

Design and Development of a Reconnaissance Micro Air Vehicle and Launch System

Matthew C. Shields, Cameron M. Hatcher, Roland A. Pitcairn, Christopher W. Aiken, David B. Berman, Christopher M. Carnahan, William A. Foley, Sean P. Hammervold, William E. Holway
and Lindsay C. Marek
University of Colorado, Boulder, CO, 80309

This paper describes the design, fabrication, and testing of a fixed wing Micro Air Vehicle (MAV), which is defined by the Defense Advanced Research Projects Agency (DARPA) standard as being smaller than 6 inches in any linear dimension. In order to make the aircraft a valid reconnaissance vehicle, it is loaded with a color video camera and GPS chip, making it capable of transmitting a video stream with a time and position stamp back to a ground station during flight. The challenges involved in designing a functional MAV are significant as conventional aerodynamic tools such as the vortex lattice method are known to give poor results for this type of aircraft. The inviscid nature of these solvers does not account for wingtip vortices which dominate the low aspect ratio of a MAV. In addition, aerodynamic analysis is difficult as the low Reynolds number flow causes an unpredictable laminar flow separation which cannot be modeled with readily available software. As a result, these traditional methods are expected to produce significant error. A final consideration is that the miniature scale of the MAV requires electronic and payload components to have the lowest possible masses and volumes. The resulting small component inertias, coupled with the requisite short span, provide minimal stabilizing moments, making the MAV extremely susceptible to turbulent flow. In order to validate the success of the design, predicted results derived from established analytical techniques are compared to experimental results obtained from empirically testing multiple MAV prototypes and errors are quantified. Finally, the design and construction of a launch mechanism to achieve repeatable launch profiles is described.

Nomenclature

AVL – Athena Vortex Lattice
DARPA – Defense Advanced Research Projects Agency
FEM – Finite Element Method
GPS – Global Positioning System
MAV – Micro Air Vehicle
R/C – Remote Control
UAS – Unmanned Aerial Systems
UAV – Unmanned Aerial Vehicle

I. Introduction

Since the mid 1990s, the size of Unmanned Aerial Systems (UAS) has decreased drastically, greatly increasing the potential for low impact reconnaissance spyplanes. One of the most significant developments has been the advent of the Micro Air Vehicle (MAV), an aircraft defined by the Defense Advanced Research Projects Agency (DARPA) as a vehicle less than 6 in (15.24 cm) in any direction. The main goal in designing any UAS is reducing risk to human life by sending an aircraft in to a “danger zone” to stream data back to a ground station without any imminent threat to a pilot. There are many advantages to using a MAV for this application instead of more conventional aircraft. The MAV does not require an expansive open area for takeoff or landing, but instead can be launched from a man-portable launcher and then crash-landed. Their extremely small size makes them difficult to detect, which is ideal for surveillance. Although each aircraft is only capable of carrying a small payload, a fleet of MAVs each carrying different sensors (for example, cameras, chemical detectors, or other equipment) could be

deployed to obtain a range of information. Finally, the cost of a MAV is on the scale of a few thousand dollars, as opposed to a conventional UAS, which is in the order of \$50,000. With these convincing reasons in mind, the University of Colorado has decided to invest significant time in designing, fabricating and testing a fixed wing MAV conforming to the DARPA standards as an Aerospace Senior Project for the 2007 – 2008 school year.

II. Mission Profile

The mission concept defined for this MAV is for a ten minute, “over the hill” surveillance deployment. The application of such a mission could allow a team of soldiers to send the MAV over a hill or around a corner and view a real-time video stream to obtain information about an area without having to actually send a human into a risky area. To allow for the aircraft to be used in as many scenarios as possible, the MAV must be able to fly at an altitude of 70 ft for a duration of 10 minutes. The payload will be a video camera and GPS unit which sends a video that contains an overlaid signal of the time/location stamp back to a ground station up to 300 ft away during flight. The vehicle will be flown by remote control (R/C) at a distance of up to 300 ft. Finally, in order to produce a constant launch profile, the MAV will be launched by a collapsible launch system with a controllable launch velocity and angle.

III. Complexities of MAV Research

The extreme small scale of micro air vehicles introduces a number of complexities into the design process. The planform area of a MAV must be extremely small with an aspect ratio of near unity to simultaneously fulfill DARPA standards for a MAV and also cause enough flow for lift. As a result, MAVs fly at low Reynolds numbers where traditional aerodynamic tools can not accurately predict flight characteristics. These methods, such as the vortex panel method, are designed to be used in inviscid conditions whereas the viscosity of a low Reynolds number flow is far more dominant than at a high Reynolds number flow. This creates two significant problems. First, the laminar flow separation for a low velocity, viscous flow is very unpredictable. In addition, the low aspect ratio of the wing means that the flow is dominated by tip vortices which wash over the wing. A high aspect ratio wing, such as a glider wing, is not adversely affected by this because so much of the wing is not reached by tip vortices, but the short span on a MAV is almost entirely influenced by the tip vortices. Aerodynamic software does not account for either of these phenomena, and thus provides inaccurate predictions for lift and drag. In addition to this concern, MAVs are notoriously unstable due to their minute moments of inertia. As all onboard components must necessarily have the most negligible masses and volumes possible, and as there is a small area in which to place this equipment, none of these parts can contribute significantly to the overall moment of inertia of the aircraft. This leads to inherent roll instability as the vehicle design cannot completely passively stabilize itself after a perturbation.

The solution to these considerable complexities is extensive testing and empirical validation of analytical results. Traditional aerodynamic tools were used to initially design the MAV, despite the inaccuracies which were expected to occur. A fabrication method was selected which allows a complete aircraft to be built in approximately one day, making it extremely efficient to construct test models for a trial-and-error approach of design development and validation.. As a result, extensive testing is underway to characterize the flight performance of the MAV.

IV. Design Process

A. Aerodynamics

The aircraft design software packages available for the aerodynamic analysis of the MAV included Athena Vortex Lattice (AVL) which is an inviscid solver used for the design of conventional aircraft and UAVs, XFLR5 which is a viscous solver created for airfoil analysis and aircraft design at low Reynolds numbers, and XWing which is a viscous solver that takes into account the effects of flow at low Reynolds numbers on low aspect ratio wings which are dominated primarily by tip vortices. XWing is a research code currently under development at the University of Colorado and AVL and XFLR5 are commercially available software.

Several planform shapes were considered for the MAV wing – elliptical, rectangular, Zimmerman, inverse Zimmerman, and trapezoidal – and for each planform, the maximum planform area was calculated for a constant aspect ratio, the lift-to-drag ratio was determined, and the cruise lift coefficient was determined. The total

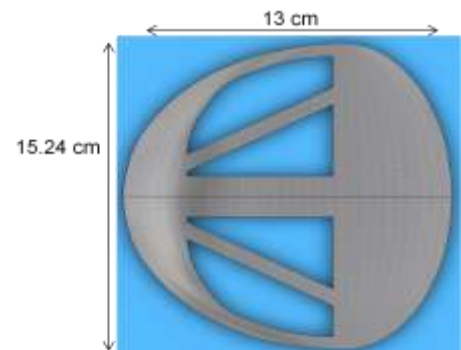


Figure 1. Final MAV planform

ratings of each planform shape were based on calculations from AVL and XFLR5 modeling each planform shape using a flat plate, and the total ratings were used to decide which would perform the best for this MAV. The inverse Zimmerman planform, shown in **Error! Reference source not found.**, was selected for the design of this MAV because it provided a high coefficient of lift when compared to the other planform shapes considered, it had a small amount of curvature along the trailing edge which allowed for easy control surface integration, and it provided a large total planform area to maximize the lifting area. The resulting planform area was 155.6 cm².

The type of airfoil selected for this MAV was determined by the required cruise lift coefficient specified by **Error! Reference source not found.** and a required flight angle of attack specified by **Equation 2**

$$C_{L_{cruise}} = \frac{W}{\frac{1}{2}\rho V^2 S}$$

Equation 1

$$\alpha = \frac{C_L}{2\pi}$$

Equation 2

The two design alternatives under consideration for the airfoil type were a conventional airfoil (i.e. NACA or Eppler) or a thin, cambered, reflexed airfoil. Due to the large thickness associated with the conventional airfoils and the complexity associated with constructing such an airfoil on such a small scale, the thin, cambered, reflexed airfoil was chosen for this design. In addition, the thin, cambered, reflexed airfoil type has been implemented in previous MAV designs with success. This airfoil is shown in Figure 2.

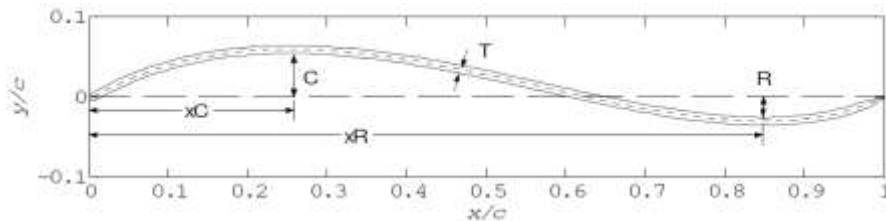


Figure 2. Thin, cambered, reflexed airfoil

Once the thin, cambered, reflexed airfoil was chosen, an iterative process was used to determine the combination of parameters which would satisfy the lifting requirement. The allowable variable parameters were the maximum camber, the position of the maximum camber, the maximum reflex, and the position of the maximum reflex. The calculated performance characteristics included the stall angle, the maximum coefficient of lift, the moment coefficient, the coefficient of drag, and the location of the coefficient of pressure. An airfoil selection index (**Error! Reference source not found.**) using these parameters was created to rank the hundreds of airfoils examined based on performance and to observe trends correlating airfoil characteristics to aerodynamic properties.

$$\text{Index} = \frac{C_{L_{max}} \cdot \alpha_{stall}}{C_m \cdot C_D}$$

Equation 3

Based on the results of this analysis, the airfoil chosen had a maximum camber of 6.5% of the chord, a maximum chord location of 19% of the chord, a maximum reflex of 1% of the chord, and a maximum reflex location of 82% of the chord. This airfoil produced the aerodynamic performance parameters shown in **Error! Reference source not found.**

Table 1. Selected airfoil performance parameters

α_{stall}	10°
$C_{l_{\text{max}}}$	1.097
C_m	0.0515
C_D	0.0580
Airfoil Index	64.15

The tail configuration of the MAV was determined using a similar process as was used to determine the planform shape. Several tail configurations were considered and each was analyzed based on certain performance characteristics. The tail configurations analyzed were the conventional tail, the T-tail, the H-tail, the tri-tail, the V-tail, the inverted V-tail, the Y-tail, and no tail. Each tail configuration was compared based on mass, fabrication complexity, and stability contribution, and the highest ranking configuration was selected for the design. The final design consisted of a modified Y-tail which incorporated a horizontal stabilizer at the base of the Y-tail portion below the wing, and the angled surfaces on top of the wing were separated to allow for less interference with the propeller wash over the wing. The final tail configuration design can be seen in Figure 3. This configuration was chosen for the large amounts of stability provided both above and below the wing as stability was determined to be the most important deciding factor in the tail configuration selection.

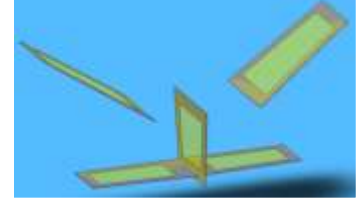


Figure 3. Final tail configuration

The required size of the tail surfaces was determined by an iterative process using the stability derivatives output by the AVL software and a MATLAB calculation using Equation 4, Equation 5, and Equation 6 obtained from *Introduction to Aircraft Flight Dynamics* (Schmidt 1998). Equation 4 uses the derivative of pitching moment coefficient with respect to change in angle of attack which is output from AVL to determine the horizontal volume coefficient, V_H . Once the horizontal tail volume coefficient was determined, Equation 5 was used to determine the required horizontal tail surface area.

$$\frac{\partial C_m}{\partial \alpha} = \left(\frac{\partial C_L}{\partial \alpha} \right)_{\text{wing}} \left(\frac{\Delta x}{c} \right)_{\text{ac}} - \left(\frac{\partial C_L}{\partial \alpha} \right)_H (1 - \epsilon_\alpha) V_H \eta_H$$

Equation 4

$$V_H = \frac{S_H l_H}{S c}$$

Equation 5

A similar method was used to determine the required vertical tail area. The derivative of the side force coefficient with respect to the change in sideslip angle was obtained from AVL and the required vertical tail area S_V was calculated. All tail surfaces were assumed to be flat plates, so in Equation 4 and Equation 6, the derivative of the coefficient of lift with respect to change in angle of attack of the tail surfaces was assumed to be $2\pi\alpha$ as determined from *Fundamentals of Flight* (Shevell 1983). The other parameters in Equation 4 and Equation 6 were estimated using methods from *Airplane Design Part VI* (Roskam 1987).

$$\frac{\partial C_Y}{\partial \beta} = \left[\frac{\Delta \partial C_Y}{\partial \beta} \right]_{\text{body}} - \left(\frac{\partial C_L}{\partial \alpha} \right)_V (1 - \sigma_\beta) \frac{S_V}{S} \eta_V$$

Equation 6

Once the required tail surface areas had been calculated, the area distribution between the upper and lower surfaces was determined. This was accomplished based on the ratios of surface area distribution of previous MAVs built at the University of Colorado as well as other institutions. Stability derivatives were then recalculated using the new required tail area and the process was repeated until the required tail area no longer changed. The required tail horizontal area was calculated to be 39.9 cm² and the required vertical tail area was calculated to be 34.3cm².

Based on research of previously built MAVs, it was determined that aircraft stability and control would be important flight parameters to the design. Aircraft stability was based on Federal Aviation Regulations for Level 1 flight and the stability derivatives were obtained by the AVL inviscid software. As the only software available that calculated the stability derivatives, these results were used for the initial design of the aircraft with the understanding

that an extensive testing plan would be required to verify the design. The resulting stability calculations based on the stability derivatives showed instability in all stability modes except the roll mode. Figure 3 displays the lateral-directional stability modes. The longitudinal modes showed similar behavior to the spiral mode.

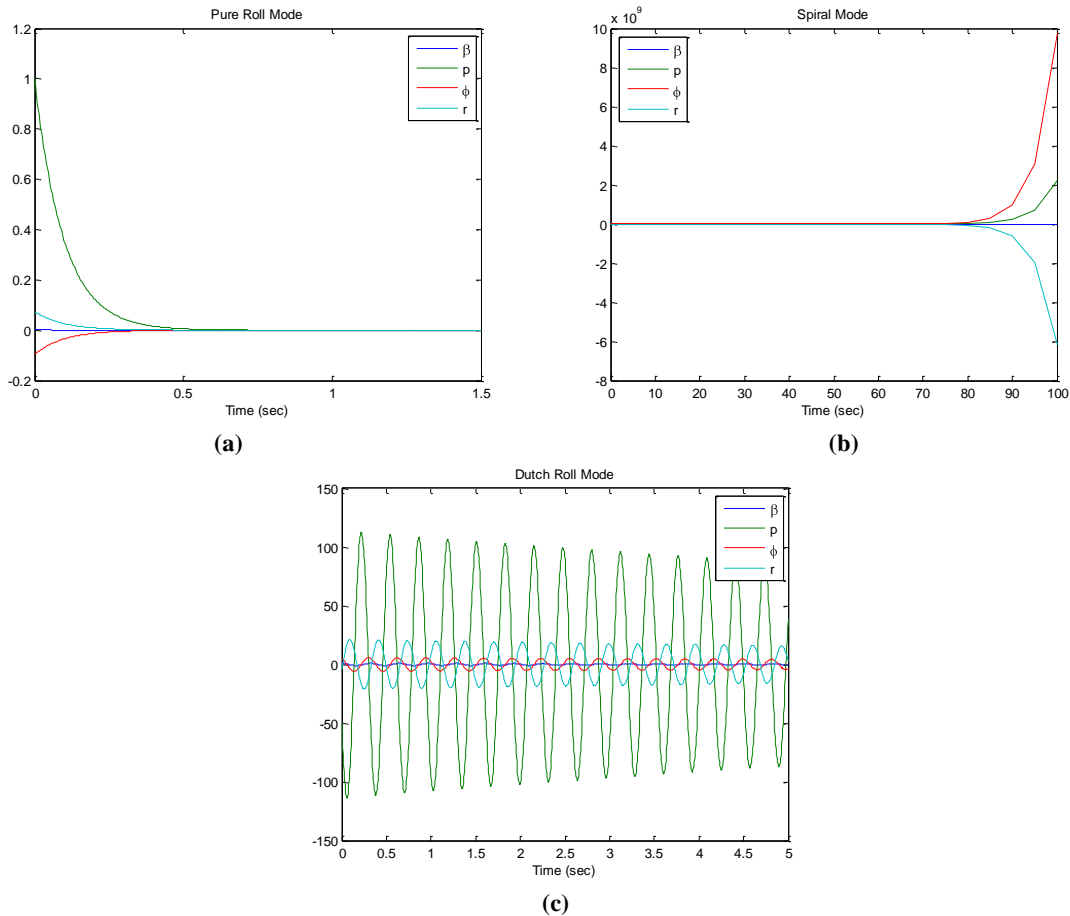


Figure 3. Lateral-directional stability modes: (a) Pure roll, (b) Spiral, (c) Dutch roll

The selection of the control surfaces for the aircraft was driven by climb and maneuvering requirements. The design of the ailerons was driven by the maneuvering requirement during the loiter segment of the mission. The sizing and required deflection angles of the ailerons and the elevator were determined using the stability derivatives produced by AVL and the aircraft equations of motion defined by *Introduction to Aircraft Flight Dynamics* (Schmidt 1998). As a result, the required aileron deflection for a steady 18° banked turn was calculated to be 12° and the required elevator deflection to maintain a steady climb after launch was calculated to be 25.5°. These control surfaces are shown in Figures 5 and 6.

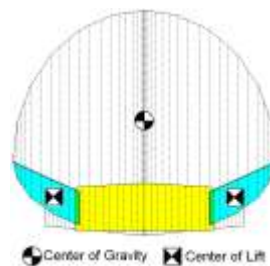


Figure 4. Bottom view of MAV with ailerons on trailing edge

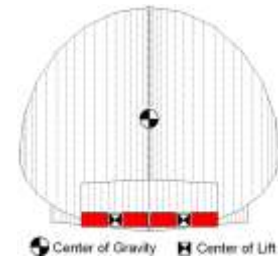


Figure 5. Bottom view of MAV with elevator on horizontal tail

B. Structures and materials

The main structural concerns were: (1) the deflection and deformation of the wing in flight, (2) the connection between the wing and the fuselage, (3) the overall structural integrity of the vehicle, including the ability to survive crash landings, and (4) the effect of the motor vibrations. While all concerns were experimentally tested, it was important to implement structural design in order to avoid any anticipated problems. This design focused on

minimizing wingtip deflection while maximizing general stiffness and durability. All analysis was done using the commercial finite element package ANSYS and was verified with experimental testing.

The materials used to construct the MAV are summarized in Table 2. The materials were chosen based primarily on their low density and secondly upon their strength, modulus and stiffness attributes.

Table 2. MAV materials

Description	Tensile strength	Tensile modulus	MAV part
Unidirectional prepreg carbon fiber	8.825 10^9 Pa	1.29 10^{11} Pa	Wing interior struts
Prepreg carbon fiber weave	4.37 10^8 Pa	2.41 10^{10} Pa	Nose cone, fuselage, wing border
Prepreg fiberglass	--	--	Wing voids
MonoKote	--	--	Entire wing
Balsa wood	73 10^6 Pa	--	Fuselage struts

Using the stated assumptions and the specified materials, an ANSYS model was built and solved. This showed that a maximum deflection of 0.058mm occurred at the wingtips, a negligible amount. A horizontal crossbar was added to the wing to increase the natural frequency (and thus the stiffness) by 200 Hz. The strength of the cyanoacrylate was found to provide a safety factor of approximately 30 from the stress of launch. Experimental testing then showed that the airframe was extremely durable and had no problem withstanding stresses from launches or crashes.

C. Propulsion

In order to determine the optimal subsystem design, many different propulsion options were analyzed. The final selection was an electric motor and Lithium-ion-polymer (LiPo) battery system used to power a single tractor propeller located on the front of the aircraft. This configuration was selected for maximum efficiency as the battery could be used to power both the motor and the electronics package. In addition, a pull propeller is more efficient as it operates in unaffected flow at the front of the airframe.

Initial design of the propeller was done using *JavaProp*. *JavaProp* is a relatively simple program, which is based on the blade element theory. Thrust and efficiency curves were produced for diameters of 3 in (.0762m), 4 in (.1016m), and 5 in (.127m) propellers at RPMs ranging from 0-15,000 and torque from 1-5 mNm . The curves were then used to determine the best configuration for the aircraft. This led to an initial selection of a 4.75in propeller.

Motor selection required empirical testing as the manufacturers of MAV scale electronics components often do not provide accurate specifications for their products. Thus, two motors were obtained and tested for the purpose of comparing their results. Empirical testing of two small motors (3.5g and 5.2g) indicated that a slightly larger motor was necessary; therefore, a 6.2g motor capable of running at a higher voltage (11.1V) was chosen. This additional available thrust made it possible to use a smaller propeller, so the size of the propeller was decreased to 4in. Using a dynamic thrust test stand, this configuration was shown to produce 0.26N of thrust which is greater than the 0.18N required for steady level flight.

D. Electronics

There are two components to the electronics system that will be used on the MAV. The first component is the R/C control system, which will allow an operator on the ground to control the MAV during flight. The second component provides a practical purpose for the MAV, as it allows it to transmit video, encoded with GPS data, back to the ground.

The R/C control system has been designed to allow the MAV to be controllable at a range of 300 ft. The R/C receiver controls two servos responsible for actuating



Figure 7. CM-588/S video camera

the ailerons and the elevator, as well as controlling the speed of the propeller. The imaging system was designed based upon “Johnson’s Criteria” which relates a statistical probability for a person to identify an object in a picture with the number of pixels representing the object. This led to the selection of the camera shown in Figure 7. In order to overlay GPS data onto the video stream, a circuit board was designed which would combine the information from the camera and GPS chip while fitting into the confines of the mass budget. A final, but crucial, aspect of the design was selecting an imaging system which operates at a different frequency than the R/C system to avoid interference between the two.

E. Launch system

The launch system's design process began with a trade study of the possible systems that would conceptually satisfy the project requirements. Three types of launch systems were considered; a compression spring loaded mechanism with a cock and lock release mechanism, a slingshot/crossbow device, and a torsion spring mechanism with a slide rail. A feasibility report evaluating the different designs was conducted and concluded that the torsion spring and rail design best fit our requirements as well as team desires for an easily manufactured system so the most amount of time could be devoted to the MAV. Although initially constrained to be only a foot long, safety considerations led the team to increase the size of the launcher to two feet, making it easier to use but still extremely portable.

V. Final Design

A. MAV

The final design of the MAV is a fixed wing puller prop aircraft. The motor, propeller, battery, speed controller, radio control receiver and servos are all hobby products. The camera and video transmitter are made for home surveillance. The fuselage and airframe are made of carbon fiber, fiberglass, MonoKote and balsa wood. The components are arranged to attain a center of gravity at the quarter cord of the center of the wing. Figure 8 shows a completely fabricated MAV which was used for flight testing.



Figure 8. Fabricated flight test MAV

B. Launch system

The final design of the launch system is depicted in Figure 9. The torsion spring provides a constant 10 pounds of force with a servo-pin combination to secure the MAV until launch. Aluminum L-brackets were used to construct the rail system that guides the MAV during launch. The telescoping legs were also made of L-brackets.



Figure 6. Launch system with test MAV

C. Mass budget

Table 3. MAV mass budget

Component	Predicted mass (grams)	Actual mass (grams)	Deviation (grams)
Airframe	10	10.5	+0.5
Fuselage	2.5	2.5	0
Motor	5.2	6.0	+0.8
Propeller	1.0	1.0	0
Rudder servo	3.3	2.9	-0.4
Aileron servo	3.3	2.9	-0.4
Speed controller	1.2	2.3	+1.1
Receiver	1.2	1.4	+0.2
Battery	18	20.5	+2.5

Video transmitter	5.0	3.3	-1.7
Camera	1.5	2.1	+0.6
PCB	12	12 (estimated)	0
Control rods, adhesives, etc	3	6 (estimated)	+3
Total	67.2	73.4	+6.2

The predicted masses were given by the manufacturers or estimated from previous MAV designs. The actual components have been measured to find the actual masses. The actual mass of the MAV is 6.2 grams heavier than estimated.

VI. Fabrication Process

A. Simplicity of fabrication

From the very beginning of the MAV design, it was known that there would be a lot of uncertainties due to the largely unexplored flight regime that the MAV would be operating under. To counteract these uncertainties, lots of flight tests were planned in order to troubleshoot problems and give the pilot experience with the vehicle. While many flight tests give obvious advantages, they often cause damage to the vehicle structure and its various electrical/mechanical components. To ensure frequent flight tests, it was necessary to have materials and manufacturing plans in place that would allow relatively quick MAV construction. Carbon fiber and fiber glass, pre-impregnated with epoxy, were found to have more than adequate strengths, and they were chosen as the MAV's main structural materials because they can be shaped and cured in a matter of hours. Easy access to the fuselage was taken into consideration during the design to allow for quick insertion of the MAV's components. Cyanoacrylate adhesives and packing tape are both light weight and strong enough to hold the structure and components together. These fasteners also have the advantage of a quick application time. All told, the entire MAV can be constructed in one work day by the group's ten members.

B. Wing and control surfaces

Wing manufacture takes approximately two hours. During the first hour, carbon fiber and fiber glass are laid out on a reusable, high temperature, hard plastic mold which is created using a CNC milling machine. Strips of release material are also applied to keep the epoxy from bonding to the mold as shown in Figure 9. Padded pieces of breather material are used to ensure that the vacuum pressure during curing is applied to all parts of the wing evenly. The final step is placing the prepared mold and wing in a vacuum bag, which has a small hole cut in it for insertion of the vacuum hose assembly. The product is attached to a vacuum pump and baked at 250 degrees Fahrenheit for 1 hour. The mold and release strips are shown in Figure 9. The control surfaces are laid up using the same method as the wing; however, since they are flat they do not require a mold to be fabricated.



Figure 9. Wing mold and release strips



Figure 10. Fuselage construction using traceable design

C. Fuselage

Each fuselage is made of balsa wood and two pieces of flat carbon fiber, cured similarly to the control surfaces. The carbon fiber pieces are cut to shape, and fastened to a balsa wood frame using cyanoacrylate adhesives. The frame is made from strips of balsa wood, cut and fashioned by hand into the required shape. This is shown in Figure 10.

D. Integration

Once the wing, fuselage, and control surfaces have been constructed, the MAV can be fully assembled. The fuselage and tail are attached to the wing using cyanoacrylate adhesives. The movable control surfaces,

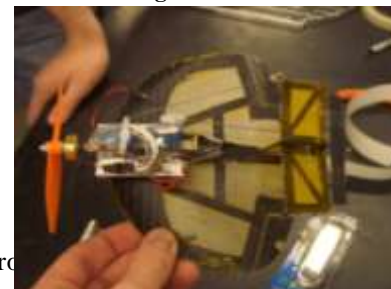


Figure 7. MAV with components

which support much smaller loads, are attached using flexible strips of packing tape or MonoKote. Control horns can either be fashioned from small pieces of balsa wood, or purchased. The control horns are firmly attached to the control surfaces by cyanoacrylate adhesives. Control rods are cut from pieces of music wire, and bent to fit the distances between servos and control surfaces using pliers. The motor box is a combination of balsa wood and plastic, which firmly grips the motor using a pin, and can be glued to the fuselage. Finally, all of the MAV's electrical components are inserted into their spaces in the fuselage and secured using packing tape as shown in Figure 11 **Error! Reference source not found.**

VII. Test Results

A. Aerodynamics

As previously mentioned, the MAV was designed for optimum performance and stability based on the results of analytical analysis software commercially available. However, there is no software package currently available that provides accurate results for low Reynolds number flight for low aspect ratio wings. These software packages are known to provide inaccurate results in this flight regime, and an extensive test plan was required to verify the performance characteristics of the aircraft.

1. Forces and moments

To verify the aerodynamic forces and moments produced by the aircraft, wind tunnel tests were conducted using the Integrated Teaching and Learning Laboratory wind tunnel at the University of Colorado. Tests were performed for a range of angles of attack at the flight velocity of 15.5 m/s and also for a range of velocities at the flight angle of attack of 8°. These tests were completed and data was gathered for the lift and drag forces as well as the pitching moment. The results were then compared to the analytical results calculated by XFLR5 and AVL to obtain an estimate of the error associated with using conventional aircraft design tools to design a micro air vehicle. The experimental results were also compared to the results of the XWing software being developed at the University of Colorado to validate the software.

The results of these comparisons are still pending, but will be available for the final draft.

2. Stability

As previously described, one of the most crucial aspects of designing a MAV is achieving stability. The analytical stability results shown in Figure 3 indicate an unstable aircraft; however, the viscous, low Reynolds number nature of the flow is so different from the nominal conditions suitable for AVL that these results did not merit a high level of confidence. Thus, the MAV design remained unaltered as experimental testing was required to determine the actual stability. Preliminary stability tests have already been performed in a low speed wind chamber, and the group is pleased to report that the MAV demonstrates passive roll and pitch stability to perturbations. These tests were initially performed without the ability to deflect control surfaces, meaning in an actual flight test the pilot should be able to control the MAV in response to gusts of wind.

However, several of the first flight tests of the MAV have resulted in an immediate roll into the ground. At present it is believed that these crashes were due to an unstable launch, as hand launches were necessary until the completion of the launcher. In addition to poor launch profiles, further stability testing has indicated that although the aircraft appears stable in roll and pitch, there is a possibility of coupled roll and yaw instability in the form of the Dutch Roll mode. Thus, more extensive stability testing is necessary to determine what modifications need to be made to the aircraft to damp out this mode. Current plans include increasing the size and incidence angle of the vertical control surfaces and remounting the motor to induce a greater flow over the wing and tail.

B. Flight testing

Ultimately, the performance of the MAV was evaluated based on flight demonstrations. In order to determine the true flight characteristics of the MAV it was necessary to eliminate as many abnormal flight parameters during testing. In order to accomplish this, it was necessary to choose an indoor space for testing. The University of Colorado Recreational Center, was used as the primary indoor test facility. Initially, flight tests were inconsistent due to the nature of the hand launch that was used. A total of 8 flight tests have been completed. In several of the tests, the MAV did not fly due to an inconsistent or incorrect launch. In three of the tests, the MAV proved that it had significant thrust and significant lift, as climbing flight was achieved. This preliminary success ultimately

confirms the lift and thrust are significant for cruise and climb flight, and allowed for team resources to be diverted from these areas. Each of the flight tests were recorded on several cameras, and review of the footage was especially important when determining problems with flight.

Preliminary flight tests suggested that the MAV is unstable in the Dutch Roll mode at high flight speeds (>6m/s). This stability was originally unforeseen due to the limited velocity of the wind chamber used for stability testing. Stability tests were continued after initial flight tests in order to damp out this mode.

VIII. Conclusions

After an extensive design period, the development of the MAV is currently in the midst of the testing phase. Results to this stage have been mixed. Although the aircraft displays acceptable stability levels in roll and pitch modes, it has been observed to struggle in the Dutch Roll mode. This instability has caused several crashes during flight testing and has currently grounded the MAV until further stability testing can be conducted to establish precisely what is causing this instability. It is conjectured that the vertical control surfaces above the wing are too small and are not providing the restoring moment that they should. This could potentially be coupled with the motor being too far beneath the wing, resulting in airflow being pulled under the wing and therefore not producing circulation and a resultant airflow over the control surfaces. The best solution to these problems is to continue stability testing to pinpoint the exact cause of instability then reconfigure the aircraft to compensate for this problem. As previously described, the turnaround time necessary to redesign and refabricate a MAV is extremely minimal, so these alterations should be able to be quickly accomplished. This will make it possible to compare the initial and final designs of the MAV, which correspond to theoretical and experimental analysis, to determine how effective conventional aerodynamic tools are for a MAV scale flow regime.

IX. Acknowledgments

The MAV team would like to thank several members of the Aerospace Engineering Sciences faculty at the University of Colorado: Dr. Kamran Mohseni and Dr. Mahmoud Hussein for being advisors to the project, and Dr. Donna Gerren for advice on writing this paper.

In addition, the MAV team would like to thank Matthew Osborn and Jason Roadman, the customers for the project, for their valuable advice and assistance as R/C pilots.

X. References

Hazen, Zachary. "Micro Air Vehicle Power Plant Modeling and Validation." 2006

Hepperle, Martin. *JavaProp - Design and Analysis of Propellers*. March 1, 2006. <http://www.mh-aerotoools.de/airfoils/javaprop.htm> (accessed September 4, 2007).

Propeller Performance. March 23, 2006. <http://ocw.mit.edu/NR/rdonlyres/Aeronautics-and-Astronautics/16-01Fall-2005-Spring-2006/CDAECADA-98A9-46AE-A163-19322ABE79DD/0/spl7a.pdf> (accessed November 30, 2007).

Roskam, J. (1987). *Airplane Design: Part IV*. Lawrence: DAR Corporation.

Schmidt, L. V. (1998). *Introduction to Aircraft Flight Dynamics*. Monterey: AIAA.

Shevell, R. S. (1989). *Fundamentals of Flight, 2nd Edition*. Prentice Hall.