Design of a Micro Air Vehicle for the 2013 SAE Aero West Competition

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 Symbols and Abbreviations

$B_W$ – Wingspan

CA - Cyanoacrylate

$C_D$ – Drag coefficient

$C_L$ – Lift coefficient

$C_{L_{aH}}$ – Slope of lift curve for tail

$C_{L_{aW}}$ – Slope of lift curve for wing

d - Distance from nose

h – Altitude

k – Spring constant

$L_{HT}$ – Moment arm to horizontal tail

$L_{VT}$ – Moment arm to vertical tail

M – mass of component

$S_H$ – Tail area

SM – Static Margin

$S_W$ – Wing area

V – Velocity of aircraft

W – Weight

WPI – Worcester Polytechnic Institute

x – Stretch distance

$X_{ACH}$ – Aerodynamic center of tail

$X_{ACW}$ – Aerodynamic center of wing

$X_{CG}$ – Center of gravity point

$X_{NP}$ – Neutral point
2 Introduction

This report is submitted as a partial requirement for the SAE Aero Design West Competition. Throughout the duration of this project the team has worked to combine aerodynamic and structural principles to design an aircraft for entry in the Micro Class division of the competition. The general objective of this project was to obtain the best payload fraction possible given a list of constraints, shown below.

While the typical approach for this competition is usually to design a plane equipped with its own propulsion system, the team decided to adopt a more innovative concept: a glider. The team decided on the glider concept for its weight savings as empty weight has the largest impact on flight score. Last year’s glider entry in the SAE Aero East competition was used as a baseline that the team has successfully improved on.

The main constraints for the Micro Class as outlined by the competition rules are shown below:

<table>
<thead>
<tr>
<th>Sizing</th>
<th>All components must fit in a box with interior dimensions of 24”x18”x8”.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload Bay</td>
<td>Must have interior dimensions of 2”x2”x5”.</td>
</tr>
<tr>
<td>Launcher</td>
<td>Must be hand launched or elastic launched.</td>
</tr>
</tbody>
</table>

The team’s design has continuously improved throughout the entire process as a number of different approaches were considered to optimize the design through research, testing, and calculation. This design is able to be successfully launched into the air and glide with precision using radio controls. The team believes this glider to be a vast improvement on past gliders in the SAE Aero Design competitions and will serve as another stepping stone for those who choose to improve on this concept in future competitions.

3 Design Process

3.1 Literature Review

WPI’s entry into the SAE East competition last year[2] paved the path to how the team was to initiate the design process. The team analyzed all entries in the competition last year from video recordings of both successful and unsuccessful flights. The video footage of Georgia Tech and Cedarville University provided the most useful information. The entry from Georgia Tech earned 1st place in the micro class last year. Their delta wing airframe established the highest standards the team is up against. The number of successful flights as well as a low weight and high payload fraction were all taken into account as the team began setting the parameters for the aircraft specifications and performance. Cedarville University was a unique
entry because they were the only group to have a glider entry. Despite Cedarville’s unsuccessful flight, the team gathered valuable information about the stresses experienced during launch as well as how integral structural integrity and weight is in order to achieve a high altitude launch.

Daniel P. Raymer’s book, *Aircraft Design: A Conceptual Approach* [3], served as a guideline while the design process was underway. With this book, the team was able to quickly reference how to determine lift coefficients, stability specifications, and complete numerous other integral steps toward creating an airworthy glider.

### 3.2 Decision Process

The competition guidelines were first factors taken into account for the design process. The team had a dimension limit and based on trends of previous entries, team determined a rough weight and payload fraction goal. These core guidelines and the project directive of having a glider entry and the use of a launcher focused the team on two main objectives. Since the airframe was going to be under extreme forces upon the launch, the team followed in the footsteps of last year’s WPI SAE Aero Design competition entry. The primary objectives are durability and simplicity. Durability plays a major factor in flight-testing because a solid airframe requires less maintenance in the event of a crash. Ultimately, a low maintenance airframe allows for aggressive testing and saves time in the manufacturing process. Simplicity in the design cuts down on overall cost and manufacturing time while making repeatability and immediate adjustments or improvements very feasible.

These basic goals narrowed down the design options. A folding fabric-wing concept or a folding fixed-wing concept were chosen based on the necessity of gaining as much altitude of the launch as possible. While folded the aircraft would have aerodynamic properties of a rocket and at the peak of its trajectory, the wings would expand and maintain high lift values based on the wing design. The fixed wing concept would require large solid wings that would be difficult to conform to a folded body and they would be considerably heavy. Fabric wings are light and wing area does not constrain the ease of folding the wings. The benefits of the folding wing characteristics greatly outweighed those of the fixed-wing design so the team decided to pursue the former.

Wind tunnel tests provided the necessary data to determine the shape of the wing. The drag and lift of a rectangular and semi-circular wing shape were analyzed using force balances. The rectangular wing was selected due to its high area and aspect ratio.
3.2.1 Payload Oriented Design

The initial mindset was to push the size limits established by the guidelines, because a larger wingspan and wing area would result in greater lift forces. The team decided that using collapsible carbon fiber rods as a leading edge could result of a wingspan of up to 2 meters. The first prototype constructed had a total wing area of 1 square meter and a length of 1 meter. The wing of this first design is shown below:

![First Prototype Glider](image)

This design focused was on achieving the highest payload possible through the utilization of a large wing area and high lift forces. Properly tensioning the fabric wing proved to be the most challenging aspect of this concept. Carbon fiber ribs were placed from the center of the leading edge to the corners and midpoints of the trailing edge and held in place by Dacron pockets to maintain a rigid airfoil. The team conducted multiple hand launches once a solid balsa tail was attached. This design was proved itself to be airworthy and stable, even at the low speeds produced from a hand launch.

3.2.2 Launcher

By assuming that a glide ratio of 10:1 would be within the realm of possibility, the launcher would need to propel the glider to an altitude of 21.34 meters in order to successfully travel the course distance around the course. The team purchased 1/2 inch hollow speargun tubing and conducted launch tests for different weights to understand the capabilities of the tubing. The most successful launch was with a 0.149 kg baseball. Higher weights did not gain sufficient altitude and wind resistance impeded lower weights. The results of the tests showed that our aircraft weight needed to decrease significantly.
3.2.3 Low Weight Oriented Design

The dimensions of the aircraft changed drastically with a new target weight. The wingspan decreased to 0.5 meters and an overall length of 0.45 meters. A fuselage able to contain the required payload volume of 2"x2"x5" was attached to the aircraft body and electronic components were added bringing the final weight to 0.149 kg. A new folding mechanism was drafted but before its incorporation, the team tested fixed wing launches to determine if the aircraft was capable of withstanding the launch forces. A preliminary draft of the folding mechanism is shown below:

![Figure 2: Folding Design](image)

The team ultimately decided that the benefit of the reduced drag does not offset the added weight of such a mechanism, and it was not included on the final aircraft.
4 Specifications

4.1 Wings

The wing of the aircraft consists of a sheet of rip-stop nylon fabric held in place by carbon fiber rods and Dacron tape. The team chose this material to allow for the possibility of adding a folding mechanism to the aircraft. A single carbon fiber rod makes up the leading edge, which is wrapped in a strip of tape. The diagonal stiffening rods terminate in triangular pockets glued to the wing. They extend from the centerline at the leading edge to the aft corners at the wingtips. Another carbon fiber rod extends along the centerline of the wing to support the tail.

4.2 Tail

The tail of the aircraft is of conventional design and includes a horizontal and vertical stabilizer. These are both constructed of sheet with holes cut in them to lighten them. The control surfaces are conventional as well. There is a rudder and single elevator, connected to two servos mounted at the rear of the fuselage by pull-pull setups to reduce weight. Roll control is provided by the rudder alone, allowing the elevator to be a single piece rather than being split to control roll. This design was chosen to eliminate a servo from the overall design, reducing weight. The control surfaces are attached to the aircraft by the covering material. This material is arranged in such a way to create hinges for the surfaces as well.

4.3 Fuselage

The fuselage of the aircraft is designed to hold the required volume of payload, contain the battery, and withstand launching and landing loads. The nose of the aircraft is removable to allow the insertion or removal of the payload and battery. It is retained by two spanwise rods extending into the fuselage walls. The walls of the fuselage have holes cut in them to accept the rods holding the nose in place, and reduce their weight while still allowing the transfer of launch and landing loads to the carbon fiber boom. The bottom and rear of the fuselage are both covered with sheet for the same reason.

4.4 Electronics

The electronics loadout onboard the aircraft was chosen as a package from Tower Hobbies to be sure that the transmitter, receiver, and servos would function properly with each other straight out of the box. It is a
conventional six channel R/C transmitter and receiver pair that operates on 2.4GHz, with standard analog micro servos.

5 Fabrication

5.1 Final Assembly

The size of the aircraft allows it to fit within the required dimensions without removing or changing any part of the configuration. Thus, the assembly process is reduced to installing the payload and battery, attaching the nose, and plugging in the receiver.

5.2 Construction Materials

The materials used throughout the aircraft are cheap, lightweight, and easy to work with. The wing spars and stiffeners are various diameter carbon fiber rods. The fuselage, tail, and control surfaces are all sheet balsa wood. The pull-pull lines connecting the servos to the control surfaces are sewing thread. The fuselage and tails are covered in a light weight heat shrink material, (Name of Material). The wing is constructed from a combination of rip-stop nylon material and Dacron tape. Both of these materials are very common in the construction of kites. Hot glue was used extensively in the construction of the aircraft due to its ease of use and its cure time, allowing parts to be aligned before setting solid. Cyanoacrylate (CA) glue was used to fasten the vertical stabilizer to the horizontal stabilizer because the hot glue beads along the inside corners of the joint proved ineffective at bonding to the covering material. A small amount of the covering material was removed along the centerline of the horizontal surface, allowing the CA to soak into the balsa to provide a strong bond.

5.3 Tools Utilized

The only specialized tool required for producing this aircraft is a laser cutter, which the team had access to on campus. This was used to cut out the balsa shapes for the tails, control surfaces, and fuselage sides. While it is within the realm of possibility to construct the aircraft with careful application of a ruler and a hobby knife, the laser tool allowed for rapid, repeatable production of parts within very small tolerances. A heat-shrink iron is required to attach the coating to the balsa before shrinking it with a heat gun, although a soldering iron would be acceptable as well. A hot glue gun is also required, along with myriad other common
items, such as a utility knife, scissors, a ruler, and a pen or pencil.

6 Calculations

6.1 Pitch Stability

Evaluating the stability of our aircraft during flight involves the calculation of two critical points. These are the center of gravity, $X_{CG}$, and the neutral point, $X_{NP}$. The center of gravity is determined by:

$$X_{CG} = \frac{1}{M} \Sigma(W \cdot d)$$  \hspace{1cm} (6.1.1)

$W$ and $d$ are the weights and distances from the nose of each respective component. These values were measured once a preliminary model was completed. Using these measurements and the equation above, the $X_{CG}$ came out to 12.5 cm from the nose cone. The equation for the neutral point is:

$$0 = (X_{CG} - X_{ACW}) - \eta \cdot \frac{S_H}{S_W} \cdot \frac{C_{LoH}}{C_{LoW}} \cdot \frac{d_{aH}}{d_{a}} \cdot (X_{ACH} - X_{CG})$$  \hspace{1cm} (6.1.2)

where $X_{CG}$ is set equal to $X_{NP}$ when solving the equation. In the case of this aircraft,

$S_W = 0.0625 m^2$

$S_H = 0.0175 m^2$

$\eta = 0.9$

$\frac{d_{aH}}{d_{a}} = 1 - \frac{2}{\pi R_W} \cdot C_{LoW}$

$X_{ACW} = 0.15 + \frac{c}{4} = 0.08 m \text{(measured)}$

$X_{ACH} = 0.40 (measured)$

Solving for $X_{CG}$ gives a neutral point of $X_{NP} = 13.9$ cm. From the difference $SM = X_{NP} - X_{CG}$ the static margin is 1.4 cm. Because the center of gravity is forward of the neutral point, the aircraft is stable during flight.

6.2 Performance

Since this aircraft is a glider and has no on-board power source, it must achieve a sufficient initial height from the launch. The absolute minimum travel distance around the course would be about 213.4 meters. The team chose a target altitude of 21.3 meters as a reasonable value to launch the aircraft to. To determine
the amount of weight that could be launched to this height required knowledge of how much energy the tubing used in the launcher can store. The spring constant of the material was found experimentally by measuring the deflection of a length of tubing when a known weight was placed on it. This spring constant was found to be 73 N/m. The potential energy in a linear spring is:

\[
\frac{1}{2} kx^2 = mgh
\]  

(6.2.1)

Solving for the mass, m, resulted in a weight of 0.159 kg. To test the performance of the launcher with this magnitude of load, a baseball weighing 0.145 kg was substituted in place of the aircraft. From reviewing videos of the test, the team estimated that the baseball reached 21.3 meters of altitude while also traveling about 45.72 meters horizontally. Thus, the team decided to build an aircraft with empty weight of 0.136 kg to carry a payload of 0.181 kg, resulting in an estimated total gross weight of 0.317 kg.

6.3 Aircraft Sizing

6.3.1 Wing sizing

The wingspan of 0.5 meters was decided upon to work around the challenge of fitting the aircraft within the box dimensions. The chord of 0.125 meters was chosen by visually proportioning the wing. This resulted in an area of 0.0625m² and an aspect ratio of 5. With these parameters set, a lift coefficient was found. The following equation was used:

\[
C_L = \frac{2L}{\rho SV^2}
\]  

(6.3.1)

Assuming the aircraft glides at a speed of about 10 meters per second, the coefficient of lift is 0.85. The airfoil was chosen as a flat plate to ease construction, and it provides enough lift for this aircraft.

6.3.2 Weight Estimate

The table below illustrates the weight buildup for the aircraft, which was used in preliminary lift calculations. Weights for all of the radio components were taken from the manufacturer specifications. Weights for the fuselage, wings and spar were calculated based on volume and material densities.
<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver</td>
<td>6.5</td>
</tr>
<tr>
<td>Tail</td>
<td>1.8</td>
</tr>
<tr>
<td>Fuselage</td>
<td>42.6</td>
</tr>
<tr>
<td>Servo</td>
<td>7.5 (x2)</td>
</tr>
<tr>
<td>Battery</td>
<td>63.9</td>
</tr>
<tr>
<td>Fabric</td>
<td>4</td>
</tr>
<tr>
<td>Spar</td>
<td>7</td>
</tr>
<tr>
<td>Payload</td>
<td>163</td>
</tr>
<tr>
<td><strong>Empty Weight</strong></td>
<td><strong>153</strong></td>
</tr>
<tr>
<td><strong>Gross Weight</strong></td>
<td><strong>316</strong></td>
</tr>
</tbody>
</table>

6.3.3 Tail sizing

After determining the wing geometry and general sizing of the aircraft, the tails can be sized. The team used the following equations for sizing the tails:

\[
S_{VerticalTail} = \frac{c_{VT} \cdot b_w \cdot S_w}{L_{VT}} \quad (6.3.2)
\]

\[
S_{HorizontalTail} = \frac{c_{HT} \cdot c_w \cdot S_w}{L_{HT}} \quad (6.3.3)
\]

These equations resulted in a vertical tail area of 25.81 cm\(^2\) and a horizontal tail area of 149.7 cm\(^2\). From these areas, the dimensions of the tail surfaces were determined through simple geometric manipulation.

7 Wind Tunnel Testing

After preliminary calculations indicated the necessary lift coefficient needed for flight, tests were begun to determine how experimental data would match theoretical results. A force balance mechanism[1] was used to collect lift drag and data, as depicted below:
Three wind tunnel tests were carried out, and the resulting data is tabulated below:

Table 3: Wind Tunnel Test Results

<table>
<thead>
<tr>
<th></th>
<th>$C_L$</th>
<th>$C_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>1.43</td>
<td>0.660</td>
</tr>
<tr>
<td>Trial 2</td>
<td>0.740</td>
<td>0.160</td>
</tr>
<tr>
<td>Trial 3</td>
<td>0.69</td>
<td>0.130</td>
</tr>
<tr>
<td>Average</td>
<td>0.715</td>
<td>0.145</td>
</tr>
</tbody>
</table>

The team decided to exclude trial 1 from the average because it is an obvious outlier, given the magnitude of the values obtained in the following two trials. The team concluded that a lift coefficient of 0.715 would suffice for the aircraft.
8 Summary

8.1 Innovations

8.1.1 Process and Methods

By virtue of being a glider, the team’s aircraft distinguishes itself from the vast majority of competitors at the Aero Design events. This report has previously touched on the lack of success and progress with gliders in recent competition entries. The fact that the team chose a glider early on has influenced the entire design process. The team’s methodology was built to address and overcome the main challenges that have caused gliders to fail in the past. Some of the materials used in this aircraft are unconventional in their use on an R/C aircraft, but were chosen because of their light weight. The placement of components was carefully chosen to give the optimum center of gravity without trimming using control surfaces, reducing drag. High power launchers are a rare sight at the competition, but having no power source forced the team to maximize the elastic energy from the system. The entire process of designing and building a glider is innovative given the lack of precedent at these competitions.

8.1.2 Design

The aircraft has many design choices that the team believes are innovative. It was found that using fabric wings is a great way to save weight. The weight savings from the wings alone lead the team to believe that we will have one of the lightest aircraft at the competition. The team also believes that the design of the launcher is innovative. The launch rail will be embedded in the outside surface of the box, so that the box itself will serve as the launcher. It is a self-contained system that was designed within the rules and has also proven very safe. The team also performed extensive research and evaluation of different styles of tubing before we settled on spear gun tubing. This tubing has great potential as an energy provider, but figuring out how to harness and optimize its energy capabilities has required innovation beyond the team’s original ideas. The team also designed, but did not build a folding wing mechanism. The reasons for not going forward with this design were detailed earlier in the report, but its construction and appearance at the competition almost certainly would have been unique among the competitors.
8.1.3 Construction

One of this aircraft’s strongest selling points is its simplicity. Manufacturing and constructing was made an easy, quick process with the team’s choice of materials. In industry, a product that is reliable, repeatable, and efficient is ideal. The team’s construction process and materials have proven themselves to have all of these characteristics. However, the construction of the launcher requires more innovation. In order to get the tubing to launch the aircraft, a launch shuttle was machined that serves as a carriage for the fuselage while it is on the launcher. The part was milled down from Delrin and it greatly simplified the interface between the elastic tubing and the aircraft. This design also reduces friction, helping the aircraft achieve maximum possible altitude with the tubing used.

Figure 4: Launch Shuttle

8.2 Conclusion

To be successful, the glider concept required a lightweight and structurally sound aircraft. The team followed the two initial objectives throughout the project process resulting in a final design that is both durable and simple in design. Vulnerable portions of the aircraft include the onboard electronics and the fuselage, due to the necessity of a small lightweight frame surrounding the minimum required payload volume. The final aircraft weighed 0.145 kg yet the launcher was unable to launch this weight to the desired altitude of 21.33 meters. A final estimated distance of 39.62 meters can be attributed to three factors: the achieved altitude of 7.62 meters, the initial launch distance prior to gaining maximum altitude of 9.14 meters, and a measured glide ratio of 4:1. Although the current launcher design would not be able to successfully allow the aircraft to navigate the competition course, the team has established the most successful unpowered micro-class aircraft to date by establishing new performance capabilities in the glider category.
References


A Payload, Score Prediction, and Three View

![Diagram of Flight Score vs. Payload and Payload Fraction vs. Empty Weight graphs.](image-url)