DESIGN AND FLIGHT TEST RESULTS FOR MICRO-SIZED FIXED-WING AND VTOL AIRCRAFT

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ABSTRACT

There has been recent interest in unmanned air vehicles with a largest linear dimension no greater than 6 inches. Micro sized air vehicles (μAV) are intended to operate close to a point of interest without detection and provide surveillance teams with critical information in life threatening situations that is currently not available in a rapid-deployment urban-environment mission scenario. This paper studies the importance of aerodynamics, propulsion, and mission requirements on the design of a μAV.

A Multi-Disciplinary Optimization method is used to size μAV's for a baseline mission. Sensitivity studies of the optimized designs identify features that most strongly affect its performance. Electric and internal combustion engine propulsion are compared. Results of these analyses show that large energy density, power density, and maximum lift capability are the most important features of successful μAV's and that ICE power is superior to electric because of its larger power density. The results also show that increases in parasite drag due to low Reynolds number is of minor importance so long as lift capability is maintained. Maneuverability constraints have the strongest influence on μAV size because smaller turn radii require lower wing loadings and for a fixed weight this implies larger wing area and size.

Three radio controlled prototypes of μAV's were built and test flown based on the design study results. These vehicles are a 9 inch span electric powered fixed-wing, a 6 inch span ICE powered fixed-wing, and a 7 inch diameter ICE powered VTOL design. Each design has been flown successfully as a radio control aircraft and the flight test results revealed several unexpected difficulties relating to aircraft stability, control, and propulsion system integration. Further numerical analysis of the VTOL design shows that the size penalty for VTOL capability is negligible and that a 6 inch tail-sitter μAV can perform all of the mission requirements and operate in VTOL and translational flight modes.

SYMBOLS

Cdo	zero lift parasite drag coefficient
Cd2	lift dependent parasite drag coefficient
Cd	total drag coefficient
f	fuselage flat-plate area (ft^2)
Sref	reference wing area (ft^2)
Cdp	parasite drag coefficient
CL	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)
CLmax	maximum lift coefficient
Waf	airframe weight (lb)
GTOW	gross take-off weight (lb)
bref	reference span (ft)
tc	airfoil thickness/chord
Ki	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)
hp	propellor efficiency

INTRODUCTION

There has been recent interest in unmanned air vehicles with a largest linear dimension no greater than 6 inches. Micro sized air vehicles (μAV) are intended to operate close to a point of interest (< 100 ft.) without detection and provide surveillance teams with critical information in life threatening situations that is currently not available in a rapid-deployment urban-environment mission scenario. Small vehicle size should lower the total system cost when compared to larger military UAV's and will also allow these aircraft to be stored and carried in a briefcase. A typical μAV mission would consist of flying 1km to a point of interest, loiter in close proximity for 1/2 hour and then return. During flight the aircraft is expected to encounter turbulent winds up to 25 mph, perform tight turns near buildings, and climb repeatedly to 350 ft. altitude. The aircraft must be stable enough to serve as a live airborne video platform and must be easy enough to fly so that an individual with minimal training can operate it.

Currently, there are no UAV designs which meet these criteria and many technical issues must be resolved before a successful μAV can be produced. This paper addresses the issues of micro-aircraft propulsion, configuration, and design by studying the problem with numerical simulations and through experimental flight tests of prototype μAV's. It is assumed that the micro-aircraft can be treated as an airborne platform with a payload of sensing devices, so that the design of the μAV is not forced to be coupled to its payload. A numerical optimization procedure is used to find the smallest aircraft design 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 these optimization studies show that the vehicle size is highly sensitive to the minimum 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 more strongly affects vehicle size than keeping parasite drag low. A comparison of designs using an advanced lithium battery versus an internal combustion engine (ICE) show that the electric powered design suffers from excessive battery weight due to the low power density of the lithium battery when compared to the ICE. A feasible μAV with ICE power, 1 ounce payload weight, and a 20 ft. minimum turn radius is recommended based upon this analysis.

Three experimental vehicles were built and test flown as demonstrators of the flight performance achievable using off-the-shelf hardware. The first aircraft is an electric powered, 9 inch wingspan design capable of 1 minute flight duration using nickel-cadmium batteries and is radio controlled (single channel). The second design uses an internal combustion engine for power and is based on the numerical optimization results for a baseline μAV. This vehicle has an 8.5 inch size, 2 channel radio control, and flies for several minutes. The last design is a vertical take-off and landing (VTOL) configuration that has a largest linear dimension of 7 inches, carries no radio control, and flies for several minutes. Since there is little flight data on any aircraft in this size range it is important to build and fly prototype μAV's to discover unforeseen design issues and operational challenges. Some of the unexpected issues encountered in flight tests include the strong effect of propellor wake on wing and control surface aerodynamics and the nonlinear effect of vortical flow at high angles of attack on aircraft stability and control.

MDO SYNTHESIS OF A FIXED-WING MICRO AIR VEHICLE

Method

Preliminary design of a μAV involves finding the necessary gross take-off weight (GTOW) and wing size needed to complete the specified mission. For the case of μAV'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 μAV. The optimizer solves for the six design variables:

Design Variables	symbol	units
wing area	sref	(sq.ft.)
wingspan	bref	(ft)
cruise CL	CLc	
loiter CL	CLl	
gross take-off weight	GTOW	(lb)
installed power	Pinst	(HP)

which satisfy six mission constraints:

Constraint	Type	Nominal Value
duration	=	0.5 hours
operational radius	=	3500 ft
minimum turn radius	< =	10 ft
minimum climb angle	> =	15 degrees
maximum altitude	=	350 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)

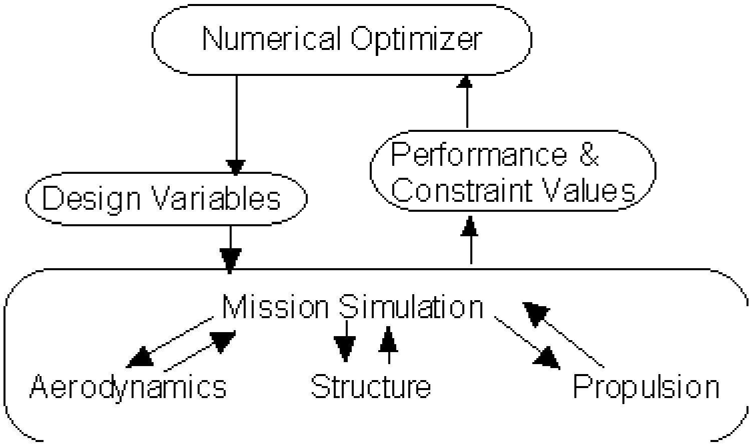


Figure 1. MDO method flowchart.

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 μAV's performance.

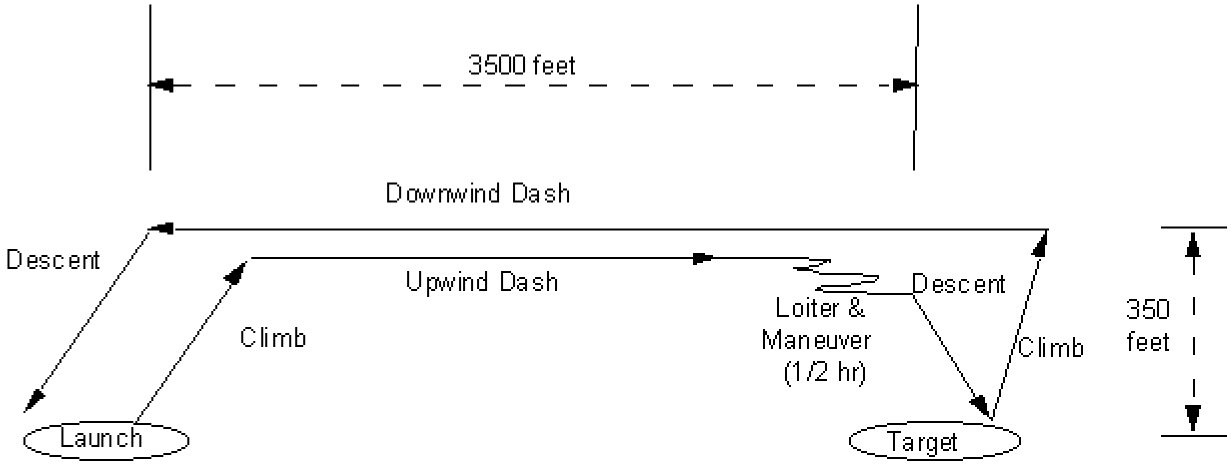


Figure 2. Mission scenario

Aerodynamics

μAV'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 CL max. The drag model for a μAV 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 CLmax = 1.2 based on the airfoil data in reference [1].

<u>Drag</u>

$Cdp = Cdo+Cd2\ CL^2$

$Cd = f / sref + Cdp + CL^2 / (\pi\ AR\ e)$

$D = 0.5\ \rho\ V^2\ Cd$

$Cdo = .015$

$Cd2 = .007$

$f = 0.5 / 144\ ft^2$

$e = 0.90$

<u>Lift</u>

$L = 0.5\ \rho\ V^2\ CL$

$CLmax = 1.2$

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

$$Waf = GTOW\ (K1((bref^{3}) / (tc\ sref)) + K2) + K3\ sref$$

$K1 = 0.0003$

$K2 = 0.10$

$K3 = 0.10$

Propulsion

For ICE powered μAV’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 the Cox model engine 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 μAV’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% and the impact of this assumption is discussed in the results section.

Fuel consumption rate

$$ff = sfc\ Pshaft$$

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 μAV 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 μAV's performance in each phase of the mission.

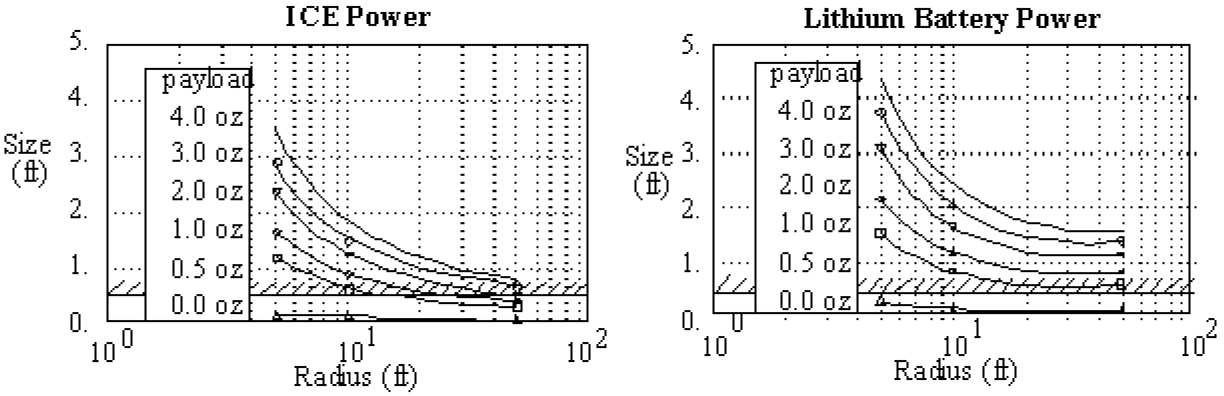


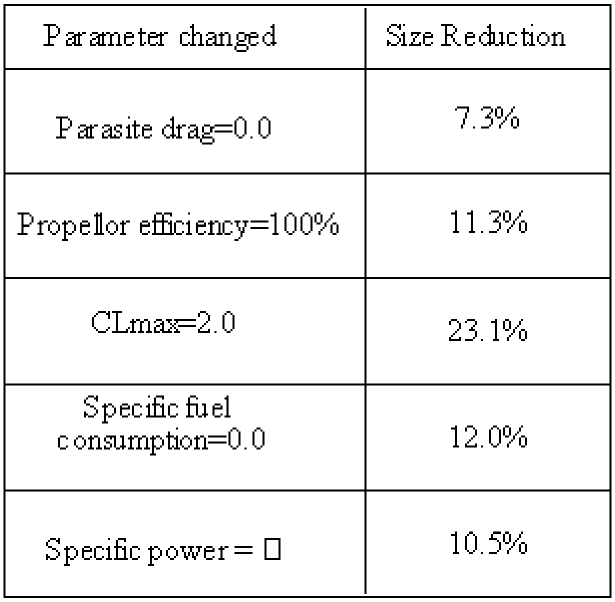
Figure 3&4. MDO results, minimum size versus turn radius for ICE and electric design

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 μAV 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 μAV designs can carry up to 2 ounces of payload for a 6 inch maximum size, but if maneuverability is required then 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 μAV's are carrying 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 μAV 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 μAV design, re-optimizing, and observing the change in performance (i.e. minimum size). Table I shows the results of these calculations for a 1 ounce payload 10 foot turning radius baseline 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 μAV size decreases by only 7.3% indicating that low Reynolds Number increase of parasite drag is of minor importance for ICE powered μAV's. The sensitivity of size to CLmax is strong (23% smaller if CLmax = 2.0) indicating that the primary aerodynamic design challenge for μAV's is increasing lift capability and not decreasing parasite drag.

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 μAV's. Table I shows increasing specific power to have 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 μAV'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.

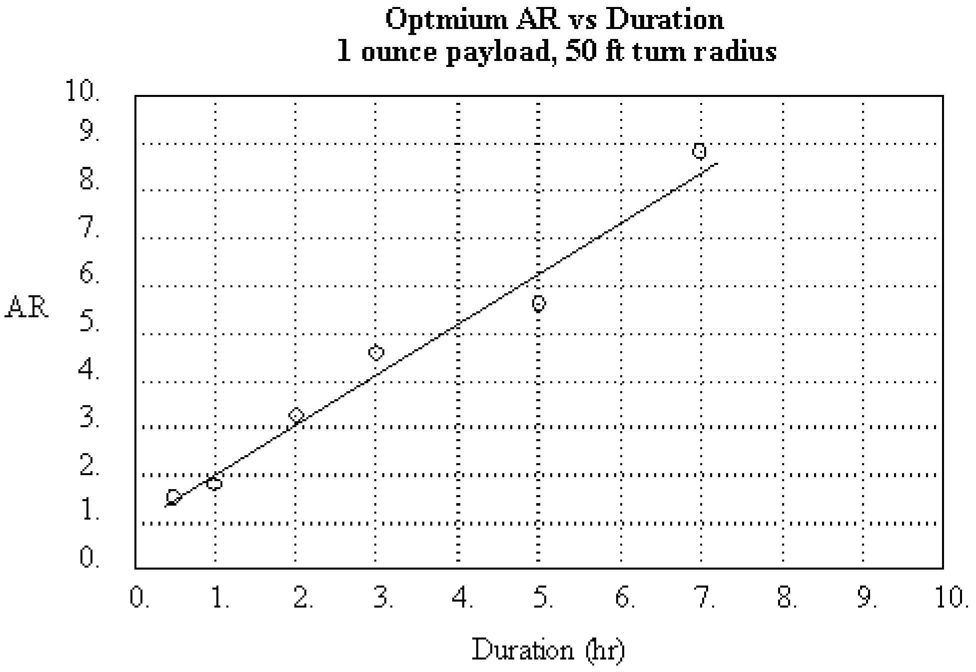


Figure 5. Effect of duration constraint on optimum aspect ratioOnly designs with a single surface rectangular wing were considered in the MDO synthesis but other configurations may prove more efficient for theμAV mission.

The results show that μAV 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.

FLYING PROTOTYPES AND FLIGHT TEST RESULTS

Fixed-Wing Electric (Ni-Cad powered)

An electric powered model using nickel-cadmium batteries was designed and built to establish a performance benchmark using off-the shelf model airplane components. This model was designed to be as small as possible, have at least 1 minute flight duration, and carry a radio control system. Because the Ni-Cad batteries have a much lower energy density (52lb/HP-HR) than lithium cells (11.82lb/HP-HR) the performance of this design is much less than the MDO synthesized electric μAV's. One minute flight duration is achieved with a 0.18 watt-hour battery pack. The two DC electric motors used are approximately 40% efficient and produce 1.0 watt shaft power (each). The propellors are approximately 50% efficient, so only 1.0 watt total is delivered to the airframe for flight power. This is sufficient for a 100 fpm maximum rate of climb at 1.5 ounce GTOW and 8:1 maximum L/D. Figure 6 shows the configuration of the 9 inch wingspan model and the high lift airfoil section designed for maximum lift at Reynolds Number 30,000. This aircraft's configuration was arrived at by trial and error experimentation and does not represent the result of an MDO synthesis. Twin engines were chosen to keep the disc loading of the propellors acceptably low (small diameter propellors are required because the motors are only efficient at high RPM's). The lightest commercially produced radio control system (0.25 ounce) has one channel that can deflect a small rudder hard-over at the pilot's command. It is possible to adjust the model so that left and right turns of a desired radius can be accomplished by appropriately pulsing the rudder control. Obviously, the model must posses a high degree of inherent stability to be flown using only rudder commands. This model averages 1 minute flight duration with a maximum altitude of 40 feet. Flight speed estimated from a video recording is 27 fps which corresponds to a lift coefficient of 0.7, very close to the airfoil CLmax = 0.9. With limited climb and maneuver capability, this µAV can not be flown in high winds (> 5mph) or turbulence.

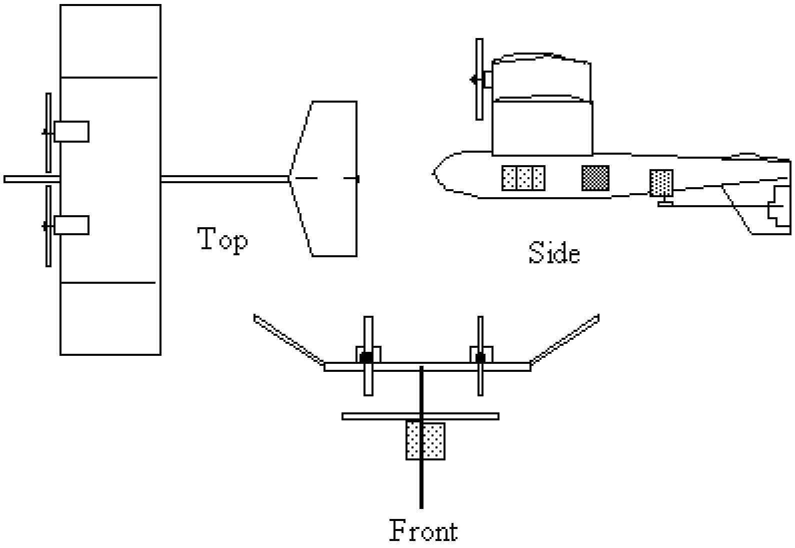
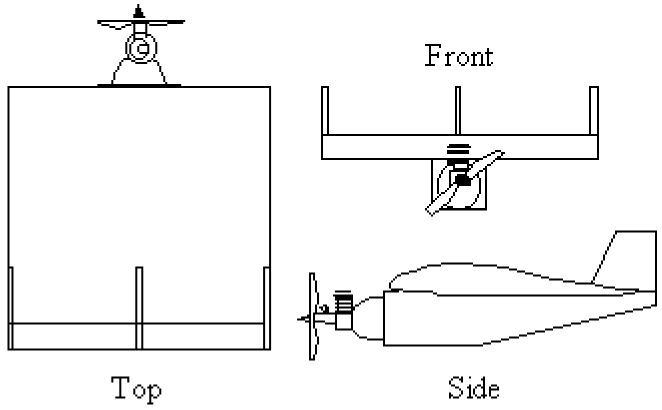


Figure 6. 9 inch span electriµAV

Fixed-Wing ICE Powered

Based on the MDO synthesis results, a µAV was designed with a largest linear dimension of 8.5 inches that could fly with a commercially available ICE and carry a two channel radio control system. Figure 7 shows the configuration of this design named Flyswatter. The Flyswatter is powered by a Cox 0.010 cubic inch engine (20 watt output), and has a 3.25 ounce GTOW (2.0 ounces are radio control unit). It flies for 2 minutes on the 0.125 ounce fuel tank with the engine at full power and can turn within a 20 foot radius. The flight speed is approximately 30 fps which corresponds to a cruise CL of 0.8 and the estimated maximum L/D is 4.5:1. The Flyswatter is somewhat overweight compared to the MDO predictions because the radio control gear is much heavier than what the MDO analysis assumes for a production µAV. When lighter radio control systems have been developed the amount of fuel appropriate for 1/2 hour duration can be carried and the GTOW reduced. An unexpected advantage of the Flyswatter's low aspect ratio planform is the development of vortex lift at high angles of attack as shown in figure 8. This allows the model to turn much tighter than expected and to fly as slowly as 20.0 fps (CLmax =1.7). Low aspect ratio along with a "high" wing loading of 0.8lb/ft2 decreases the µAV's gust sensitivity and the Flyswatter can be flown in winds up to 15 mph. Rudder and elevator surfaces are used to control the µAV and the rudder is particularly sensitive due to the high velocity propellor wake that impinges on it. The airflow over the wing is dominated by the vortical flow for lift coefficient above 0.2 and it is the strength of these vortices that determine the control power of the rudder through sideslip-roll coupling. This causes the rudder authority to vary considerably with trimmed lift coefficient and also leads to a wing-rock limit cycle motion at high angle of attack. Experimenting with larger vertical tail surfaces and adding an active control system would further improve the handling qualities. Initial versions of the Flyswatter used ailerons for roll control, but they proved to be ineffective due to the strong vortical flow at the wing tips. Rudder control provides more than adequate roll authority through sideslip-roll coupling so long as the lift coefficient of the wing is positive. A typical flight profile involves hand-launching the μAV, climbing to 50 feet altitude and then performing reversal turns every 50 - 100 feet in order to keep the aircraft in visual contact. When the fuel runs out the Flyswatter is glided in for landing. The vehicle is strong enough to survive full-power crashes into a grass field without damage because of its small weight and size.



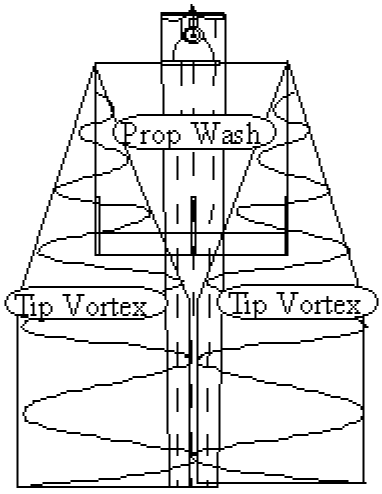


Figure 7. Flyswatter 6 inch span μAV Figure 8. Vortex lift and propulsion slipstream acting on Flyswatter wing.

VTOL ICE Powered

Figure 9 shows a μAV VTOL design named the Heli-Rocket. It consists of a Cox 0.049 cu inch motor, a 7 inch propellor, and 4 torque reaction / control vanes. This μAV was designed to demonstrate the feasibility of VTOL flight using an ICE engine. The current Heli-Rocket is a free-flight design that is inherently stable while climbing. It climbs at 1000 fpm and can fly for 2.5 minutes using a 0.4 ounce fuel tank. When the engine quits the μAV falls (tumbling) until it hits the ground and because of its small weight sustains little damage. This model has been flown with 1.5 ounce payload weight and can be controlled using aerodynamic flaps on each of the torque reaction vanes along with engine throttle. With actively controlled flaps the μAV is essentially a miniaturized tail-sitter configuration that can be hovered or flown in translational flight.

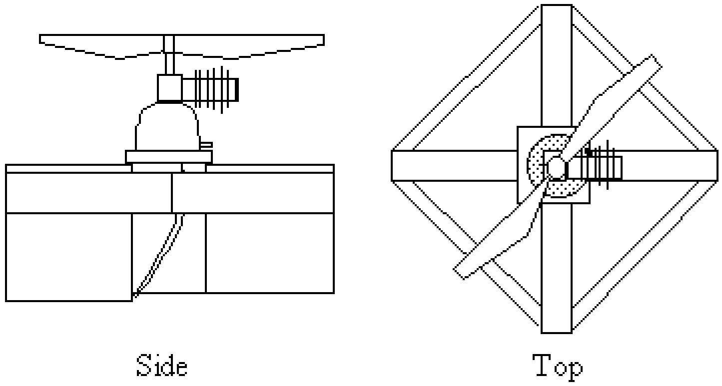


Figure 9. Heli-Rocket 7 inch size VTOL μAV

Using a propellor optimization code,the estimated power required to fly a VTOL μAV with a 6 inch diameter and a 2 ounce GTOW was found to be nearly equal to the power required by a similarly sized fixed wing μAV. Fixed wing aircraft engine size is determined by the maneuver requirement and the optimized designs operate with a lift-to-drag ratio of 3:1 at 2-g's and flight speed of 25 fps while turning. The increased 'g' loading doubles the aircraft drag and this moderate speed high drag flight condition sizes the engine The optimized VTOL design can maneuver at low speeds in a near-hover, so it does not suffer the power loss incurred in high-speed turning flight, but does require greater power to hover than a similarly sized fixed wing aircraft in 1-g level flight. The net result is that the power required to perform the baseline mission is nearly equal for the two designs. This implies that their is little penalty in size for designing a μAV for VTOL flight when the maneuverability constraints are critical.

Flight Test Summary

The three models presented demonstrate that micro-sized aircraft are feasible and that power density, CLmax, and energy density are more critical to μAV flight performance than achieving high lift-to drag ratio. Both ICE powered models have been flown with more payload weight than a production μAV requires. The vehicles are simple to build and do not rely on a high degree of system integration in their construction. Each μAV costs less than $250.00 to duplicate, including radio control unit.

ADVANCED CONFIGURATIONS AND FLIGHT MODES

Based on the flight tests of the Flyswatter μAV several ideas for improving L/D and handling qualities over a wide range of speed are suggested. The fixed wing μAV's studied have reduced L/D and poor handling qualities at high speeds because of their large wing area, required for maneuverability. For the short range and duration studied in this paper, the reduced L/D is not a critical issue, but if either of these mission parameters increases μAV performance benefits from reduced wing area. The sensitivity to gusts and control inputs increases dramatically at higher speeds and reduced wing area would minimize these effects also. In nature, birds overcome these problems by using several design innovations that might have application for advanced μAV designs. Birds have wings that can be retracted and folded, changing span and area in a way that optimizes the bird's performance over a wide speed range.

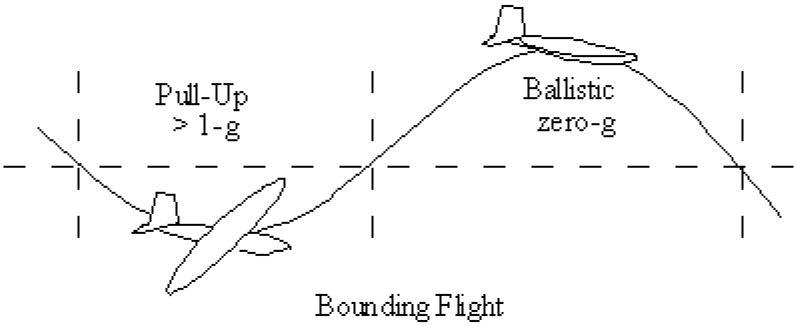


Figure 10. Bounding flight trajectory

An excellent example of this is bounding flight (fig. 10, [2]) in which a bird alternates between a zero lift trajectory and high 'g' pull-up. The wings are retracted during the zero lift phase reducing the parasite drag area significantly and during the pull-up the wings are fully extended for minimum induced drag. Birds can fly at near double their best L/D gliding speed while maintaining nearly maximum L/D by using this technique. Figure 11 shows a sketch of a µAV configuration that could perform bounding flight with a stowable wing. If the µAV is propellor driven, bounding can be used during cruise flight as a way to achieve high cruise speeds with little penalty in maximum range and maneuverability.

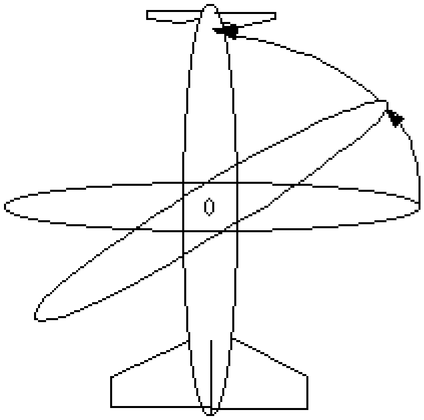


Figure 11.µAV with stowable wing for bounding flight.

Aeroelastic wing deformation is another innovation birds use to decrease their gust sensitivity. Wings that twist and unload at high ‘g’ can significantly reduced the lift loads due to turbulence and could be incorporated on µAV aircraft.

The MDO µAV analysis assumed a steady turn rate for the maneuverability constraint evaluation. Birds can achieve tighter turn radius by performing unsteady direction change maneuvers, where altitude, speed, and bank angle vary continuously. When advanced autopilots become commonplace in µAV’s these more complicated maneuvers can be performed automatically, reducing the wing area required to meet maneuverability requirements.

Flight tests and analysis of the Heli-Rocket have shown that a feasible VTOL µAV can be designed with no penalty in size for the proposed baseline µAV mission. It is possible to combine the desirable attributes of both the Flyswatter and Heli-Rocket designs into a single µAV that has VTOL and translational flight capabilities and meets all the mission requirements. Figure 12 shows the proposed configuration of such a µAV which uses a circular duct as a wing and internal vanes for control. The circular duct becomes a low aspect ratio wing when the aircraft is trimmed for translational flight. Control vanes located inside the duct provide yaw, pitch, and roll control even in hover because they are immersed in the propellor wash. The configuration is a tail-sitter aircraft built in miniature.

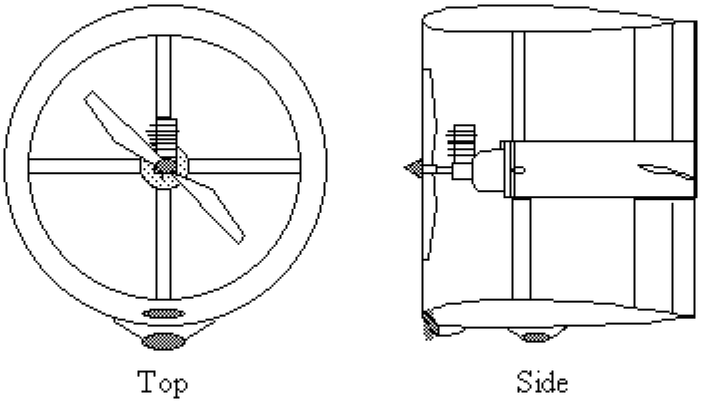


Figure 12. Tail-SitterμAV

CONCLUSIONS

Results of the MDO optimization studies show that the vehicle size is highly sensitive to the minimum required turning radius because vehicles that must turn tightly require lower wing loading which implies greater size for a fixed total mass. Performing tight turns doubles the drag load for a given flight speed and as a result becomes the primary factor in sizing the engine for highly maneuverable μAV’s. Sensitivity studies show that maintaining a high lift coefficient more strongly affects vehicle size than keeping parasite drag low for mission duration less than one hour because of maneuver constraints. A comparison of designs using an advanced lithium battery versus an internal combustion engine (ICE) show that the electric powered design suffers from excessive battery weight due to the low power density of the lithium battery when compared to the ICE. A feasible fixed-wing μAV with ICE power, 1 ounce payload weight, and a 20 ft. minimum turn radius is recommended based upon this analysis.

Three experimental vehicles were built and test flown to serve as demonstrators of the flight performance achievable using off-the-shelf hardware. These prototypes use both electric and ICE propulsion and demonstrate VTOL and fixed wing flight modes. The designs presented here are large enough in size that a high degree of component integration (i.e. propulsion, airframe, controls) is not necessary for successful performance. This is considered an advantage because the problem of sensor, telemetry , and propulsion development can remain separate from the μAV airframe design. When the miniaturized electronic systems have been developed they could be flight tested on proven airframes such as those presented in this paper.

Flight tests of the fixed wing Flyswatter μAV showed the strong effect of propellor wake on control authority and the nonlinear effect of vortical flow at high angles of attack on aircraft stability and control. Experimental and numerical analysis results for the VTOL configuration have shown that the size penalty for VTOL capability is negligible. A tail-sitter configuration has been proposed with VTOL and translational flight capability that meets all of the μAV mission requirements.

Future μAV design efforts should focus on propulsion system developement, μAV configurations that can fly in VTOL and translational modes, and the suitability of μAV’s as camera platforms. Propulsion work should focus on small two-stroke ICE engines that are throttlable and run use higher heating value fuels (i.e. kerosene, butane, etc.) for improved fuel economy. As soon as a miniature stability augmentation system is available designs such as the tail sitter could be flight tested in a stabilized hover. When miniature video equipment becomes available the suitability of μAV’s as camera platforms can be measured.

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