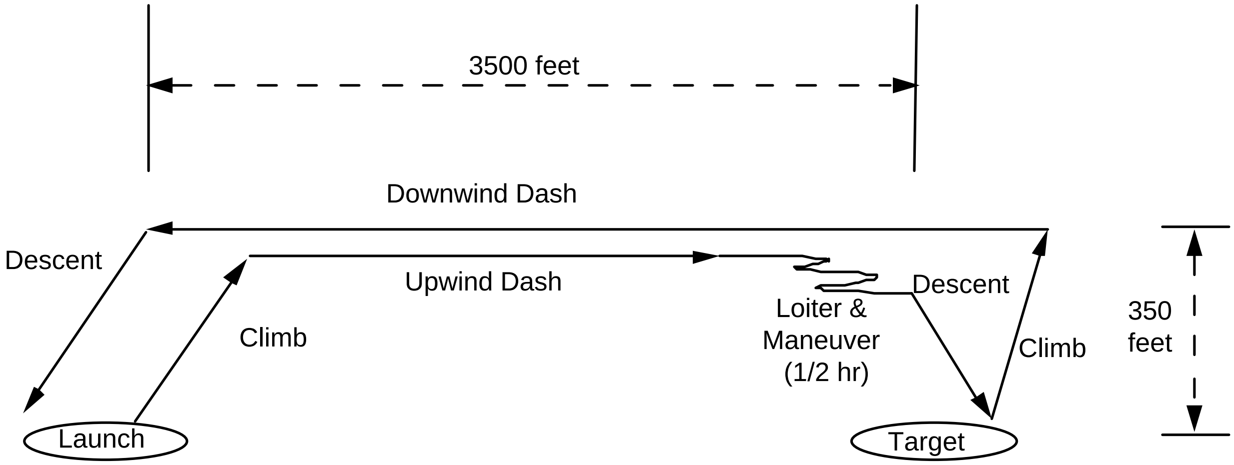

Figure 2. Mission scenario

Aerodynamics

MAV's operate at low Reynolds Number (20,000 to 1,000,000) over their entire flight envelope. The flow over airfoils in this regime includes effects that are difficult to model, such as hysteresis stall due to laminar separation bubbles, but it is possible to conservatively account for the effects of low Reynolds Number by assuming large parasite drag and low C_L max. The drag model for a MAV consists of a parabolic variation of parasite drag with lift coefficient and additional terms for induced and fuselage drag. The coefficients for the parasite drag are chosen from an average performing airfoil section at Reynolds Number 80,000 (ref 1) and the fuselage flat plate area is fixed at 1/2 sq in based on an assumed fixed payload volume. The lift coefficient is limited to $C_{Lmax} = 1.2$ based on the airfoil data in reference [1].

Drag

$C_{dp} = C_{do} + C_{d2}\ CL^2$

$C_d = f / sref + C_{dp} + C_L{}^2 / (\pi\ AR\ e)$

$D = 0.5\ \rho\ v2\ C_d$

$C_{do} = .015$

$C_{d2} = .007$

$f = 0.5 / 144\ ft^2$

$e = 0.90$

Lift

$L = 0.5\ \rho\ v2\ C_L$

$C_{Lmax} = 1.2$

Structures

Structural weight is modeled by an empirical curve fit of model aircraft structural weight to an equation that accounts for wing bending, wing skin, and fuselage weight.

Airframe weight

$W_{af} = GTOW\ (K_1((bref^3) / (t_c\ sref)) + K_2) + K_3\ sref$

$K_1 = 0.0003$

$K_2 = 0.10$

$K_3 = 0.10$

Propulsion

For ICE powered MAV's it is assumed that the engine technology will closely follow existing small model aircraft engine performance. Data for these motors is based on a family of motors produced by Cox model airplane company. Because limited data is available for these small engines, the specific fuel consumption (sfc) is assumed constant for all throttle and RPM values. The optimizer is free to choose the value of the installed power, so the method assumes that engines of the sizes appropriate for MAV's will all have the same specific weight and sfc. This is not accurate, but by choosing modest numbers for these constants the analysis will at least be conservative in estimating engine performance. Electric powered designs use a similar propulsion model but with different values for the constants based upon an advanced Lithium battery and a rare earth magnet DC electric motor with 80% conversion efficiency. Electric propulsion systems are often limited by the maximum power delivery capability of the batteries and if needed the battery size is increased to match the power instead of the energy requirements. Regardless of propulsion system, the propellor efficiency is assumed constant at 50%. The impact of this assumption is discussed in the results section.

Fuel consumption rate
$ff = sfc\ P_{shaft}$
Engine weight
Wprop = spw Pinst
sfc = 8.0 Lb / HP-HR (ICE), 11.82 Lb / HP-HR (Lithium)
spw = 0.67 HP / Lb (ICE), 0.31 HP / Lb (electric)
pdens =0 .12 HP / Lb (Lithium battery power density limit)
$\eta_p = 0.50$

Mission Simulation

The flight phases depicted in figure 2 are simulated by modeling the MAV as a point mass with thrust, lift, and drag forces acting on it during flight. Standard flight mechanics equations for climb, cruise, and steady turning flight are used to predict the MAV's performance in each phase of the mission.

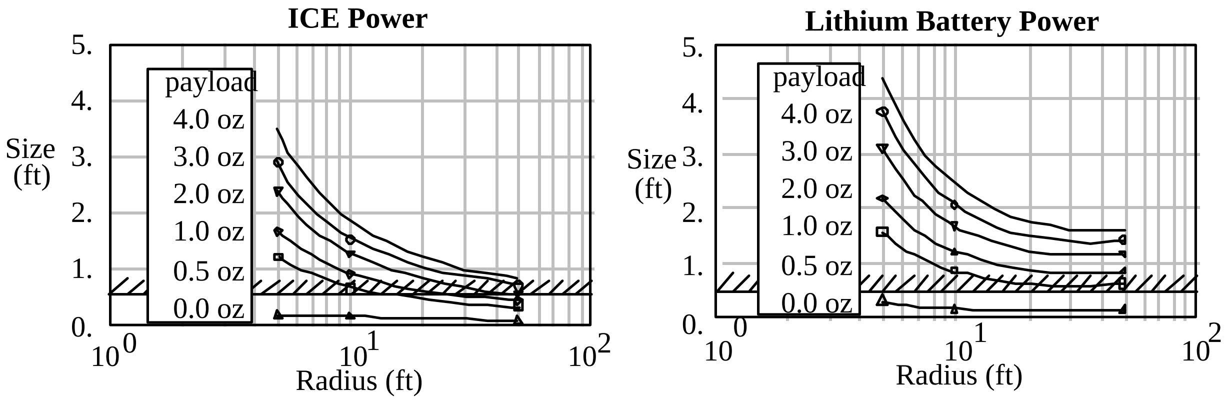

Figure 3 & 4. MDO results, minimum size versus turn radius for ICE and electric designs

MDO RESULTS

Figures 3& 4 show the variation of aircraft size with minimum turning radius and payload mass. Each data point represents the smallest size MAV that meets the mission constraints. There is a strong coupling between aircraft size and minimum turning radius because increased wing area is necessary for maneuverability. For the baseline mission and modeling parameters, the ICE MAV designs can carry up to 2 ounces of payload for a 6 inch maximum size, but if maneuverability is required, the payload capability drops dramatically (< 1 ounce for 20 ft turn radius). The electric power designs show the same behavior but have lower payload capability for a given size because of increased battery weight. All of the electric designs are limited by the power output of the battery pack, not the energy storage. This means that the electric MAV's carry more energy than needed in order to achieve the peak power required for climbs and turns and consequently have lower payload margin (< 1/2 oz for all designs under 6 inch size).

Sensitivity Studies

Many simplifying assumptions were made in the MAV modeling and their impact can be quantified by using the MDO analysis to perform sensitivity studies. This involves perturbing the parameters of an optimized baseline MAV design, re-optimizing, and observing the change in performance (i.e. minimum size). Table 1 shows the results of these calculations for a 1 ounce payload 10 foot turning radius design as aerodynamic and propulsion parameters are varied.

Parameter changed	Size Reduction
Parasite drag=0.0	7.3%
Propellor efficiency=100%	11.3%
CLmax=2.0	23.1%
Specific fuel consumption=0.0	12.0%
Specific power = ∞	10.5%

Table 1. Sensitivity study results

If all the parasite drag contributions are set to zero the MAV size decreases by only 7.3% indicating the increase of parasite drag at low Reynolds Number is of minor importance for ICE powered MAV's. The sensitivity of size to C_{Lmax} is strong (23% smaller if C_{Lmax} = 2.0) indicating that the primary aerodynamic design challenge for MAV's is increasing lift capability and not decreasing parasite drag, unless the mission duration is greater than 3 hours.

Aircraft size is sensitive to the propulsion system performance especially in the cumulative effect of increased specific fuel consumption and decreased specific power. This has already been demonstrated in the comparison of ICE and electric designs where the electric propulsion system's larger installed weight results in larger MAV's. Table 1 shows that increasing specific power has a small influence on size (7%), but this is misleading because the ICE baseline design already has a large power density and the engine weight is only a small fraction of the total weight. A more useful comparison is between the ICE and electric designs where the difference in power density is large enough that MAV's designed for the same mission differ in size by 40% - 50%.

All of the ICE designs considered assume an engine technology similar to commercially available 2-stroke model airplane engines. These motors use a fuel containing methanol, nitromethane, and castor oil and have large sfc (10-20 times higher) compared to conventional 4-stroke aircraft engines. For increased duration, it is possible to reduce the sfc by a factor of two by switching to a diesel fuel (ether, kerosene, and castor oil) and using a commercially produced diesel conversion cylinder head to adjust the compression ratio. Because the kerosene has nearly twice the heating value of methanol the fuel economy is significantly improved and the torque output is also increased. Diesel converted glow engines can turn larger propellors for a given RPM than glow engines and this further improves the propulsive efficiency.

The MDO synthesis assumes that sfc does not vary as engine power is adjusted (throttled) to meet the flight condition requirements. Throttling of the small ICE engines has been demonstrated on commercially produced motors and is normally accomplished by varying the size of the exhaust port opening.

All optimized designs shown in figures 3 and 4 have aspect ratios between 1.2 and 2.0. Aspect ratio is small because the duration constraint of 1/2 hour is achievable with small fuel weight fraction and low maximum lift to drag ratio (5:1). As the duration constraint is increased (figure 5) the optimal aspect ratio increases (up to 8.8 at 7 hour duration), reflecting the importance of L/D in long endurance designs. Parasite drag and Reynolds Number effects will be important if flight duration greater than 3 hours is required.

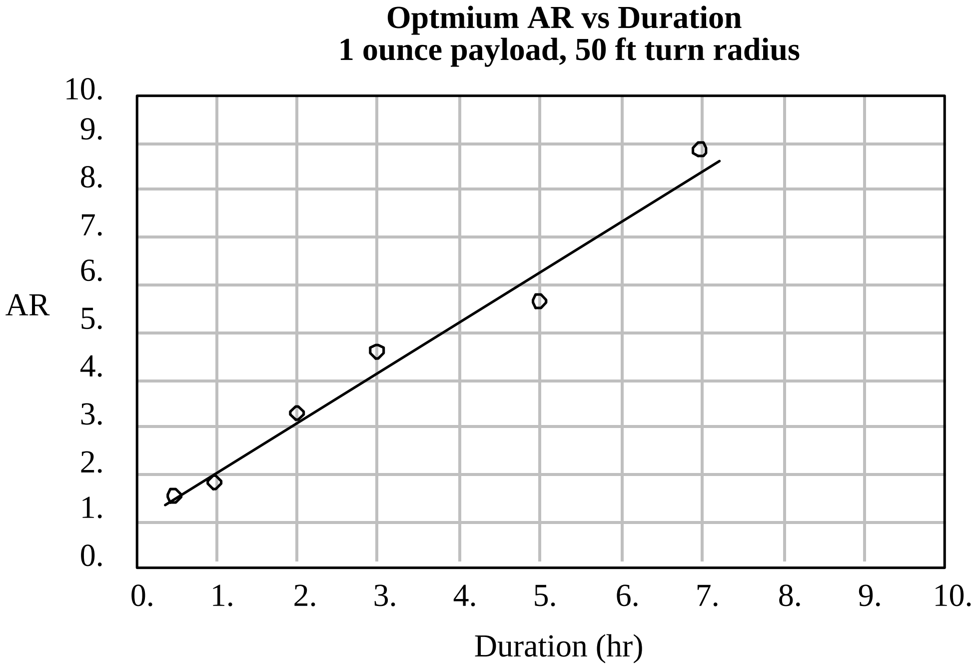

Figure 5. Effect of duration constraint on optimum aspect ratio

Only designs with a single surface rectangular wing were considered in the MDO synthesis but other configurations may prove more efficient for the MAV mission. The results show that MAV size is strongly dependent on maximum wing lift, which might be made larger for a given size by considering a biplane configuration. The biplane layout offers twice as much wing area for a fixed linear size and it is often possible to arrange the wings so that their mutual interference improves maximum lift capability. A more careful analysis of the propulsion system and wing integration may also result in improved lift capability.

This analysis does not account for the effect of large thrust deflection on maneuverability and minimum flight speed. As will be discussed in the next section, the tilting of the propellor disc from the flight direction influences turn radius and fight speed significantly.

MAV CONFIGURATIONS DEVELOPED AND TESTED BY MLB

MLB Trochoid

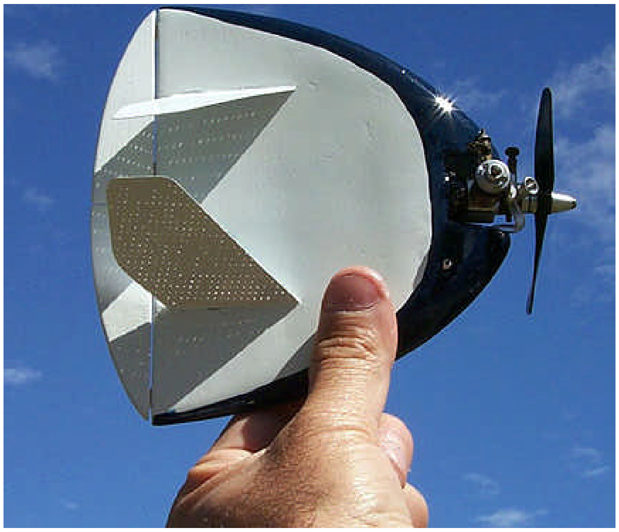

Figure 6. 15 cm Trochoid aircraft

Based on the MDO study results MLB designed several low aspect ratio, 15 cm sized MAVs. The most successful of these configurations is the Trochoid aircraft, shown in figure 6. Its name is derived from the trochoidal geometric shape of the wing planform.

The MDO results show that maximum wing area (and lift capability) for a given size is critical to achieving performance in an MAV. Circular wing planforms have maximum area for a given size, but have poor aileron effectiveness because the control surfaces are located close to the wing centerline in a region of strong vortical flow. We tested several circular wing designs (figure 7) and found that a slot between the upper and lower wing surfaces restored control effectiveness, but reduced the wing's internal payload volume. Rudder control can also be used for turning because low AR designs have strong yaw-roll coupling due to side edge wing vortices, but this type of control is very nonlinear with angle of attack.

Figure 7. MLB MicroDot Circular wing 35cm MAV
Winner of 1998 ISSMO MAV Competition

The trochoidal wing planform has only 11% less area than a circular wing for a given size, yet has the desirable aerodynamic properties of a delta wing planform because its size normal to the flow direction increases along the wing centerline. This allows the control surfaces to be very effective even in the presence of strong vortical flow. Figure 8 shows our most successful version of this design, a 20 cm Trochoid with a video downlink and a stability augmentation system. This aircraft has demonstrated 20 minute flight duration, flight speeds from 10 to 60 mph, and turn radius of 15 feet. It has regularly been flown in gusty winds up to 20 mph.

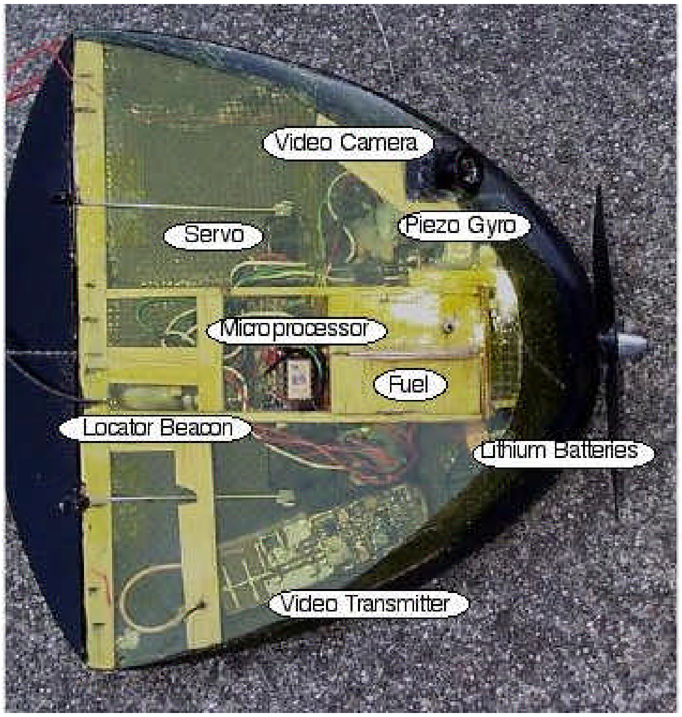

Figure 8. Hardware layout 20 cm Trochoid MAV

In the course of flight testing our MAV designs, it became obvious that vortical flow at high angles of attack and the influence of the propellor wake on the wing were significantly influencing the aircraft's flight performance (figure 9). Both of these effects augment the lift capability of the wing at low Reynolds Number and the propellor wake impinging on the control surfaces produces an effect similar to vectored thrust control. Neither effect is strongly altered by low Reynolds Number (Re > 10,000) and therefore provides a simple way to overcome the poor lift capability of the low Re 2-D airfoil sections. The aerodynamics of the Trochoid MAV more closely resemble that of a jet fighter than that of a bird because of these phenomenon.

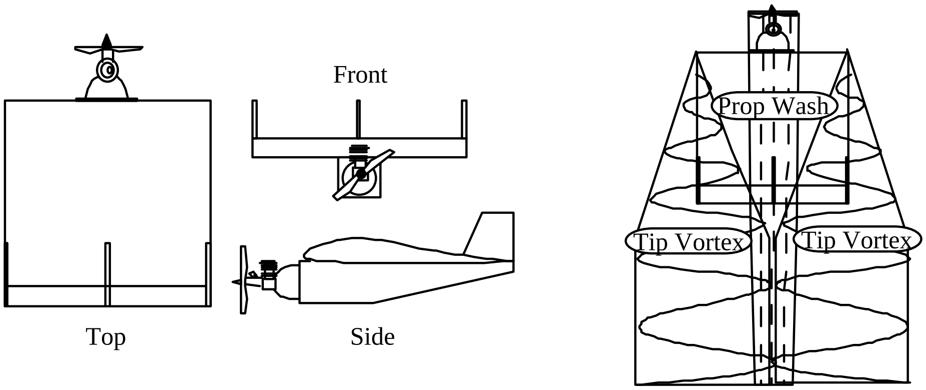

Figure 9. Regions of vortical and propulsion influenced flow on a low AR MAV wing

The Trochoid aircraft's cruise speed is 30 mph and because of its small wingspan it lacks roll damping at these speeds. For a given aileron deflection, a 15 cm wingspan aircraft travelling at 30 mph has a steady state roll rate similar to a high performance jet fighter (approx. 720 deg/sec.). For remotely piloted flight roll damping and spiral stability augmentation are required because of the very fast aircraft dynamics. We developed a tilted axis rate gyro system that damps the roll and spiral dynamics of the Trochoid MAV. Without this system it is nearly impossible to fly the aircraft at speeds above 20 mph.

The MDO synthesis favors MAVs with poor L/D and large thrust to weight ratio. The Trochoid has thrust/weight of 0.75 and can fly very slowly (10 mph) at 45 degree angle of attack. Similar 'nose-high' flight attitude allows the aircraft to fly continuous 15 foot radius 360 degree turns by using the engine thrust to directly support most of the aircraft's weight. The gliding L/D was measured to be 3:1 and is somewhat low because of the 20% thick airfoil section used for increased wing volume.

MLB Bat

Figure 10. MLB Bat 60cm MAV

With current off-the-shelf electronic equipment technology, it is very difficult to carry any useful sensors or flight control system in a 15 cm size MAV and still achieve decent duration. As size decreases the aircraft's payload capability and internal volume decrease rapidly (by the square and cube of the size respectively) , yet the requirement for duration, range, and telemetry range don't change. We developed the 60 cm Bat as a mission capable MAV that can carry an autopilot and a dual camera telemetry system. The Bat is capable of flying 1/2 hour (or longer with optional fuel system) and has an autopilot which can hold altitude and level the airplane's wings. The Bat MAV system is shown in figure 11 and consists of 2 aircraft, ground station, all support equipment, and a 30 x 24 x 12 inch hardened container. It is interesting to note that due to the amount of ground-station equipment that must be carried with any MAV (video display and downlink, control uplink, and particularly the antennas), the overall system sizes for the 15 cm Trochoid and the 60 cm bat are very similar.

Figure 11. MLB Bat MAV system

The dual camera telemetry system uses a wide angle lens camera for navigating but also has a narrow angle lens "zoom" camera for taking a closer look at ground targets. This was our first attempt to address the imaging restrictions of a single camera fixed to the

MAV, which produces poor image quality at altitudes above 100 feet. With the dual camera system we are able to see objects as small as 20 cm in size from 500 feet altitude. Staying this high allows the MAV to maintain line-of-sight (LOS) telemetry communication while flying at its maximum range. The Bat is well suited to quick deployment and operates easily from small clearings (20 x 50 feet). The Bat has flown in gusty winds over 25 mph in strength.

The 60 cm Bat lacks the ability to fly autonomously and its fixed camera system limits its effectiveness as a surveillance platform. With cameras fixed to the airframe, the entire aircraft must be maneuvered to keep objects of interest in sight. This is very difficult to do, particularly with a downward looking camera, because the initial roll motion in a turn moves the camera's field of view away from the point of interest. As the turn develops the field of view may recapture the target, but it takes some skill to do this. We have accumulated over 100 hours of remotely piloted flight time with 3 different Bat MAVs and are convinced that the fixed camera system is barely adequate for quality surveillance. A gimbaled camera system that holds the field of view fixed on the target area is essential for adequate surveillance capability. This appears to be true for any real-time video surveillance application regardless of the size of aircraft being used. A hovering MAV would have an advantage in this application because the aircraft's velocity can be brought to zero during surveillance.

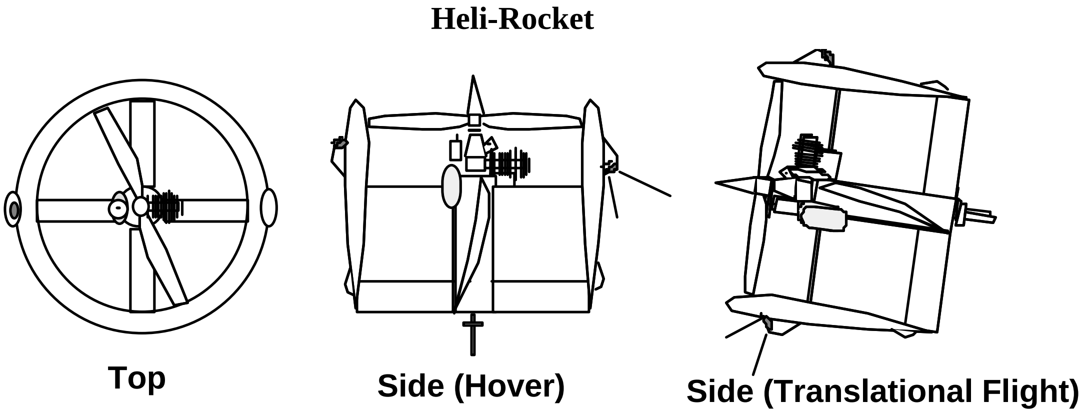

Figure 12. Heli-Rocket VTOL MAV

The MDO study results favor MAVs with low aspect ratio and poor L/D (< 3:1). These designs require thrust to weigt ratios approaching 1.0 to achieve the maneuverability and climb performance required. It is well known that the effective L/D of a single rotor helicopter can approach 5:1 and for a 15 cm rotor, an L/D of 3:1 is easily achieved. This implies that a single rotor MAV could have the same translational flight performance as a similarly sized fixed wing counterpart, yet with the addition of a slightly larger engine it would be able to hover. The fuel consumption during hover would be greater than in forward flight, but the overall vehicle size and weight would be the same as a fixed wing design and the VTOL version would have more versatility. In 1997 MLB pursued this approach and tested prototype versions of a ducted, single rotor, MAV that could hover and fly at high speed. Figure 12 shows the general layout of this design named the Heli-Rocket. This configuration has almost 3 times the useable internal volume of a similar sized monoplane MAV, because it's wing is circular and not planar. The propellor is shielded by the ring-wing/duct and this reduces the noise signature from the sides of the MAV. The shielded propellor is also safer for the operator when launching. Control surfaces are located on the torque reaction vanes inside the duct and provide roll, pitch, and yaw control. In 1997 MLB flight tested a free-flight version of the Heli-Rocket that demonstrated inherent stability while climbing.

THE MAV SYSTEM

Until this point we have only considered the MAV aircraft and its flying ability as a measure of performance, but real-world application of MAVs requires a complete system that is convenient to operate, provides high quality video information, is rugged, easily transported, and deployed. If any one of these criteria is not met the MAV system will not be useful in battlefield situations. In this section we will discuss the design issues associated with achieving MAV system performance and the impact these have on the design of MAVs.

Flight Control

Ease of operation implies autonomous flight control capability. Achieving this is primarily a function of appropriate flight control hardware (sensors, computer, actuators) and software. We have developed a prototype version of a flight control system based on solid state inertial and pressure sensors, CPU, and a miniature GPS receiver. This system has been flown in our 1-meter sized Bat aircraft (figure 13) and software has been developed that accomplishes autonomous flight with GPS waypoint navigation. Because this system uses only solid-state sensors it can be miniaturized for use in smaller vehicles in the future. Figure 14 is flight data from the 1-meter Bat showing the MAV responding to pilot commands through the autopilot and autonomous GPS navigation. When flown through the autopilot the operator commands rate of climb, airspeed, and turn rate. When climb or turn rate is commanded to zero, the aircraft holds constant altitude and the wings level. Using this system any person can fly the aircraft and if desired it will fly hands-off until the fuel is exhausted. The addition of GPS allows the MAV to navigate on its own so that the operator can focus on the video surveillance data rather than navigating the MAV.

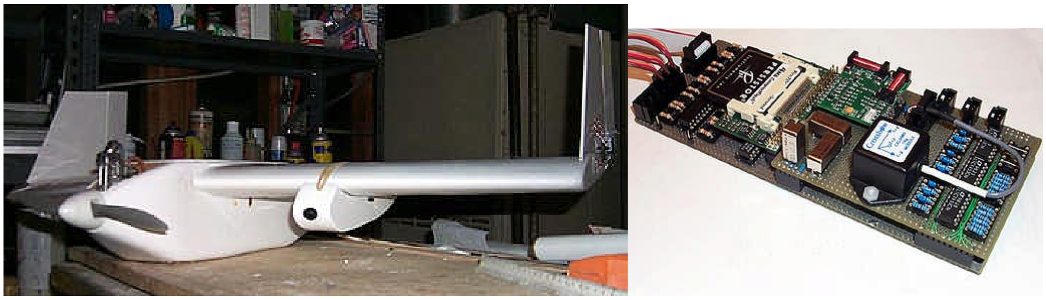

Figure 13. 1-meter Bat and GPS flight control system hardware

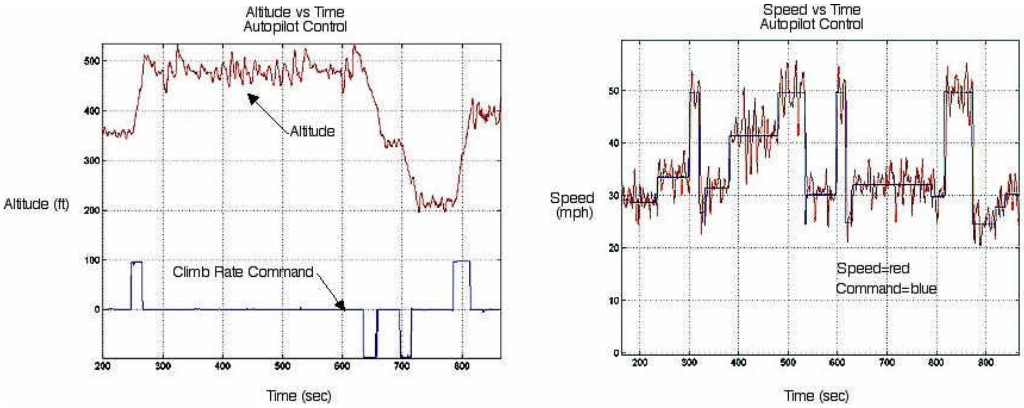

Figure 14.a. Altitude and speed versus time for 1-meter Bat, autopilot control

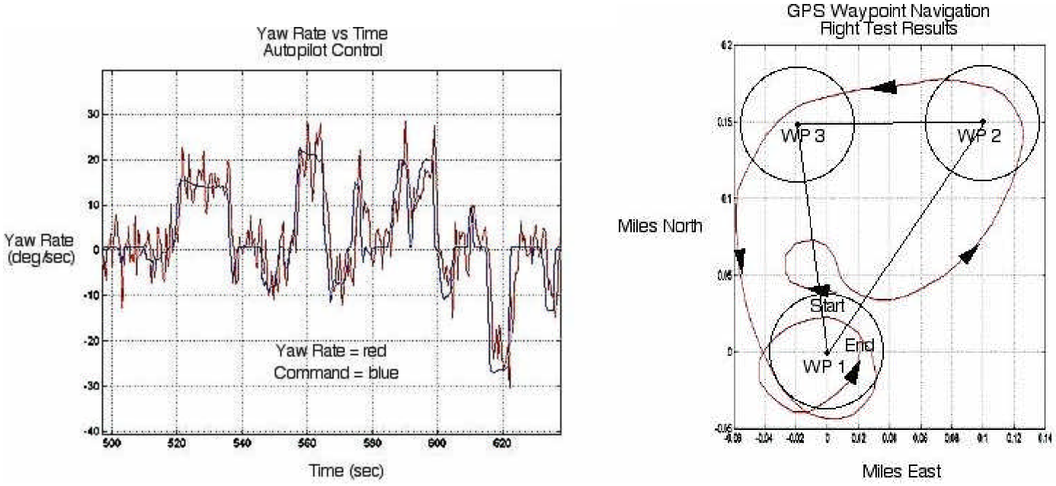

Figure 14.b. Yaw rate versus time and autonomous waypoint navigation for 1-meter Bat

Telemetry

Real-time communication with the MAV is essential for providing situational awareness to the operators on the battlefield. Unfortunately, the power required to communicate a given distance remains fixed (d^2 dependence) regardless of aircraft size. This fact puts small UAV's at a disadvantage when trying to communicate over large distances. Most MAVs being developed rely on automatic-tracking antenna systems as part of the ground station. These antennas are necessary to receive the low power signal emitted from the MAV and their deployed size is often on the order of 6 feet or more. Erecting and operating this fragile antenna system on the battlefield may be an unacceptable burden. A better solution is to make the MAV slightly larger, carry a more powerful telemetry transmitter, and use simple low-gain antennas on the aircraft and ground station. This solution keeps the system size the same and greatly improves the system's capability. Our 1-meter Bat MAV uses a 1 watt telemetry transmitter which is capable of sending signals 10 miles LOS with a ground station antenna that is 12 x 12 inches in size.

Vehicle Size

Some researchers have proposed using teams of MAVs to self-organize into data gathering and communicating networks. This solution makes sense when an individual MAV lacks the capability to accomplish the baseline mission on its own. There is a direct analog to this in nature, where colonies of ants and bees work together cooperatively to survive. The idea of cooperative action of MAVs can be used to enhance the capability of aircraft of any size and achieving this type of group control is a worthy topic of advanced research. However, the near term need is for MAVs that can perform the baseline mission with a single vehicle. Other MAVs can be added to the team in future versions of the system, but the basic functionality must be achievable with one aircraft and ground station. Figure 15 shows qualitatively how the number of vehicles needed to accomplish a task varies with system size. We have found that a reasonable MAV size may be as large as 1 meter and still have a system size similar to a 15 cm MAV, but with vastly greater near term capability. Figure 16 shows our 1 meter bat MAV disassembled for transport in the same carrying case that holds its ground station. This size for the MAV system remains essentially constant for 15 cm through 1 meter size MAVs because of the larger antenna systems used by the smaller vehicles.

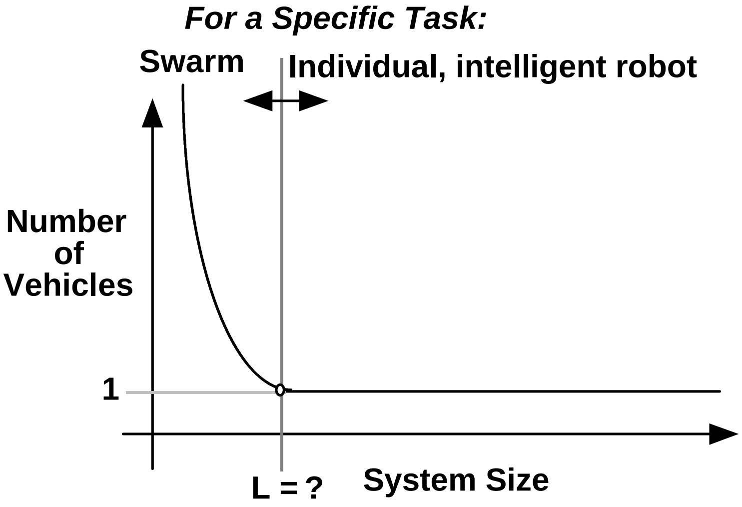

Figure 15. Number of vehicles versus system size

Figure 16. 1 meter Bat disassembled for transport

Imaging System

Our flight experience with MAVs that have cameras fixed to the airframe has shown that the video imagery is unstable and it is very difficult to aim the camera by maneuvering the aircraft. Figure 17 shows qualitatively how the aircraft's motion results in large image plane motion over the ground, particularly when lens' field of view is narrow. We have developed and test flown a miniature inertially stabilized camera system that uses information from the flight control system and a servo controlled mount to remove aircraft dynamic motion from the image. This system also allows the operator to independently control the camera during flight.

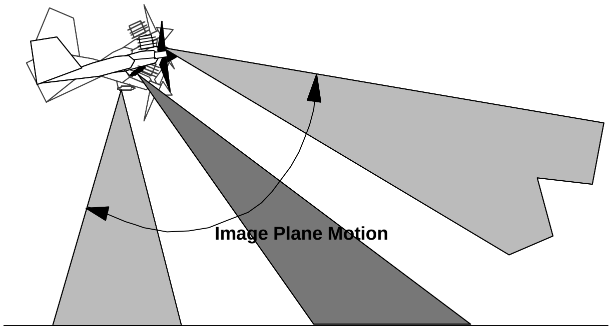

Figure 17. Image plane motion due to aircraft dynamics

Even though a fixed camera system is difficult to use and is not suitable for a production MAV, our 60 cm Bat has successfully used this system (figure 18) in a military exercise. In September 1999 we participated in a Limited Operational Exercise (LOE #4) with the US Marines. We carried only our suitcase-sized container with 2 Bat aircraft and ground station into the field and provided aerial imagery to the Marine commanders of specific vehicles travelling along a roadway. The weather was very windy (gusts > 25 mph) due to a passing storm front, but we were able to provide aerial coverage for over one hour and successfully identified mobile rocket launcher and a SCUD mobile missile launcher vehicles (figure 19).

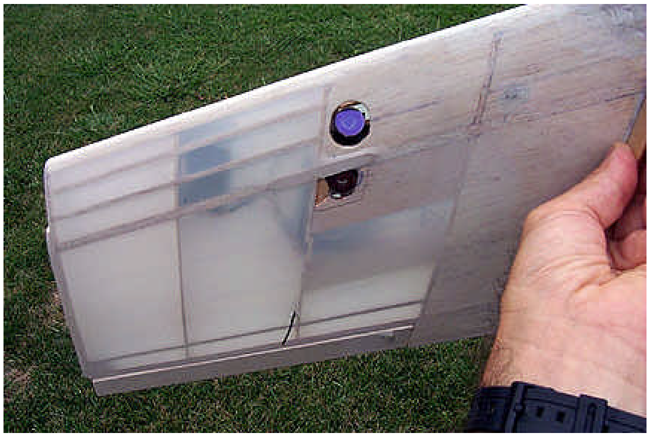

Figure 18. Dual video camera system installed in 60 cm Bat MAV

Figure 19. Bat 60 cm participating in Marines LOE 4 Quantico, VA, September 1999

CONCLUSIONS

Our MDO analysis revealed the importance of maximum lift capability and large power to weight ratio for mission capable MAVs. Surprisingly, the need for low drag, or high values of lift to drag ratio, is relatively unimportant for meeting the mission constraints. Based on these observations we were able to design and flight test a fixed wing Trochoid MAV that demonstrated the use of vortex lift and propulsion effects to increase maximum lift. These design features are important because they provide a means to improve MAV performance that is not sensitive to low Reynolds Number effects. AVTOL MAV design, the Heli-Rocket, has also been proposed based on the observation that for low values of L/D and high power to weight ratio, a VTOL aircraft is nearly as efficient as a fixed wing design.

Flight tests of MAVs ranging in size from 15 cm to 100 cm has shown that the MAV system size changes little as aircraft size increases because of the fixed power requirements for communicating over a fixed distance. Smaller MAVs require larger ground station equipment and this offsets the impact on system size compared to using a larger more capable MAV.

Based on our participation in military exercises with the Marines, we have realized the importance of the video imagery quality that MAVs deliver. If the imagery is not clear, not georeferenced, or lacks resolution, then the value of the entire MAV system may be insignificant. It is essential that MAVs be designed to meet performance requirements appropriate for an imaging platform in the initial design phase. This will insure that the proper camera system and optics will be included in the system and that the dynamic motion of the image plane will be addressed. Similarly, a flight control system with autonomous flight capability and simple user interface is essential if MAVs are to be operated by users without specialist skills. The miniaturization and integration of these systems into MAVs is a primary technical challenge that must be solved before any MAV system can be useful beyond the research laboratory. MLB has demonstrated autonomous flight with GPS waypoint navigation in our 100 cm Bat MAV and we have also demonstrated a prototype inertially stabilized camera system in the same aircraft.

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