MICRO AERIAL VEHICLE DEVELOPMENT: DESIGN, COMPONENTS, FABRICATION, AND FLIGHT-TESTING

Gabriel Torres and Thomas J. Mueller

117 Hessert Center, University of Notre Dame
Notre Dame, IN 46556
Phone: (219) 631-4334 | Fax: (219) 631-8355

Abstract

The design of micro aerial vehicles (MAVs) is currently hindered by the lack of a thorough understanding of the flow physics of very small aircraft flying at low speeds. Trial and error has been the most effective design tool in many cases, often leading to lengthy and costly design processes. The unavailability of complete analytical methods and the computational expense of numerical methods make an empirically-based design optimization approach a practical alternative. This paper will describe the use of wind tunnel data in the implementation of such a procedure for the design of a micro aerial vehicle. This MAV was the University of Notre Dame's entry for the fourth annual Micro Aerial Vehicle Student Competition, held at Fort Huachuca, AZ in May 2000. Restrictions imposed by the use of COTS components, as well as issues in fabrication and durability, will be discussed. Key features of the final MAV prototype will be outlined and a summary of test flights will be presented.

1. INTRODUCTION

The development of functional micro aerial vehicles (MAVs) within the last several years has been hindered by a limited understanding of the aerodynamics of small aircraft flying at low speeds. Classical aerodynamic theory provides reasonably accurate performance predictions for airplanes flying at Reynolds numbers larger than approximately one million (typically found in full scale aircraft). The emergence of remotely piloted vehicles for military surveillance missions during the late seventies led to an increase in research of lower Reynolds numbers aerodynamics (in the range below 500,000). Comprehensive literature surveys of this area of research can be found in Mueller (1985) and Lissaman (1983).

Micro aerial vehicles, in contrast, operate at significantly lower speeds and have smaller dimensions; their Reynolds numbers range is approximately 150,000 or lower. In the last five years, ongoing research has revealed the dominant flight mechanisms present at these Reynolds numbers. Nevertheless, a complete analytical or theoretical procedure for predicting low Reynolds number aircraft performance is not yet available. Computational techniques are under development but they take considerable computer time as the equations that must be solved are fully viscous for such low Reynolds numbers.

Another complication of MAV design stems from the desire to minimize the overall size of the MAV (sometimes defined as the vehicle’s maximum dimension). This restriction suggests that in order to maximize the available lifting wing area, the chord and wingspan should be roughly equal to each other. In other words, the aspect ratio (*AR*, defined as the square of the wingspan divided by the total wing area) of MAV wings should be approximately one. Wings of such low aspect ratios exhibit unique aerodynamic properties such as high stall-angles of attack and nonlinear lift versus angle of attack curves. These characteristics resemble those seen in delta wings at higher Reynolds numbers and are particularly dominant for wings of *AR* less than or equal to unity. The MAV designer is faced with the difficulty of developing aircraft with inherently low aspect ratios which will operate at very low Reynolds numbers. Furthermore, the designer has very little theoretical, analytical, numerical, or empirical data for use as a base for design calculations. A possible solution to this dilemma is presented in this paper in the form of an empirically-based method which can be used to design a functional micro aerial vehicle. The procedure is exemplified herein through the design of an aircraft to be entered into a student design competition.

2. THE MICRO AERIAL VEHICLE STUDENT COMPETITION

The motivation for the work presented in this paper was the design of an entry for the 2000 Micro Aerial Vehicle Student Competition, which was held in Fort Huachuca, AZ, in May 2000. The main objective of this competition is to design and build the **smallest** micro aerial vehicle that can perform the following mission:

- Fly and photograph a 1.5-meter size symbol on the ground located 600 meters from the launch site and hidden from view by a square enclosing fence 3.5 meters wide and 1.5 meters high.
- Provide a legible image of the symbol to the competition judges at the launch site.

The size of the MAV is defined as the largest linear dimension, that is, the largest linear distance between any two points located on the MAV while it is airborne. The definition of the MAV size as the largest dimension suggests that the optimum design will fit inside a sphere of the smallest possible radius. This in turn leads one to conclude that if the lifting area of the vehicle is to be maximized such as to minimize size, a wing of aspect ratio close to unity should be used.

The mission profile is shown in Figure 1. At an estimated cruise speed of 25 mph, it takes approximately 1 minute to reach the target and 1 minute to return. One minute of loiter time to acquire the image is also included.

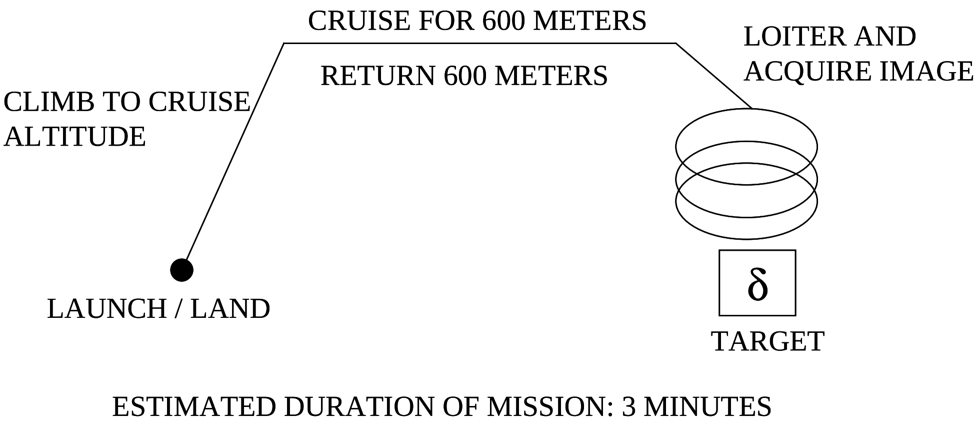
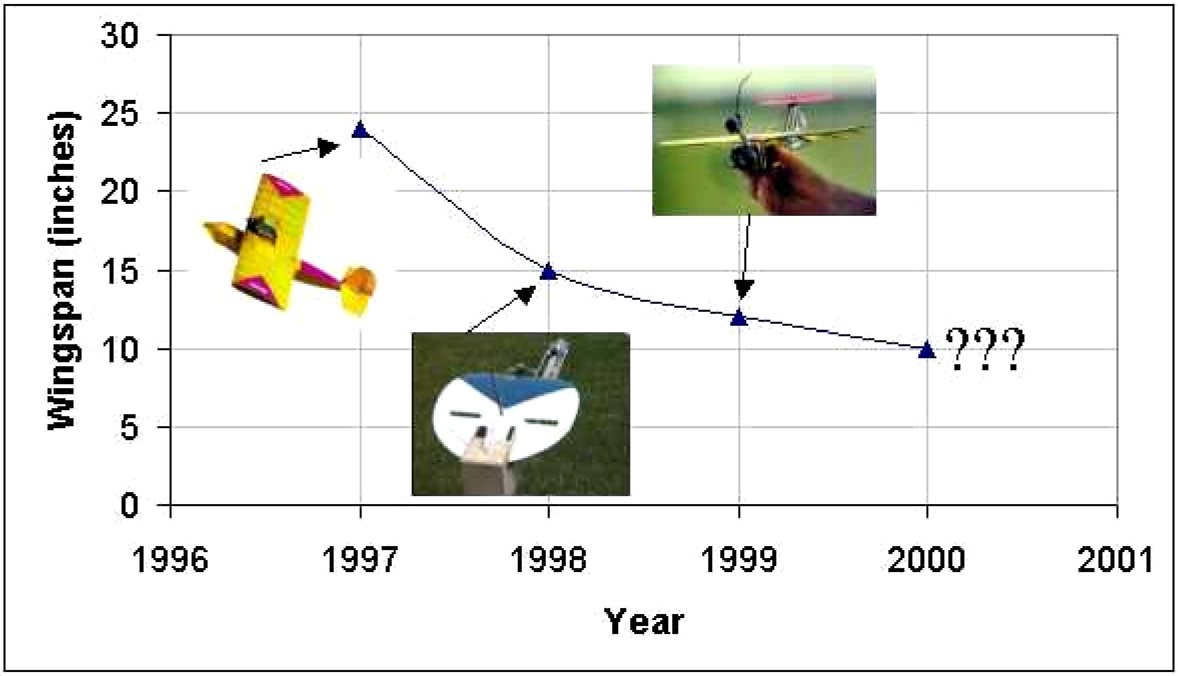


Figure 1: Mission Profile for Micro Aerial Vehicle Student Competition

The winning designs of past competitions can be used to provide a rough estimate of what size vehicle can be considered competitive. Figure 2 below plots the maximum dimensions of the winning entries for the first three years that the competition was held. An extrapolated estimate of the likely size of the 2000 competition winner is also shown.



*The 1997 vehicle shown was not the official winner but was smallest one to complete mission

Figure 2: Maximum Dimensions of Winning Entries for MAV Student Competition

From this figure it can be concluded that in order to be competitive, the maximum dimension of the MAV should not exceed approximately 10 inches. But can this be achieved?

3. CONCEPTUAL DESIGN

Before answering that question the designer must go through a preliminary design procedure where the overall size and shape of the vehicle will be determined. This conceptual process is the focus of this paper and it is outlined in Figure 3 below.

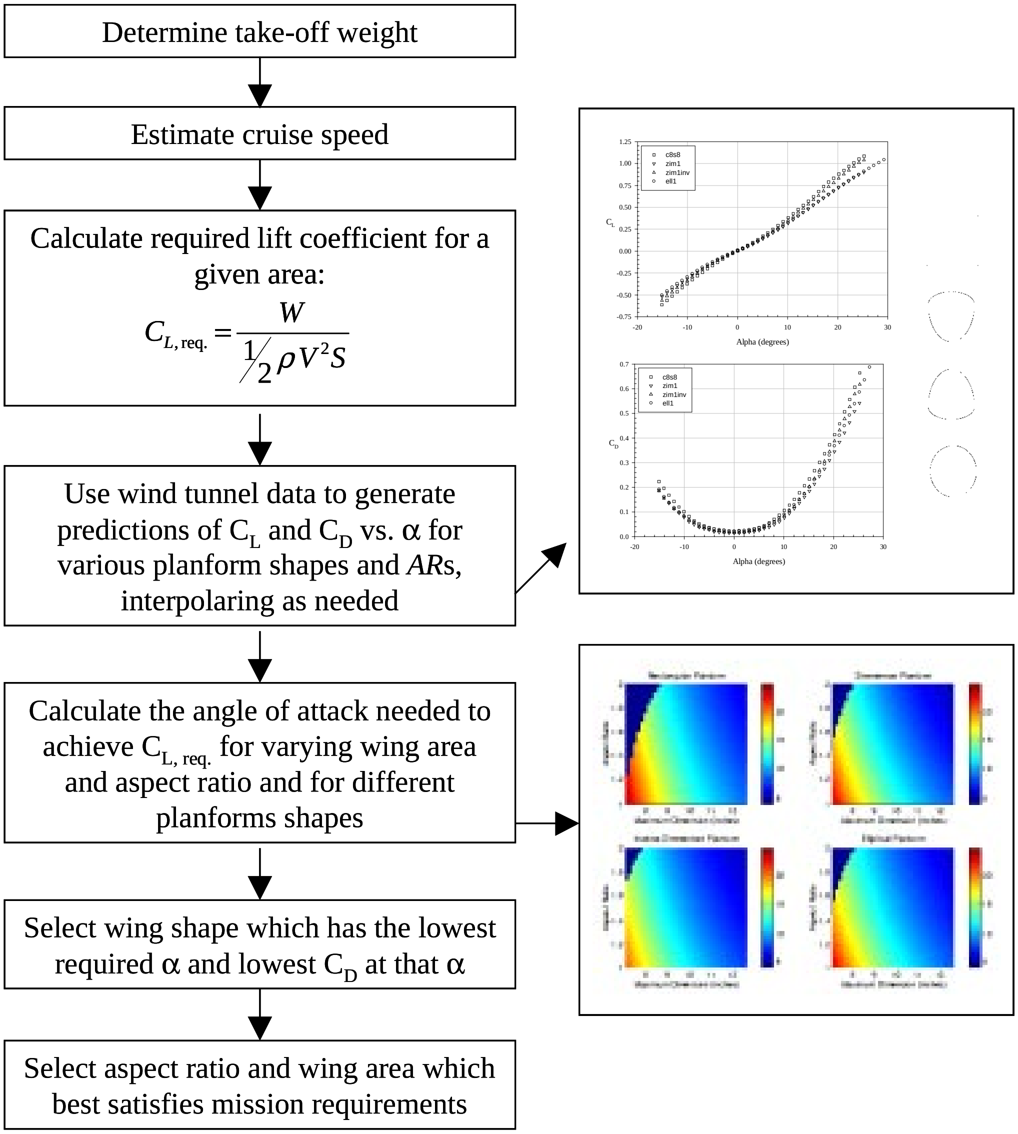


Figure 3: Design Procedure for Micro Aerial Vehicle

3.1 Components and Take-Off Weight

One advantage of MAV design over conventional full-scale aircraft design is that the calculation of take-off weight can be performed with relatively little use of empirical data. This is due to the fact that most of the components to be carried, as well as their size and weight, are known. The disadvantage, however, is that the vehicle must be designed such as to accommodate these components. For the MAV competition, the components to be carried were a propulsion system, video camera and transmitter, radio control receiver and actuators, and batteries for the electronic components.

The propulsion system deserves the most attention as there are two distinct options: electric power or internal combustion engines. Although off-the-shelf (and affordable) battery technology is steadily improving, it is not yet at the stage where it can outperform an internal combustion engine in terms of thrust per unit weight (this is more due to a deficiency in battery technology rather than motor efficiency). Early on, the decision to use an internal combustion engine for propulsion was made due to the availability, low cost, and high thrust to weight ratio achievable with glow-fuel engines. A Cox 0.010 cubic-inch-displacement model airplane engine was used coupled with a 3.25 inch-diameter propeller. The selection of this particular engine displacement was made through trial and error and through experience with radio control models because very limited performance information is available for model engines of this size.

Figure 4: Propulsion System

The video transmitter and camera used were the smallest and lightest that could be found within budget limitations. The transmitter has a mass of 8 grams and operates on 2.4 GHz at 80 mW. The range of the video signal has been tested to more than one mile. The camera used was a small 5-gram pinhole-lens black and white camera with a 80 degree field of view.

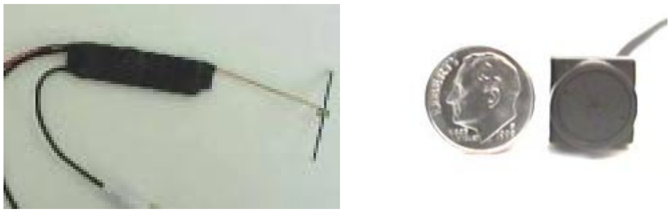


Figure 5: Video Transmitter and Miniature Camera

Radio control electronics consisted of a 12 gram receiver operating on 72 MHz and two micro servos weighing 5.5 grams each. The radio control equipment and video camera/transmitter run on 9 volts at approximately half an amp of current draw. The duration of the MAV competition mission was expected to be about 3 minutes, so a 50 mAh battery pack was more than sufficient. After a thorough search of commercially available battery technology, the design team settled on Nickel-Cadmium batteries. Commercially available Lithium batteries have significantly higher capacity to weight ratio, but are unfortunately not able to provide the 500 mA current required for operation of the electronic components.

Figure 6: Radio Control Receiver, Servos, and NiCd batteries

The last item contributing to take-off weight is the structure of the MAV. The most effective way to obtain an estimate for structural mass is to approximate it based on the structures of other micro aerial vehicles. The airframe used for the Notre Dame MAV was a balsa wood frame, reinforced with carbon fiber strips and fiberglass cloth (details in Section 4). The structure was covered with a light fabric material. Average structural weight of similar MAV test models constructed since the beginning of the project was 15 grams. Indeed, this estimate was very close (usually within a few grams) of the actual structural weight of all vehicles built up to date. Table 1 presents a summary of component mass for a competition-ready MAV. The overall take-off mass is 105 grams.

Internal combustion engine, propeller	15g
Fuel, fuel tank	9g
Radio control electronics (two servos, receiver)	26g
Video electronics (camera, transmitter)	14g
Batteries (9-volt, 50 mAh NiCd)	26g
Structure	15g
Total	**105g**

Table 1:Components of MAV.

3.2 Estimation of Cruise Velocity

With the take-off mass defined, the next step in the design procedure is to determine the cruise speed of the MAV. This step is particularly difficult because, as mentioned earlier, there is no experimental data of the thrust of the engine selected versus airspeed. Without this information, the typical method of determining cruise speed (in which the cruise speed is the velocity at which the thrust of the engine equals the drag of the airplane) cannot be used. An approximation of the expected cruise speed must be made instead. Furthermore, it must be assumed that this speed will not vary much with the shape of the wing or the configuration of the airplane. Although this method may not yield exact solutions to be used for design, it will provide a way of comparing different planform shapes to determine which is best suited for a micro aerial vehicle that satisfies the mission of the competition. A reasonable estimate of the cruise speed of an MAV which uses the Cox 0.010 engine for propulsion is 25 mph. This approximation is based on test flights of other airplanes with the same engine.

3.3 Required Lift Coefficient

With the take-off weight and estimated airspeed known, it is possible to calculate the lift coefficient required to sustain level flight. That is,

$$C_{L,\,\text{req.}} = \frac{W}{\frac{1}{2}\rho V^2 S} \quad ,$$

where *W* is the weight of the aircraft, *V* is the estimated cruise speed, and *S* is the wing area.

For a weight corresponding to 105 grams at an approximated airspeed of 25 mph and sea-level conditions, the required C_L varies linearly between 0.83 and 0.26 as the wing area varies from 25 in^2 to 80 in^2.

3.4 Selection of Wing Planform Shape

In order to determine which wing shape is best suited for a micro aerial vehicle, wind tunnel experimental data was used to develop an empirically-based design and analysis procedure. In a series of experiments, four wing shapes with aspect ratios of 1 and 2 were tested. The wings had zero camber and a thickness-to-chord ratio of 1.96%. The shapes tested are shown in Figure 7.

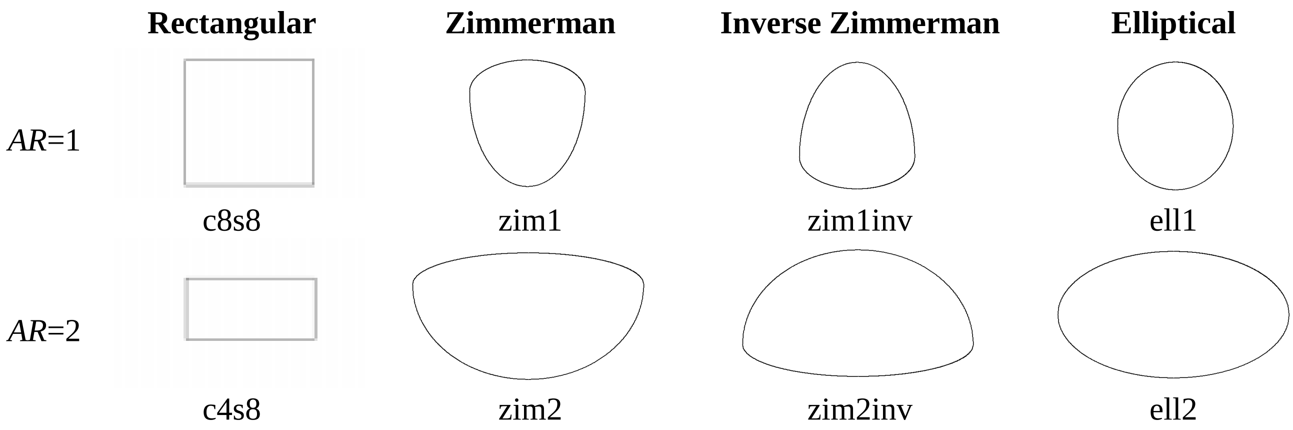


Figure 7: Shapes of the Wings Tested in Wind Tunnel Experiments

Lift and drag of the models were measured using a highly sensitive force balance at chord-Reynolds numbers of 70,000, 100,000, and 140,000. Representative plots of C_L and C_D versus angle of attack for all four wing types of *AR* 1 and 2 are shown in Figure 8.

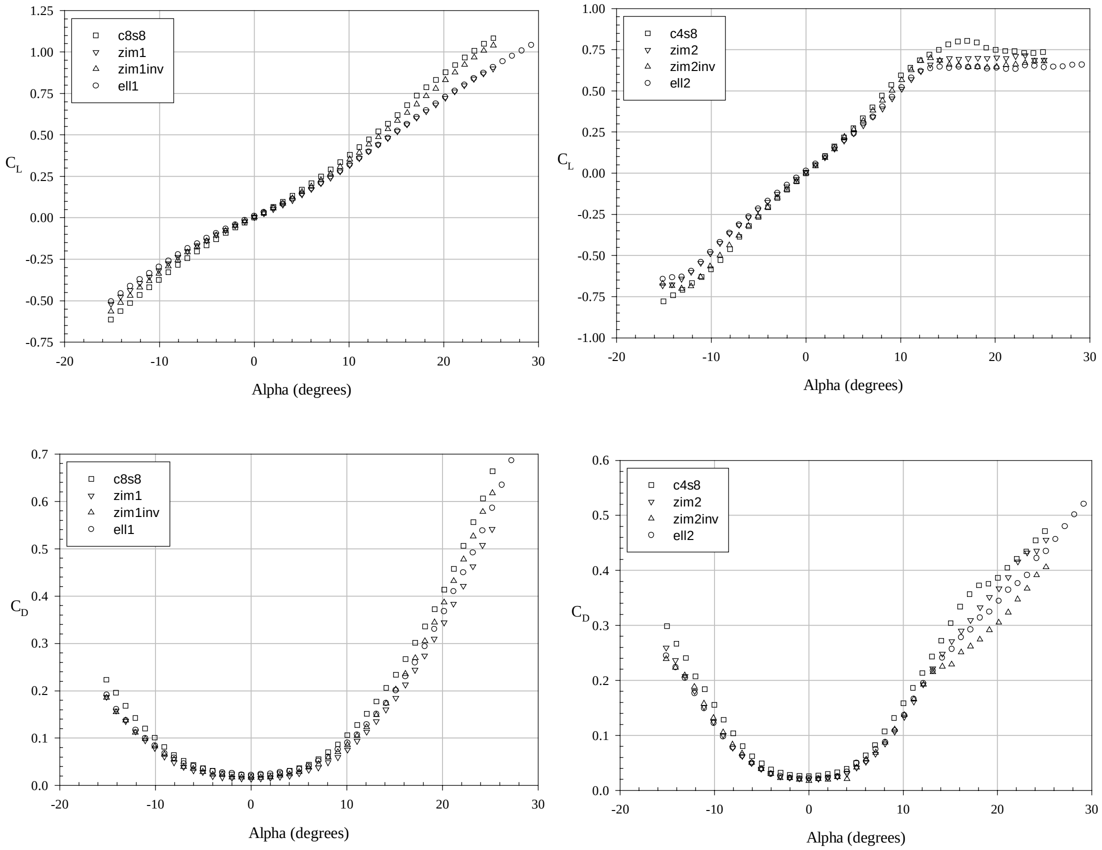


Figure 8: Lift and Drag Coefficients versus Angle of Attack for Low Aspect Ratio Wings

As can be seen from these figures, the rectangular and inverse Zimmerman planforms have significantly better performance than the other *AR*=1 wings. But which wing shape is really optimal? Which one has the least drag for a given C_L? And at what angle of attack is that C_L achieved? These questions were answered by the use of the following procedure:

A second-degree polynomial was fitted in a least-squares sense to the data shown in Figure 8 (one polynomial for each of the four wing shapes). Note that a quadratic equation was applied to the C_L versus angle of attack curve as opposed to the more common linear approximation. A quadratic must be used because of the inherently nonlinear character of the lift of low aspect ratio wings. Only lift and drag coefficients corresponding to angles of attack in the range $0° <= \alpha <= 25°$ for *AR* 1 wings and $0° <= \alpha <= 12°$ for *AR* 2 wings were used in the least-squares polynomial fit. The reason for these limits is that *AR* 1 were not tested beyond $\alpha = 25°$ and *AR* 2 wings stall at $\alpha = 12°$.

The resulting polynomials have the following form:

$$C_{X,\ AR=i}(\alpha) = a_{AR=i} + b_{AR=i}\,\alpha + c_{AR=i}\,\alpha^2 \quad , \quad i = 1 \text{ or } 2\ ,\ X = L \text{ or } D$$

For wings of aspect ratio between 1 and 2, the coefficients of the quadratic polynomials were linearly interpolated. That is, for a wing of aspect ratio 1.5, for instance, the $b_{AR=1.5}$ coefficient will be the average of the $b_{AR=1}$ and $b_{AR=2}$ coefficients, and so on. In addition, the angle of attack at which stall occurs was assumed to also vary linearly with *AR*.

The assumption that the coefficients of the quadratic functions and the stall angle of attack vary linearly with respect to aspect ratio has not been validated and is the focus of future research. The results obtained using this assumption do not necessarily give exact predictions of absolute lift and drag. They do, however, permit the direct comparison of different wing shapes. Also, they are expected to provide a reasonably good first estimate of the lift and drag forces for wings of *AR* between 1 and 2.

For each value of the parameters of wing area and aspect ratio there exists an angle of attack at which a given wing shape achieves the required lift coefficient. As the aspect ratio increases, however, the required lift coefficient may exceed the wing's maximum C_L. When this happens, the wing stalls and there is no angle of attack at which the required C_L can be achieved. These cases must be considered unattainable under the assumptions listed herein.

Once the required angle of attack was known, the drag coefficient at that angle of attack was calculated and/or interpolated from the best-fit quadratic polynomials corresponding to the C_D versus α curves of wings with $AR = 1$ and 2. The results are best presented in colored contour plots where wing area and aspect ratio are the independent variables and the angle of attack needed to achieve the required C_L is the dependent variable. Instead of using wing area as one of the parameters, however, the maximum dimension corresponding to a certain wing area and wing shape was used. For the rectangular wings, the maximum dimension is the diagonal of the wing while for the elliptical, Zimmerman, and inverse Zimmerman wings, the maximum dimension is either the chord or the span depending on whether the aspect ratio is less than or greater than unity. In other words, a rectangular wing has a higher maximum dimension than elliptical or Zimmerman type wings of the same wing area. Figures 8 and 9 show contour plots of maximum dimension (inches) and aspect ratio versus required angle of attack and also versus drag coefficient.

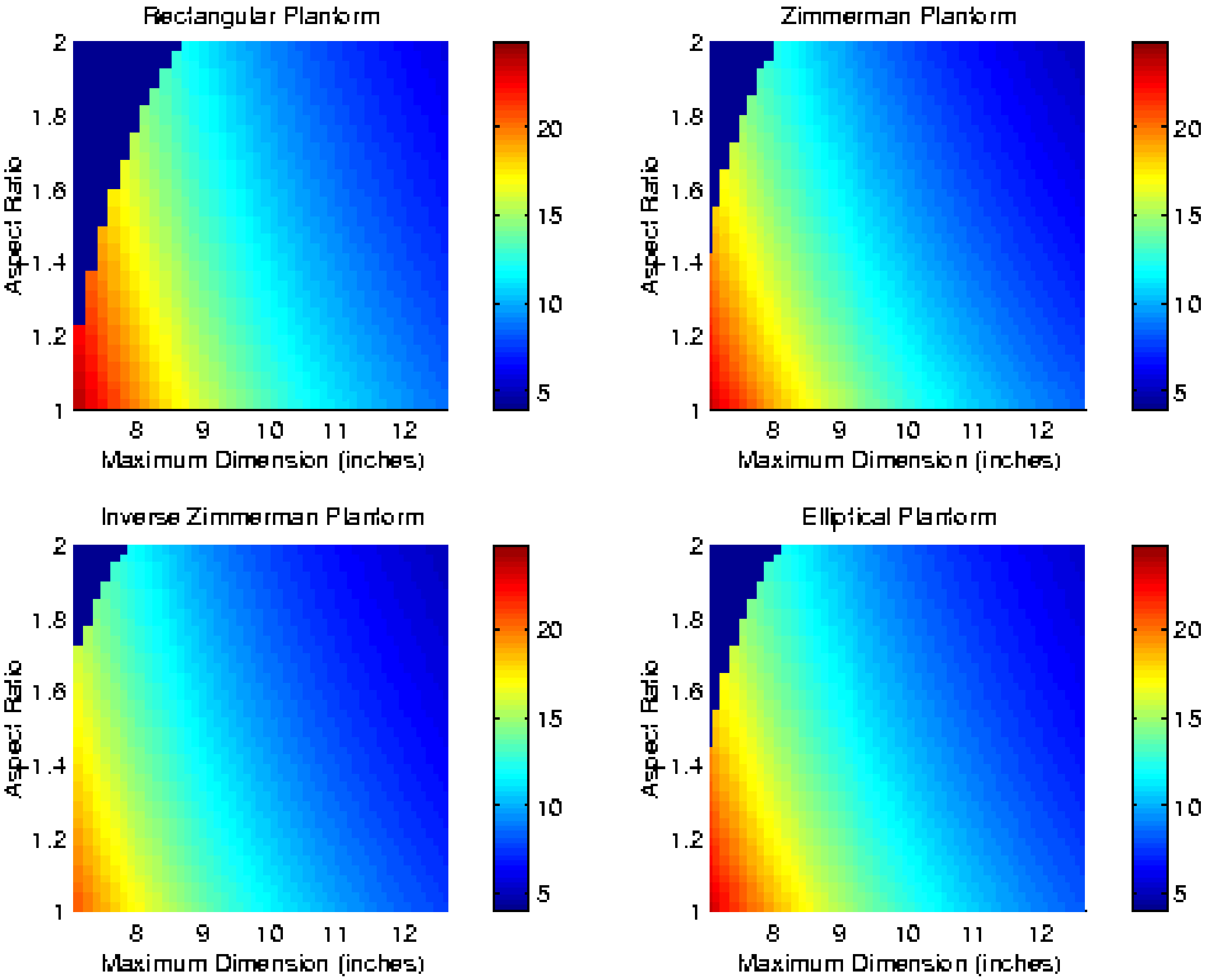


Figure 9: Angle of Attack Needed to Achieve $C_{L,\ req.}$ as a function of Maximum Dimension and *AR*

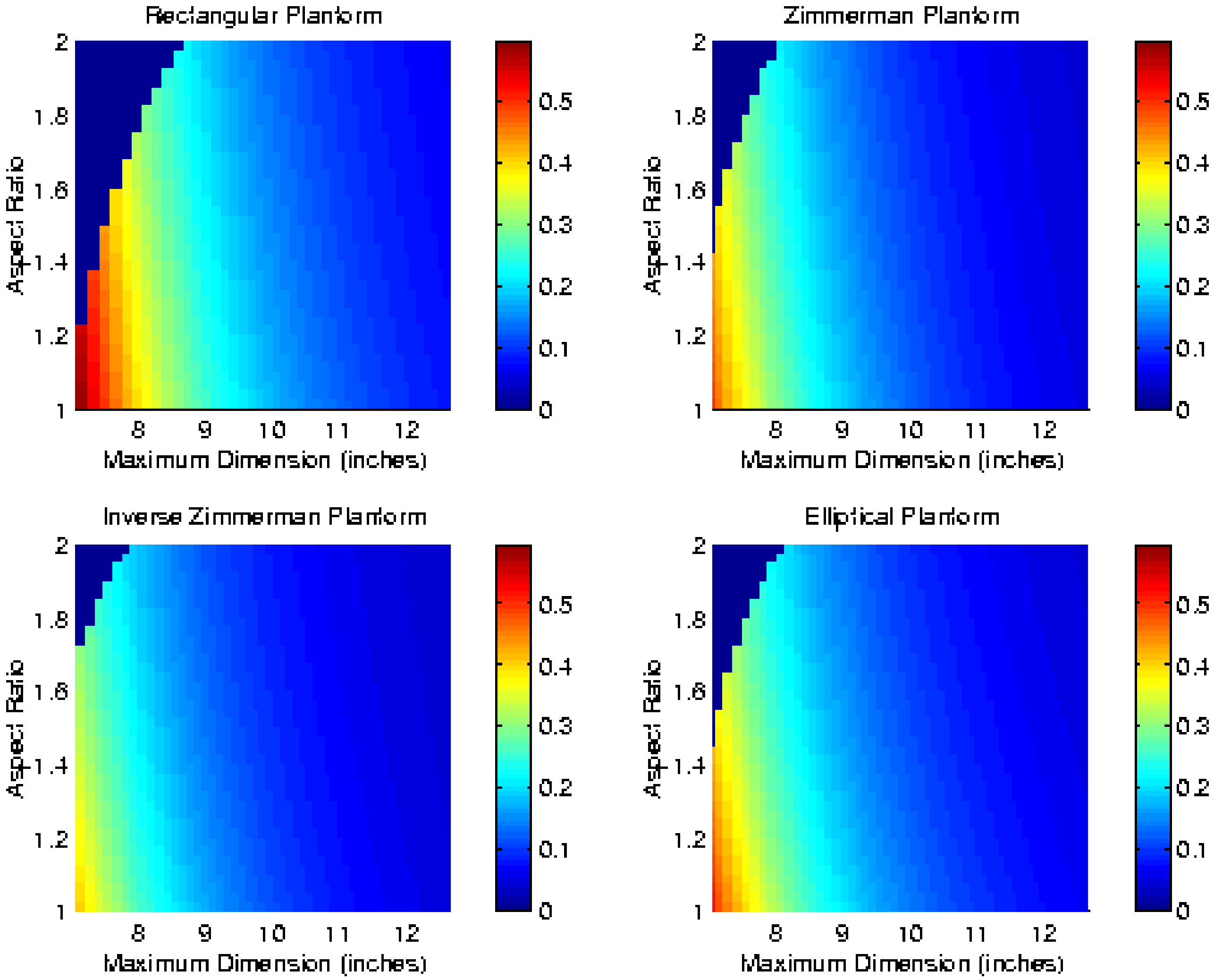


Figure 10: Drag Coefficient at $C_{L,\ req.}$ as a function of
Maximum Dimension and *AR*

In Figure 9, the areas of very dark blue near the top-left represent the regions where the wing is stalled and the required lift coefficient cannot be achieved. A short examination of these plots reveals that the inverse Zimmerman planform offers the best shape for an MAV which is restricted by maximum dimension. For a given maximum dimension and aspect ratio, the inverse Zimmerman planform has the lowest required α and also the lowest value of C_D at that α of all the planform shapes tested.

3.5 Selection of Aspect Ratio and Wing Area

Having determined that a shape similar to the inverse Zimmerman is the optimum, the next task was to size it: that is, to select the aspect ratio and wing area. As was discussed earlier, this step is difficult to do accurately due to the uncertainty of the estimated airspeed, the assumptions used in the generation of the interpolation model, and the fact that a thin wing with zero camber will have different lift and drag characteristics than a ready-to-fly MAV with a fuselage and wings with camber and thickness. The presence of these new variables will likely change the absolute aerodynamic performance but is unlikely to change the difference in performance between wings of various shapes.

It is here that detailed aerodynamics must be set aside and the overall aircraft configuration must be considered. In order to maximize the lifting area available for a given maximum dimension, a flying wing configuration should be used. Flying wings have pitch-stability characteristics that require the center of gravity (CG) of the aircraft to be farther forward than for tailed configurations. In most cases, a tailless aircraft will need to have its CG located at approximately 15% of the chord. The weight and placement of the components to be carried in the MAV is crucial to stability. In order to achieve a 15% CG location, most of the components must be located forward of the half-chord point. One possibility is to place the components inside the wing, spread out evenly throughout the inside of the wing structure. This arrangement allows for a minimization of the frontal area (and thus less friction drag) but has the disadvantage of increasing the roll-moment of inertia of the vehicle. By placing weight near the wingtips, the airplane becomes more susceptible to roll disturbances. The other option is to place all components in a central fuselage. This option minimizes the moment of inertia but requires the use of a very deep fuselage such that all the components fit and such that they are all as far forward as possible. Tests conducted using this type of fuselage showed degraded flight performance due to the increased drag of this configuration.

A third option is to lengthen the fuselage slightly forward of the leading edge such that the wing area is no longer as large as it could be for a given maximum dimension. By lengthening the fuselage, the weight of the engine and batteries near the nose will more easily offset the weight of other components located further back. The electronics and batteries no longer need to be stacked near the nose in order to achieve the correct location of the center of gravity, and thus the frontal area of the vehicle is reduced. This third configuration was the one chosen for the design of the MAV competition vehicle. By shifting the engine forward of the wing's leading edge, the depth of the fuselage was significantly reduced while still allowing a forward position of the CG.

One ramification of this configuration of component placement is that the wingspan can be increased such as to match the length of the airplane. Therefore, the aspect ratio of the wing increases slightly. A number of design concepts were drawn in an effort to find the aspect ratio of the wing which best suited the location of the components in the aircraft and which minimized the maximum dimension. It was found that a wing with AR=1.5 was close to the most efficient use of maximum dimension for a wing planform similar in shape to the inverse Zimmerman wing.

The final step in wing sizing was defining the wing area. The requirement that the maximum dimension of the wing should not exceed 10 inches meant that the wing area was to be less than 66 in^2 for an inverse Zimmerman planform. From Figure 9, the angle of attack required to achieve $C_{L,req.}$ for an inverse Zimmerman wing of AR=1.5 and maximum dimension 10 inches is approximately 10°. The stall angle of attack for a wing of aspect ratio 1.5 is expected to be 18.5° using a linear interpolation of α_{stall}. Thus 10° is a relatively conservative angle of attack for this airplane. If the maximum dimension was made 9 inches instead, the required angle of attack increased to about 12°. This angle is still conservative in terms of stall but allows the use of a wing of very competitive maximum dimension. A number of prototypes were built and flight tested. It was found that an airplane with a wingspan of 9.25 inches could fly consistently with a take-off mass of 105 grams. Figure 11 below shows the finalized design of the Notre Dame MAV. Note the shape of the wing which resembles an inverse Zimmerman planform but is squared-off to ease construction. The maximum dimension of the MAV shown is 9.75 inches.

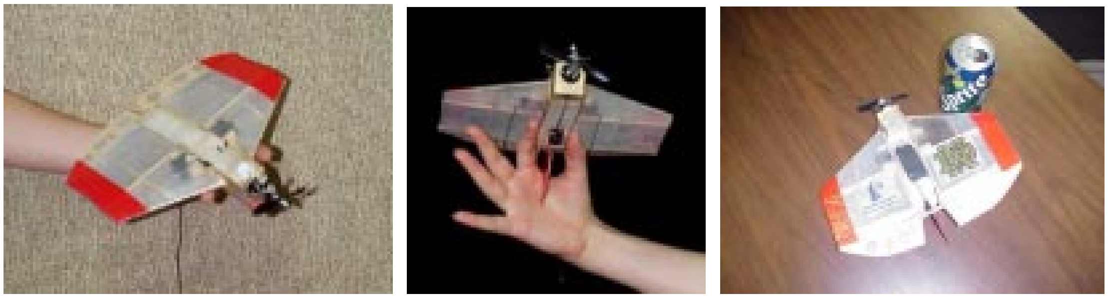


Figure 11: Competition-Ready Micro Aerial Vehicle

4. FABRICATION

Since the start of the MAV project at Notre Dame, it had been desired to build MAVs using composite materials. The wings were initially constructed using a single or double layer of carbon fiber cloth wetted with epoxy resin. The carbon fiber cloth was molded on a specially constructed base which had the contour of the desired airfoil shape. When cured, the wing was very strong and extremely thin. Furthermore, it could be cut (with scissors even) to whatever shape needed. The drawback was weight; a carbon fiber cloth structure weighed approximately twice as much as was desired. A number of trials using carbon fiber cloth strips, composite frames, carbon fiber-balsa sandwiches and other techniques yielded amazingly resistant structures which weighed too much.

The desire for a state-of-the-art composite structure was soon overtaken by the need to have a light airframe. The airplanes built using the more conventional method of balsa wood were found to be significantly lighter than their composite counterparts. Carbon fiber strips and small patches of fiberglass cloth were used to reinforce critical areas of the airframe such as the nose, leading edge, and wingtips. This balsa structure was found to be durable but not indestructible. The MAV prototypes have no landing gear and usually land with full throttle at very high speeds. Throughout the period of flight-testing, the airplanes with balsa structures survived numerous hard landings with little irreparable damage.

5. TEST-FLIGHTS AND COMPETITION SUMMARY

5.1 Test Flights

The MAV design shown in Figure 11 had its first successful flight with full payload weight in March 2000. Flights up to 4 minutes in duration were achieved consistently. The video transmitter and radio control systems were tested to a range of 800 meters with no loss of signal. During the month of April, a number of flights with the video transmitter and camera were made in order to learn piloting of the MAV only through the use of the camera image. Successful training missions were flown where a simulated target was placed on the ground and an image of the target was acquired with the video camera. A week before the competition, the MAV had flown several successful mission simulations.

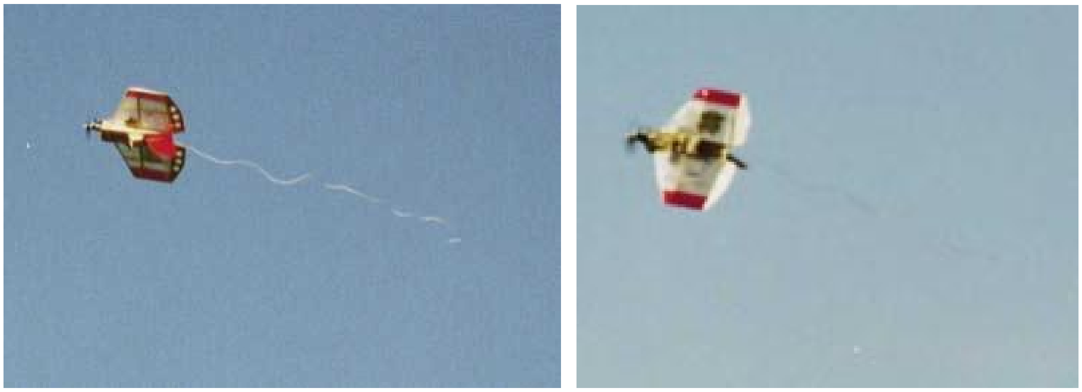


Figure 12: The Notre Dame MAV in Flight

5.2 Micro Aerial Vehicle Competition

The Notre Dame MAV team took three identical MAVs to the competition in Fort Huachuca, AZ. The first attempts at flying with the mission-ready airplane were disappointing. The MAV performed controlled powered glides but was not able to sustain flight. The difference in altitude between South Bend, IN (773 feet) and Fort Huachuca, AZ (4,600 feet) had been taken into account during the design process in terms of the change in air density and the decreased lift that would ensue from such a change. What had not been anticipated, however, was the effect of the altitude on the performance of the engines. The engines ran poorly and were not able to develop the thrust which had been available at lower elevations. Despite the team's efforts to extract more power out of the engines, the thrust could not be increased. The Notre Dame MAV team went back to Indiana after the competition having learned a very important lesson about changes in environment and how the whole system must be considered, not just aerodynamics.

The winner of the competition was the University of Florida with an entry of maximum dimension equal to 10 inches exactly (the extrapolation of Figure 2 was exactly correct). The Florida team experienced similar problems in engine performance but were able nevertheless to complete the mission. Of the seven teams who competed in the 2000 competition, only the University of Florida was able to complete the mission, and only three other teams were able to fly their video-equipped airplanes in a controlled (though not sustained) manner. The University of Notre Dame is looking forward to the 2001 competition for a chance to improve the MAV design and return with the winning prize. The 2001 competition will be held in late May or early June of 2001 in Gainesville, FL (website: http://www.aero.ufl.edu/~issmo/mav/mav.htm).

6. ACKNOWLEDGEMENTS

The authors wish to acknowledge the excellent work done by the undergraduate members of the Notre Dame Micro Aerial Vehicle Design team: M. Burgart, L. Murphy, J. Miller, C. Kruse, and J. Visner. Their support in the ongoing experimentation of MAV designs and fabrication techniques was invaluable. Most details of the vehicle included in this paper are taken from Burgart et. al. (2000).

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