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## **Design/Build/Fly The Evolution of a Model Airplane**

Soumyo Dutta

*University of Tennessee - Knoxville*

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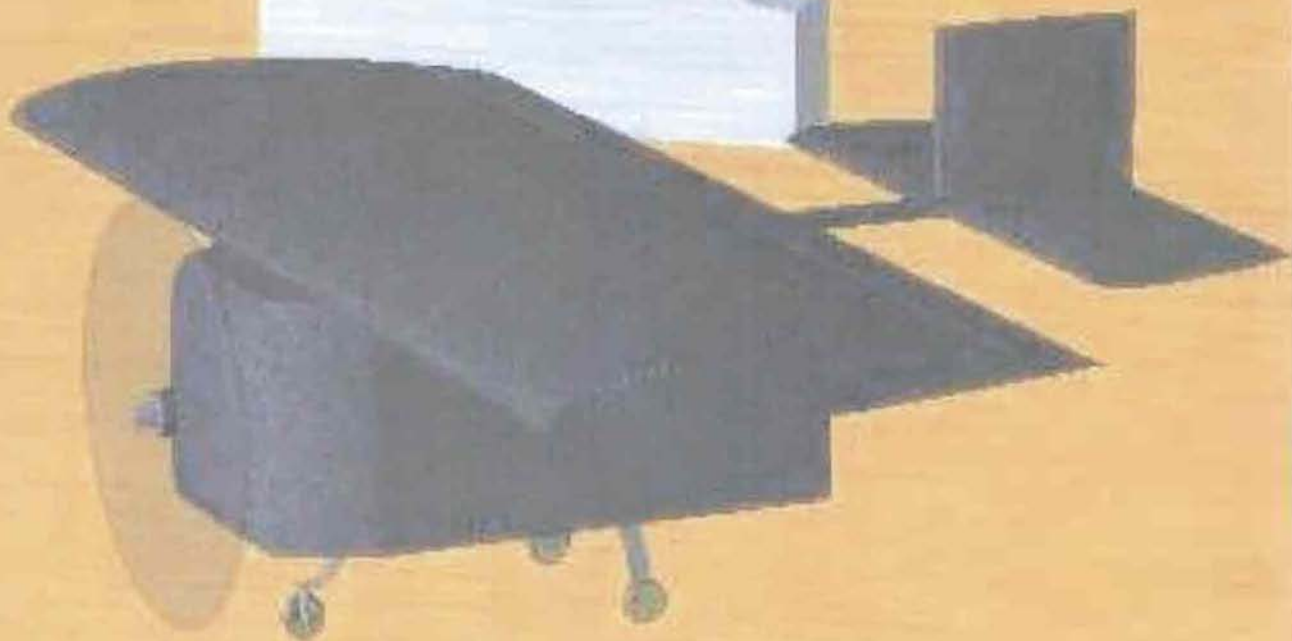
# **DESIGN/BUILD/FLY**

## **The Evolution of a Model Airplane**

Sponsored by: Cessna Aircrafts and Raytheon  
Missile Systems

Spring 2008

**Team VOLocity**  
**University of Tennessee**



# AIAA Design/Build/Fly: Evolution of a Model Aircraft

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Senior Capstone Design

Spring 2008

## Awards:

Winner, Exhibition of Undergraduate Research and Creative Achievement, University of Tennessee, Spring 2008.

Winner, Phi Kappa Phi Award, Undergraduate Research Award, University of Tennessee, Spring 2008.

Winner, Chancellor's Honors Program Senior Project Grant, University of Tennessee, 2007-2008.

Grant Winner, Tennessee Space Grant Consortium, Senior Project Grant, 2007-2008.

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## 1.0 Executive Summary

The mission requirement was to design an electric motor powered, radio-controlled aircraft capable of carrying multiple payload configurations for the AIAA Design/Build/Fly 2007-2008 competition. The goal of the University of Tennessee team was to design the aircraft to maximize the highest possible score.

### 1.1 *Analysis*

The scoring of the competition was divided into two categories for this year's competition: a written report score and total flight score. The total flight score consisted of scores from two flight missions around a predetermined course. The first mission was designated as the delivery flight and the second was designated as the payload flight. The score for the delivery flight was calculated by dividing the number of complete laps around the course by the total battery weight. The score for the payload flight was the reciprocal of the rated aircraft cost (RAC) multiplied by the loading time of the payload. The RAC was defined as the system weight multiplied by the battery weight.

From the onset of the analysis phase, it was seen that the weight of the aircraft would be the main scoring parameter for this competition. Battery weight was a function of the type of motor used. Thus, the propulsion group had to maximize propulsion performance without sacrificing weight. System weight was reduced by using low density materials. Significant time was spent on conceptual and preliminary designs to optimize weight.

A major restriction put on the design was that the aircraft must be able to fit in a five foot by four foot square while sitting on its landing gear in normal ground attitude. This placed a limit on the wing span and length of the aircraft. The aircraft was also required to takeoff within seventy-five feet while carrying the payload. These restrictions led the group to design an aircraft with a very low aspect ratio wing.

The conceptual design phase consisted of the team members comparing their ideas for an optimal solution to the problem. Each of the six senior members of the team presented their ideas for an aircraft to be used in this year's competition. The various designs included traditional mono-wing airplanes and unconventional tandem-wing models. Some key design elements that were considered were whether to use a high wing or a low wing and should a conventional tail or a T-tail be used. Payload location and the

loading mechanism were also points of discussion as those decisions would significantly influence “loading time,” another scoring parameter. The various designs were analyzed using estimates for the flight characteristics of the aircraft such as stall speed, takeoff speed, and ground roll versus chord length. Due to the small size of the team, a major emphasis was on the simplicity of the manufacturing process so that a feasible plane could be designed and constructed by the group. With all things considered a high-wing conventional-tail airplane was chosen.

In the preliminary design phase, the group concentrated on augmenting the design for the chosen high-wing conventional-tail airplane. A preliminary weight estimate or RAC was made. In addition, in order to analyze the airplane in detail, the team separated into sub groups: aerodynamics, structures, payload, and propulsion. Since the weight of the plane was a major parameter for the score, the payload and the propulsion group were to create the lightest possible solution to design problems.

Preliminary design led to more detailed designs which required testing information. The group used thrust-stand tests to generate propulsion data. Lifting line theory and vortex lattice methods were used to conduct aerodynamic analysis. Furthermore, payload mechanism modeling allowed the team to test parameters such as loading time and ease of loading. Real time testing together with common engineering tools ultimately allowed the team to optimize the airplane designs.

### ***1.2 Construction and Flight Testing***

A manufacturing plan was formulated to construct the high-wing airplane. Using the advice of experts in carbon fiber modeling and model-airplane designs, the team created molds for the fuselage and wing. The six seniors in the team also enlisted the help of underclassmen in the building process. At the time of this report, many significant parts of the plane were already under construction.

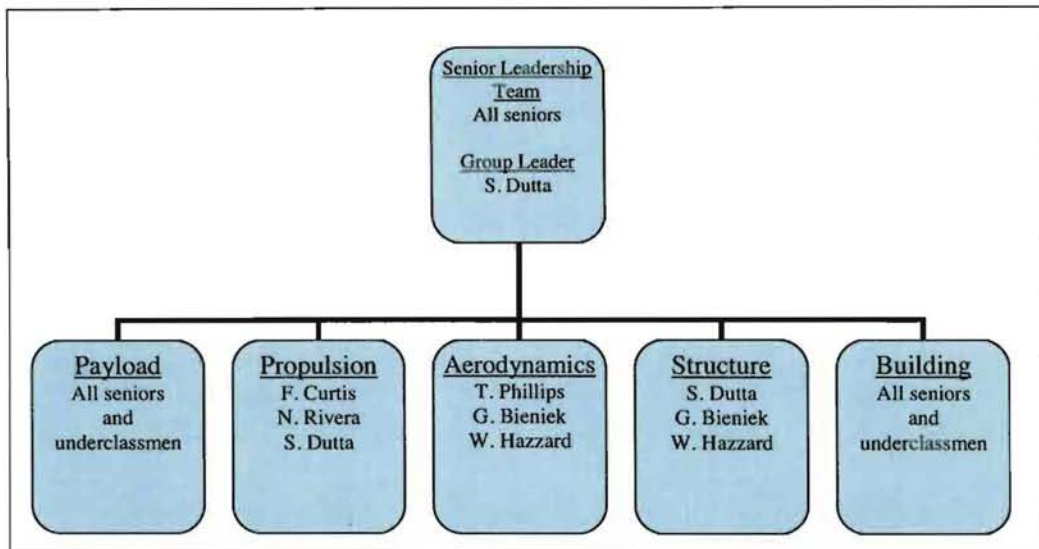
Late March and early April have been designated as testing periods for the full-scale plane. Testing procedures will include rigorous examination of the propulsion systems for the performance needed, payload loading simulations for the crew that will participate at the actual competition, and recreations of the course to allow the pilot to develop familiarity with handling the aircraft.



## 2.0 Team Management Summary

The team consisted of six seniors in aerospace engineering as well as five underclassmen who ranged from freshmen to juniors in mechanical and aerospace engineering. Seniors in aerospace engineering at the University of Tennessee are required to participate in a senior capstone design project, and this team was one of those groups. Thus, the team operated as a class project and had to meet requirements for both the competition and the design class. The team was advised by an aerospace engineering faculty member, and received help from model airplane enthusiasts from the community.

The core team of six seniors was sub-divided into smaller groups to analyze the various components of the design. These groups were aerodynamics, structures, propulsion, and payload. Furthermore, all senior students as well as the underclassmen participated in the construction process. The following flow chart (Figure 2.1) describes the layout of the team.



**Figure 2.1:** Team management layout.

## **2.1 Sub-group descriptions**

### **Senior Leadership**

The team was guided by a group leader, but the most important decisions were made by the group as a whole.

### **Payload**

The goal of the payload group was to create a payload design that optimized both loading time and weight of the mechanism.

### **Propulsion**

The propulsion group was charged with designing a motor/battery combination that would allow the maximum amount of thrust with the least amount of weight. Since the competition rules restricted the choice of a motor to one that could be found off-the-shelf and the choice of the batteries were only limited to NiCad or NiMH types, this group had to find the best design within the bounds of several restrictions.

### **Aerodynamics**

The aerodynamics group had to design any surface exposed to air. Some design problems they faced included the choice of the airfoil for the wing and the tail, wing and tail sizing, fuselage shape, and stability analysis.

### **Structure**

The goal of the structures group was to create the soundest design possible while keeping the system weight as low as possible. In order to achieve these goals, the structures group assisted other groups such as the payload and aerodynamics design, created the rib-spar system for the wing, and designed the system to attach the fuselage with the wings. Landing gear design was also one of the responsibilities for this group.

### **Building**

This group consisted of all of the team members. These group members helped with the construction process of the airplane and also built some of the sub-components needed for testing of the design.

## **2.2 Time management**

The team started work on the project in late October when the senior capstone design groups were formed. Since the team's inception, a master plan was created to complete the design and building components of the project. Figure 2.2 details this plan.



### **3.0 Conceptual Design**

The conceptual design process consisted of interpreting the rules for the competition and then creating initial designs that can possibly meet the requirements of the contest. The conceptual design phase was also the time that major parameters of the contest were discussed in details, and various optimization processes were considered. Finally, figures of merits were used to select a design for the project.

#### **3.1 *Mission Requirements***

The AIAA Design, Build, and Fly competition for 2007-2008 required teams to design an electric motor-powered remote control plane that had to meet several requirements.

##### **3.1.1 *Sizing and takeoff***

The plane had to fit in a box of 4 feet by 5 feet in its normal ground attitude. In addition, the plane had to takeoff within seventy-five feet and five minutes after the initial roll-out.

##### **3.1.2 *Propulsion***

The plane had to utilize an off the shelf motor and off the shelf propellers. The batteries that could be used with the plane were limited to NiCad and NiMH types. The maximum amperage draw for each motor was limited to 40 amps. Finally, the total weight of the batteries used for motors was limited to four pounds.

##### **3.1.3 *Payload***

For one of the missions, certain payloads have to be carried by the airplane. These payloads consist of water bottles that weigh approximately one-half pounds and US half-size bricks that approximately weigh 1.8 pounds. There were five predetermined payload combinations which might have to be carried by the airplane. Although the weight of each bottle and each brick vary slightly, the total weight of the payload combinations ranges near seven pounds. Thus, a major point of analysis is to determine the optimum loading layout of the payload in order to maximum performance of the plane while not increasing the need for extra structural materials that might cost weight savings.

##### **3.1.4 *Mission Descriptions—Delivery Flight***

The delivery flight mission consisted of flying the airplane without any payloads (although all payload mechanisms must not be removed) for as many laps as possible

within a five minute time span. The scoring is maximized by increasing the number of laps and decreasing the weight of the batteries for the motors.

### 3.1.5 Mission Descriptions—Payload Flight

The payload flight mission consisted of flying the airplane with a given payload combination for two laps. There was no time limit for this mission except for the five minute takeoff deadline. The score for this mission depended on the rated aircraft cost (RAC) which consisted of the empty weight of the plane times the battery weight of the plane. Another parameter in scoring was the loading time of the payload. A decrease in weight of either the battery or the empty plane as well as decrease in the loading time led to an increase in total score.

### 3.1.6 Flight course

The flight course was predetermined by the event organizers and consisted of an oval which was more than two thousand feet long. The plane also had to do a 360 degree turn during the course. See figure 3.1 for a description of the course.

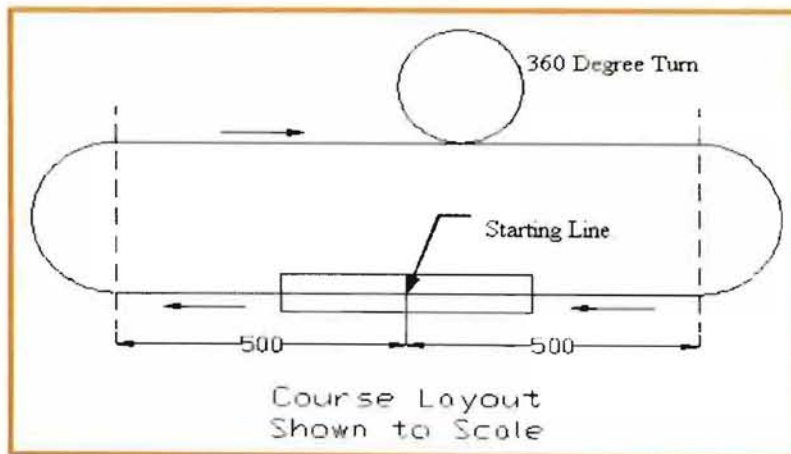


Figure 3.1: Course layout.

## 3.2 Score Analysis

The team performed a score analysis to gain some guidance on which design components to concentrate on more. The scoring for this competition was a combination of the report score multiplied by the flight scores. The flight scores were subdivided into two missions:

1. Delivery flight—the objective of which is to travel the largest number of laps.



2. Payload flight—the objective of which is to carry the required payload.

The total flight score was a summation of each score.

For the delivery flight, teams utilize an empty aircraft (without any payloads) to complete as many laps as possible within five minutes. The scoring for this flight is number of complete laps divided by the battery weight. The score can be represented as follows:

$$Score_{Delivery} = \frac{Laps}{Weight_{battery}} \quad (3.1)$$

From a simple analysis it is easy to see that by having the lightest battery possible and the largest range possible would increase the score most.

The payload flight required the aircraft to carry the randomly assigned payload. There was no time limit for this flight and the only requirements are that the aircraft must take off in seventy-five feet and complete two laps while landing successfully. The score for this mission is one over the loading time multiplied by the RAC. The RAC is defined as system weight multiplied by the battery weight. The following equation represents the score for this mission:

$$Score_{Payload} = \frac{1}{Weight_{battery} * Weight_{empty} * Load\_Time} \quad (3.2)$$

Again it is easy to see that by decreasing the weight of the battery a score can be increased. However, in order to use lighter batteries, the aircraft too must be as light so that smaller motors may be used. Minimizing the weight of the aircraft also increase the score for the payload flight.

Loading time deserves special mention because it is extremely hard to quantify this score. According the contest rules, loading time consists of the following:

- “Go and get their payload assignment sheet.”
- “Determine which payload elements they will require.”
- “Retrieve those elements from storage.”
- “Open the cargo compartment and configure their restraint system for the specified payload combination.”
- “Load the payload into the aircraft and secure all payload elements.”



- “Return and secure any un-used restraint system components into the aircraft.”
- “Secure the cargo compartment.”
- “Return to the starting line.”

As one can see, there are several parts to the “loading” process, and many of these events are highly dependent on parameters out of the hand of the aircraft designer. For example, how fast the crew “retrieves” elements from the storage is a function of how well the storage is labeled and how quickly crew members can locate needed elements. In addition, teams which have to use fourteen bottles for payloads will be at tremendous disadvantage over the group that has to only use four bricks. Although the contest organizers have stated that a normalization process will be followed, due to lack of more information about this normalizing process, considering loading time in score analysis is difficult. Thus, the team hopes that plenty of time for loading practice for the crew members will be sufficient to optimize score for that situation.

Using the two flight scores, an overall score equation was created.

$$Score_{Flight} = \frac{Laps * Weight_{empty} * Load\_Time + 1}{Weight_{battery} * Weight_{empty} * Load\_Time} = S_F = \frac{l \cdot W_e \cdot t_{load} + 1}{W_b \cdot W_e \cdot t_{load}} \quad (3.3)$$

Sensitivity analysis was conducted by taking the partial derivative with respect to the three parameters that were easy to quantify: number of laps (l), empty weight (W<sub>e</sub>), and battery weight (W<sub>b</sub>). Table 3.1 tabulates the initial values of each parameter, and table 3.2 lists the results of the sensitivity analysis.

**Table 3.1:** Initial value of parameters

We	15 lb	240 oz
Wb	2 lb	32 oz
t	1 min	60 sec
l	5	5

**Table 3.2:** Sensitivity analysis results

	Initial	Delta	% Change	Final
Laps (l)	0.156252	0.03125	20.00%	0.187502
We	0.156252	-9E-09	0.00%	0.156252
Wb	0.156252	-0.00488	-3.13%	0.151369

The results of the sensitivity analysis show that an additional completed lap in the increases the total score dramatically. In addition, an increase in battery weight by one ounce decreases the total score appreciably (meaning a decrease in battery weight leads

to a appreciable increase in score). The surprisingly result of the analysis was that change in empty weight by a pound does not change the score significantly. However, this can be explained by the fact that the empty weight of the plane is so big in ounces already that minute changes do not reflect immediately in the score analysis. Nevertheless, if weight is decreased significantly, not only will score analysis show an increase in total score directly due to the effect of empty weight but the weight loss would also boost performance and the number of laps will increase, thus affecting the scoring indirectly. Thus, as was earlier concluded, weight optimization is a key task for the group.

### 3.3 Weather analysis

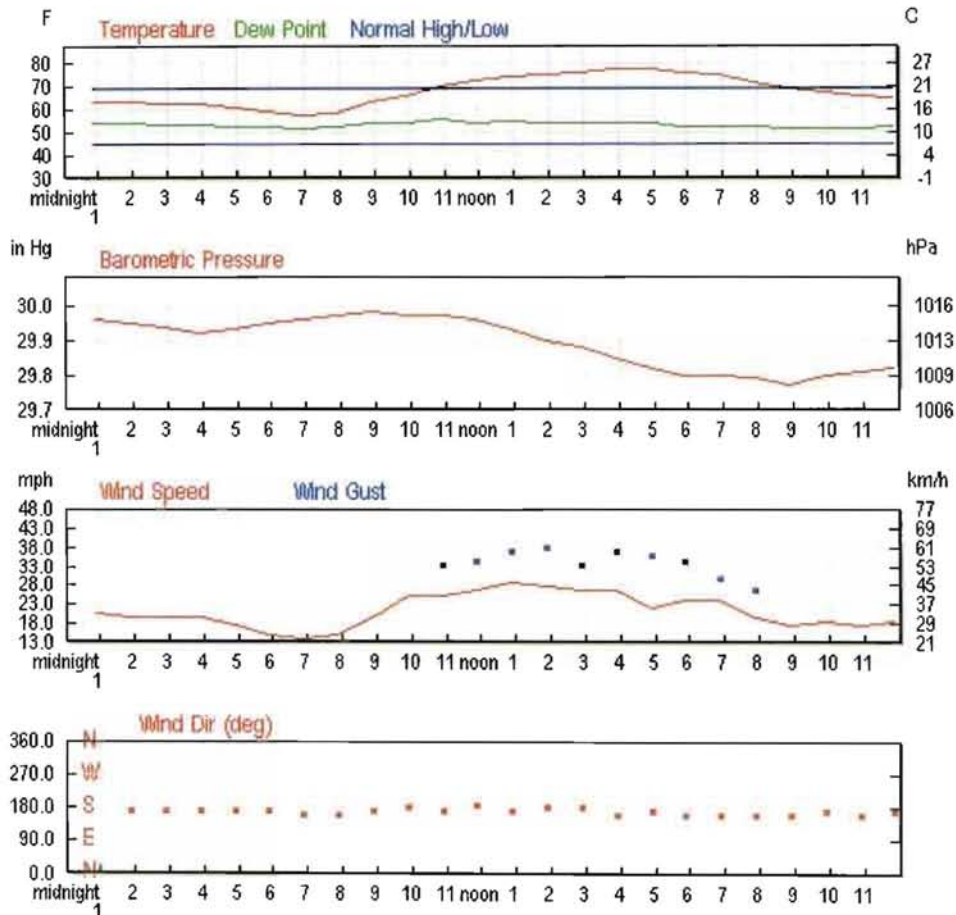
The competition site this year will be in Wichita, KS. Weather conditions for the day of the competition was predicted using historical weather data from weather almanacs. Table 3.3 displays the weather data from a year before the competition weekend for this year.

**Table 3.3:** Historical Weather Conditions.

Wichita, Kansas Elevation: 1321 feet April 21, 2007	
Maximum Temperature	78° F
Minimum Temperature	57° F
Average Temperature	68° F
Precipitation	0.00 in
Average Wind Speed	21 mph (South)
Max Wind Speed	33 mph
Max Wind Gust	40 mph
Average Wind Gust	20 mph
Average Pressure	101,200 kPa
Average Density	0.002214 slugs/ft <sup>3</sup>

Figure 3.2 shows the weather conditions at hourly intervals throughout the day. It was found that the temperature continually rises as the day progresses, and falls during the night hours. These moderate temperatures should not pose any problems to any of the airplane's components. The barometric pressure does not vary enough to cause any significant changes to how the airplane will fly. As the day progresses, the temperature increases while the pressure drops. This results in a steady density value throughout the day.

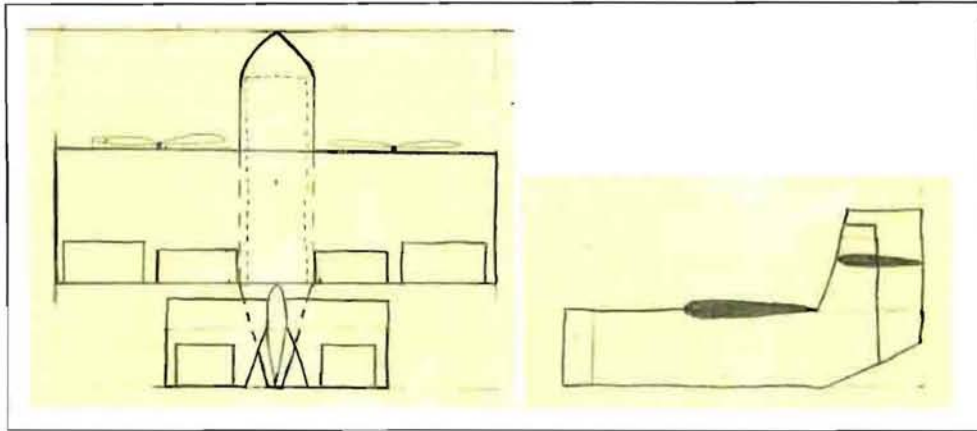
The most significant factor that the weather will have on the airplane will be the wind. With the average wind speed at 21 mph and gust up to 40 mph, it could pose significant control and flight problems. The wind direction is typically constant, heading towards the south throughout the day. This will make the airplane's flight characteristics predictable in the windy conditions.



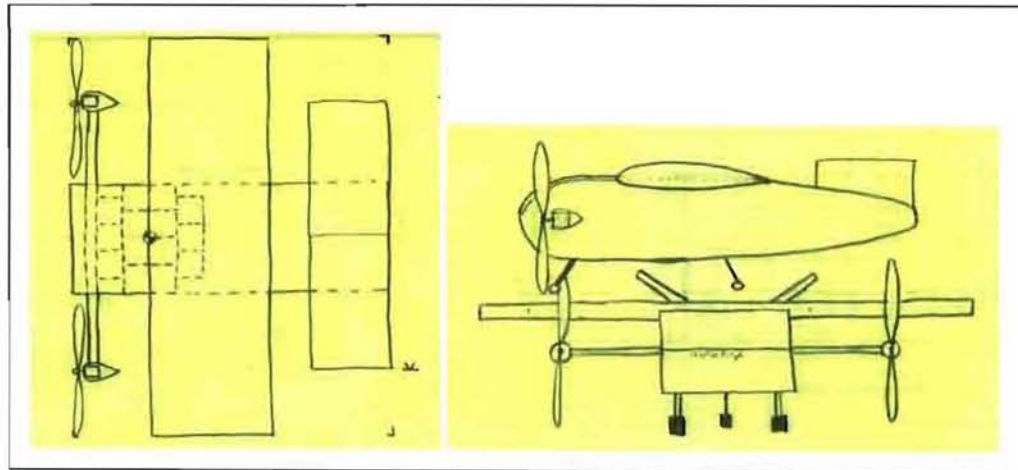
**Figure 3.2:** Historical Data—Weather Conditions in Wichita, KS on April 21, 2007.

### 3.4 Configuration Selection

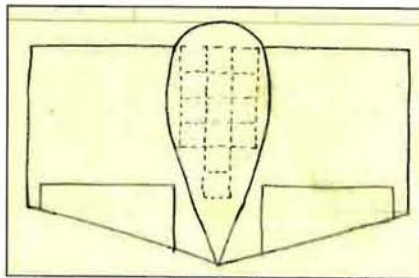
The team collaborated together to brainstorm various possible solutions to the design problem. Figures 3.3 through 3.7 display many different plane designs that were considered.



**Figure 3.3:** Conceptual configuration # 1—High wing, conventional tail, wing-mounted, two-motored solution.

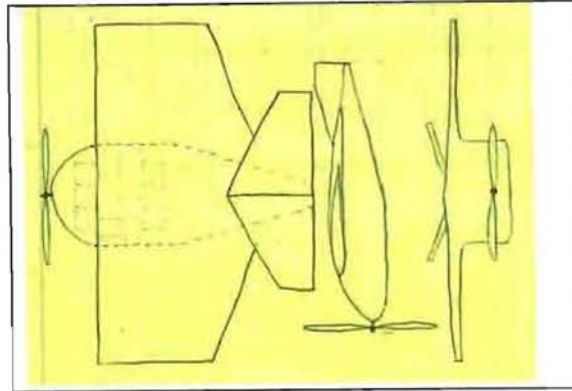


**Figure 3.4:** Conceptual configuration # 2—High wing, conventional tail, nose-mounted, two-motored solution.

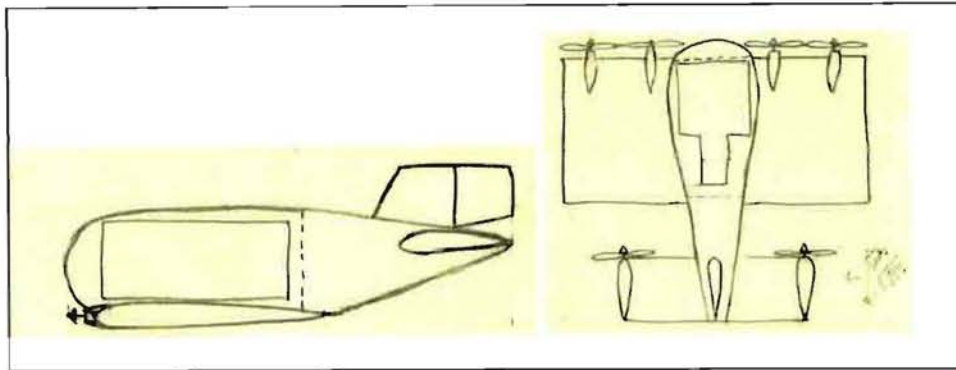


**Figure 3.5:** Conceptual configuration # 3—Flying wing design





**Figure 3.6:** Conceptual configuration # 4—Single-motor, nose-mounted design with V-tail.



**Figure 3.7:** Conceptual configuration # 5—Low wing, conventional tail, wing and tail-mounted motor solution.

### 3.4.1 Configuration descriptions

- **Configuration # 1** is a high wing airplane with conventional tail. The plane is powered by two motors both of which are wing mounted.
- **Configuration # 2** is also a high wing airplane with conventional tail. The plane is powered by two motors both of which are nose mounted. This variation allowed the team to compare the merits and demerits of a nose-mounted motor with a wing-mounted motor.
- **Configuration # 3** is a flying wing concept. In this variation, the team was able to compare conventional mono wing planes with the flying wing, which is an

innovative approach to increasing planform area (and thus lift). Since the main concept of this design is comparing wing configurations, the placement of motors is not considered for this design.

- **Configuration # 4** is a single, nose-mounted motor plane with low wings and V-tail. This design allowed the team to consider the merits of a low wing design as well as analyze an unconventional tail design.
- **Configuration # 5** is a low wing airplane with conventional tails. However, motors are mounted on both the wing and the tail. This design allowed the team to consider tail mounted motors, a design variable not considered in the other configurations.

### 3.4.2 *Figure of Merit*

In order to narrow the choices of design from the five considered configurations to one conceptual design, several parameters were studied under a figure of merit.

- **Weight** was perhaps the most important parameter considered. Since the RAC includes the empty weight of the plane, the final design needed to be the most weight-effective plan.
- **Thrust** was another important characteristic for the design. Higher thrust values increased the range of the airplane, and thus increased the number of laps finished in the delivery flight. In addition, a minimal thrust value was needed for the plane to takeoff within seventy-five feet.
- **Controls** was a key criterion since high wind speeds in Wichita requires the plane to be very stable. Stability was important to allow a pilot to adjust to the plane.
- **Payload layout space** was the final important criterion in choosing a conceptual design. The plane must have ample space to allow an optimal payload mechanism layout. Any design whose structure could interfere with the payload mechanism space, and thus slow down the loading process, would be penalized.

Each configuration was graded on a scale of 1 to 10 for each criterion and then the scores were normalized. See Table 3.4 for the conceptual design figure of merit.



**Table 3.4:** Conceptual design configurations—figure of merit.

Configuration	Weight	Thrust	Controls	Payload	Total Score
1	4	7	8	7	1
2	5	7	5	7	0
3	8	2	3	5	-1
4	6	5	8	7	1
5	2	9	8	4	0

### 3.4.3 Conclusion

Based on the figure of merit analysis, configuration # 1 and configuration # 4 were adjudged to be the best designs. However, since configuration # 1 was a high wing plane with dual motors and configuration # 4 was a low wing plane with a single motor, the team realized that a combination of these designs would ultimately lead to the best solution to the problem. Conventional tail design was fixed, since it had a huge advantage in providing stable controls. As far as the wing height, the team decided on a high-wing design to allow for more room in the fuselage for payloads. A low wing design would have meant that the spar running across the span of the wing would have gone through the bottom of the fuselage, thus taking important real-estate that should be devoted to the payload. Finally, the single motor design was chosen over the two motor design due to the reduction in weight despite the small loss in thrust performance. Since a single motor design was chosen, the motor was mounted on the nose. So in the end, the team had decided on a high-wing, single motor, conventional tail design.

#### 4.0 Preliminary Design

In the preliminary analysis portion of the design, the team moved to examine various components of the chosen high-wing conventional tail design. Investigations were conducted to study the aerodynamics, payload design, and propulsion systems that were to be used with the airplane.

#### 4.1 *Aerodynamics*

Based on the requirements of the competition, certain performance criteria had to be met. The most critical criterion was the maximum takeoff distance of seventy-five feet. Moreover, the plane's dimensions were limited to four feet by five feet, which further restricted the sizing of the plane. Planform area is proportional to lift produced, and in order to maximize that parameter, a wingspan of five feet was set. MATLAB simulations were done to determine the importance of certain design variables that affected the seventy-five feet takeoff distance. These variables included the chord length, taper ratio, system weight, coefficient of lift provided by the wing facing at takeoff attitude, and wing height from the ground.

##### 4.1.1 *Takeoff simulation*

The takeoff simulation used an equation that attempts to capture all forces that will act on the plane as it runs down the runway. The major forces involved are thrust (T), drag (D), rolling resistance (R), and ground effect (G). A drag polar was created from this analysis based on concepts developed by John D. Anderson [1]. The drag polar was of the form:

$$C_D = C_{D,0} + (k_1 + Gk_3)C_L^2 \quad (4.1)$$

G was the ground effect term and was calculated using the equation

$$G = (16h/b)^2 / (1 + (16h/b)^2) \quad (4.2)$$

Here h represents the wing height and b stands for wing span. The differential equation for the takeoff situation was as follows:

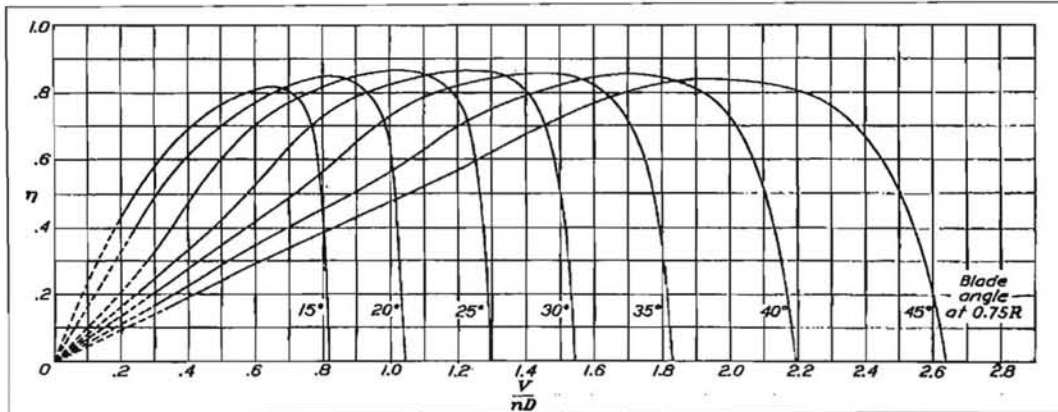
$$M(dV/dt) = T(V) - D(V) - R(V)$$

This expanded to

$$a = dV/dt = (T(V) - C_D(.5\rho V^2)cb - \mu_r(mg - C_L(.5\rho V^2)cb))/m \quad (4.3)$$

The differential equation was solved by numeric integration methods with boundary conditions defined. Thrust can be defined as a function of advance ratio (J), which in turn is a function of V. NACA technical report 340 provided the team with propeller efficiency versus advance ratio for a Clark-Y airfoil, which was the airfoil used in propeller blades considered for the various

motors that were analyzed (Figure 4.1). The rolling resistance ( $\mu_r$ ) was based on historical estimates for various takeoff surfaces [1].



**Figure 4.1:** Propeller efficiency as a function of advance ratio and propeller pitch angles [2].

#### 4.1.2 Design characteristics

Certain parameters were held constant to run the simulation. An initial weight estimate for the plane is shown in Table 4.1. The parameters held constant are shown in Table 4.2.

Table 4.1: Initial weight estimates		
Payload:	7.5	lbf
Fuselage:	2.5	lbf
Max Battery:	4.0	lbf
Electronics:	1.3	lbf
Motor:	3.2	lbf
Tail:	0.5	lbf
Wing:	1.0	lbf
<b>TOTAL:</b>	<b>20.0</b>	<b>lbf</b>

Table 4.2: Standards for comparison		
Chord Length	1.5	feet
Taper Ratio	1	
Weight	20	pounds
$C_l$	0	
Wing Height	20	inches

#### 4.1.3 Chord length and aspect ratio

The first simulation was run with variable chord. The results showed that takeoff distance was largely dependent on chord length (see Figure 4.2a). Moreover, the change in aspect ratio drastically affected the lift (figure 4.2b). Thus, a further analysis of the lift distribution was warranted. Such an analysis was done using lifting line theory in detailed design.

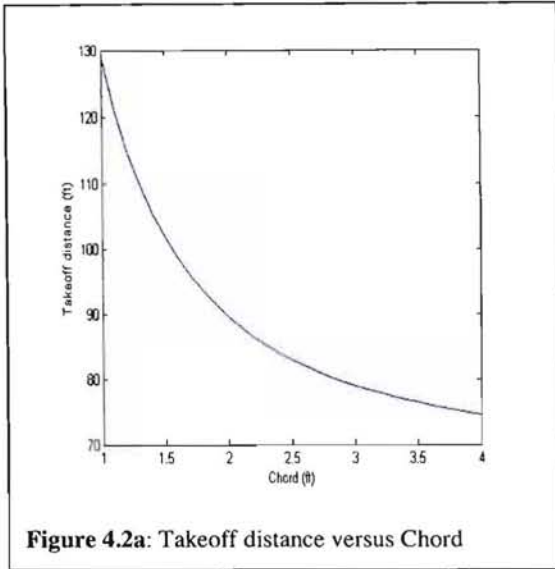


Figure 4.2a: Takeoff distance versus Chord

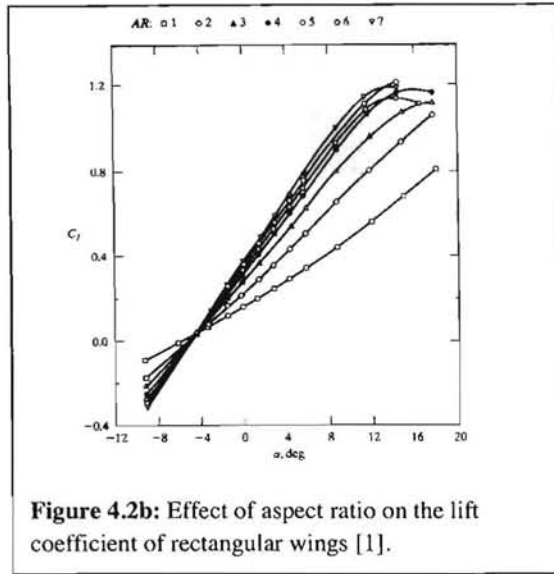


Figure 4.2b: Effect of aspect ratio on the lift coefficient of rectangular wings [1].

#### 4.1.4 System weight

It was also found that takeoff distance had a large dependence on overall weight of the plane (see Figure 4.3). From the figure, it can be discerned that for seventy-five feet takeoff distance, the plane would weigh approximately sixteen pounds. Any weight higher than that would not allow the plane to take off in the required distance.

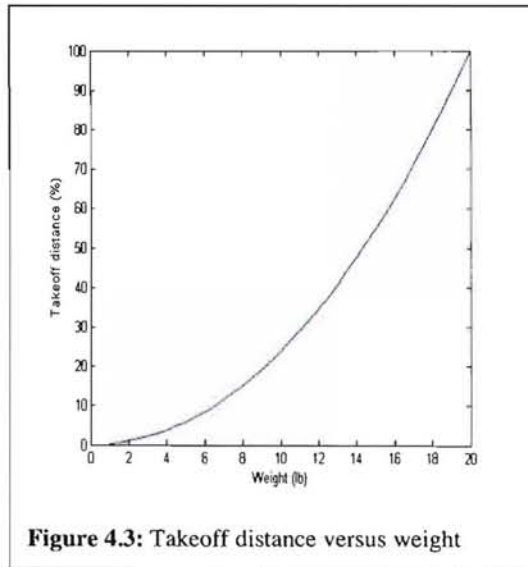


Figure 4.3: Takeoff distance versus weight



#### 4.1.5 Taper ratio, coefficient of lift, and wing height

The next three simulations had very little effect on the takeoff distance. An analysis of variable taper ratio (while keeping the total planform area constant) was done to estimate the amount of induced drag and how it affected the takeoff distance. This resulted in almost no noticeable change. Next, the coefficient of lift for the wing was varied. With an increase of coefficient of lift from 0 to 1, the takeoff distance was decreased by five percent (Figure 4.4a). Lastly, the effect of wing height on takeoff distance was tested. This test included the ground effects of the airplane and its consequences. The wing height was varied from 0 inches to 35 inches. The wing height had almost no effect on the takeoff distance (Figure 4.4b).

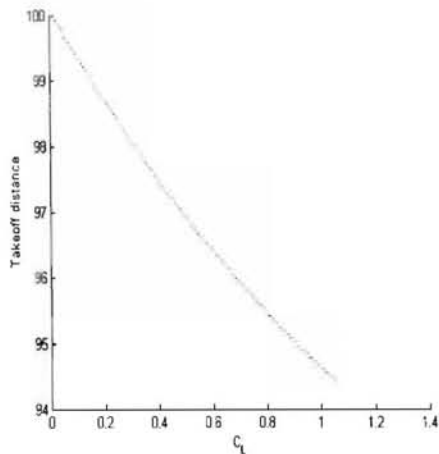


Figure 4.4a: Takeoff distance versus  $C_L$

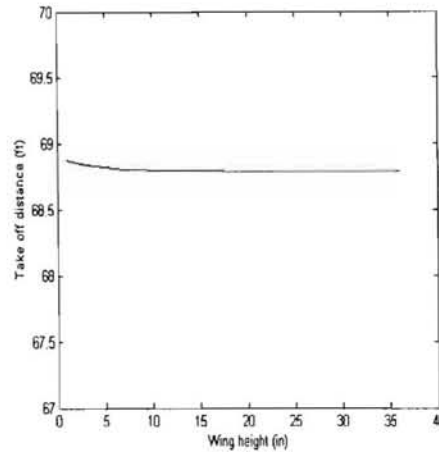


Figure 4.4b: Takeoff distance versus wing height from ground

#### 4.1.6 Conclusion

In conclusion, the factors that should have the most focus on design are the chord length and the weight. One needs to optimize the chord length for a takeoff distance of seventy-five feet. Too long of a chord would lead to takeoff in less than seventy-five feet, but will also add unnecessary drag that will rob from maximum performance. Yet, the chord has to still be long enough to allow the plane to takeoff in the required distance. Moreover, besides being a scoring criterion, the weight is also a big factor in the takeoff distance. Thus, every effort has to be made to minimize this parameter in the design. The rolling resistance has a small effect on the takeoff distance but is worth consideration in the final design. Ground effect and taper ratio have a

negligible effect on takeoff distance, and so decisions based on these parameters, such as whether to use a high wing or low wing, will be influence more by factors such as ease of construction rather than any performance-based reasoning.

**4.2 Payload layout**

Another requirement for this year’s competition was to construct a device that could securely hold a given payload. The payload would consist of water bottles that would simulate passengers and clay bricks that would simulate cargo. Five different combinations of the payload were given as possible loads for the payload flight. The combinations are shown below in Table 4.3.

**Table 4.3:** Possible Payload Configurations for Payload Flight.

Configuration	Number of Bottles	Number of Bricks	Nominal Weight (lbs)
1	14	0	7
2	0	4	7.2
3	10	1	6.8
4	7	2	7.1
5	3	3	6.9

**4.2.1 Restraining device**

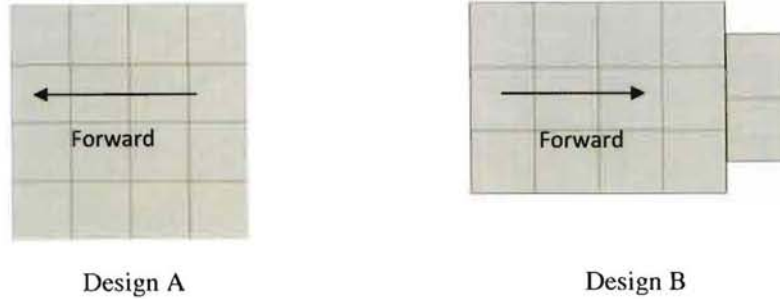
The first problem the payload group tried to solve was how to secure the payloads in the aircraft. The payload restraining mechanism must be able to secure the payload in place while the plane is flipped onto its loading side during testing at the competition. For example, a top loading mechanism would be flipped upside down, and a rear loading mechanism would be flipped over to have its tail down. In order to make sure that the payload remains secure, the team decided to use elastic straps to simulate seatbelts for the payloads. The payload would be placed into to the loading device and held into place using these straps. The straps would have to be able to secure not only a water bottle but must able to adapt as a restraining device for the bricks.

**4.2.2 Payload configuration**

Another consideration for the payload group during the conceptual design was the layout of the payload within the fuselage. Various configurations included a “long” payload layout (2 rows of payloads) as well as “short” layouts (4 rows of payload). After following an iterative



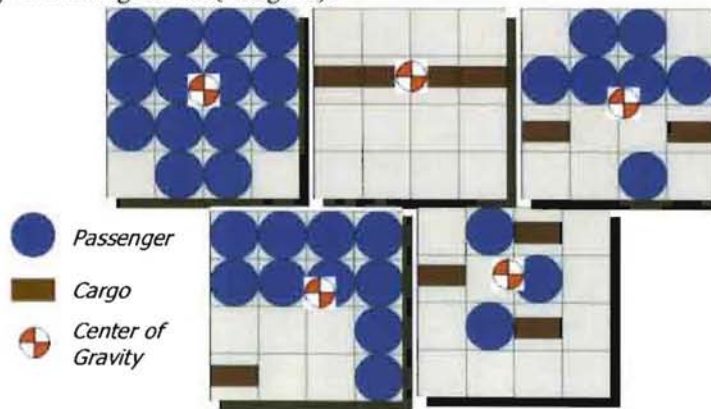
process, two designs for payload configurations were considered. These designs are shown in figure 4.5.



**Figure 4.5:** Layouts considered for payload mechanism

**4.2.3 Center of gravity calculations**

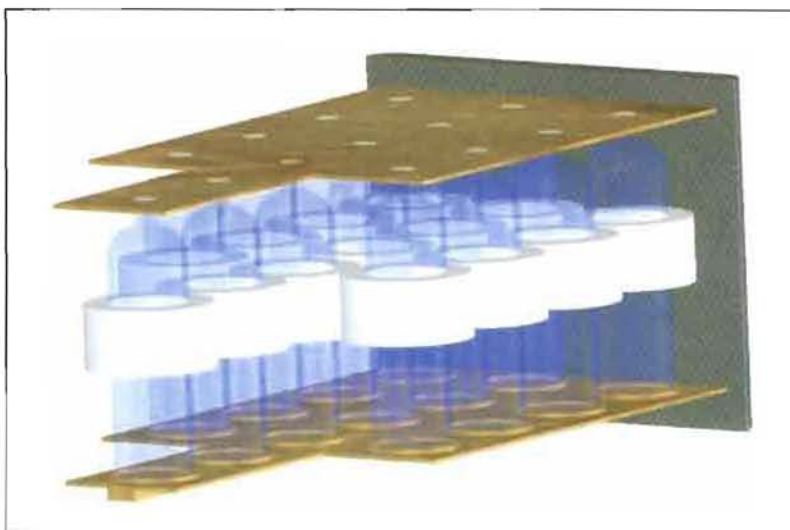
The payload group had to also estimate where the center of gravity would be and determine how it affected the stability of the aircraft. Just like in a small commercial plane, the placement of the payload can greatly affect the stability of the airplane, thus a detailed center of gravity analysis was a prerequisite for analysis. A program was generated that would easily be manipulated to show the desired layout for the bricks and the bottle. This program allowed the team to create an optimum layout for each of the five possible combinations. An optimum layout was defined as the plan which created the least variation for the position of the center of gravity for the different payload combinations. Figure 4.6 displays where the effective center of gravity laid for a 4 x 4 payload configuration (design A). Similar calculations were also made for the 3 x 5 payload configuration (design B).



**Figure 4.6:** Payload center of gravity calculations.

#### 4.2.4 Payload layout selection

Ultimately, it was decided that payload design B would be used for this year's competition. This payload layout allowed the center of gravity to be closer to the front of the aircraft providing a larger static margin and thus increased stability for the aircraft. In addition, this layout also minimized the movement of the center of gravity for various payload combinations. This robustness in center of gravity location will make loading a simpler task as the group will not have to worry too much about putting a payload in the wrong place. Figure 4.7 displays the final layout of the payload mechanism.



**Figure 4.7:** Payload mechanism design

#### 4.2.5 Conclusion

After the design was decided, the payload group built a prototype. By creating the prototype unexpected problems could be dealt with before the final design was created. Also, by building a prototype of the restraint system early in the design phase the team could begin practicing the technique to load the system earlier instead of waiting for the final design. Testing revealed that the chosen payload mechanism actually did work well. However, plans were made for additional testing of the mechanism during flight tests so that the ground crew could familiarize themselves with the loading process.

### 4.3 *Propulsion Preliminary Analysis*

For the preliminary analysis of the airplane's propulsion system, the following considerations had to be made to determine the most efficient system configuration: number of motors, motor type, propeller types, motor mounting location, drive train, and battery configuration. The ultimate goal of the propulsion preliminary analysis was to determine which motor class (large, medium, or small) will require the least amount of battery weight and propulsion system weight.

- **Number of Motors** – Smaller, lower weight motors can be used if multiple motors were used. Although, the overall system would be more complicated due to wiring and mounting limitations.
- **Motor Type** – There are two major types of motors: brushed and brushless. Brushless motors are significantly more efficient and require less maintenance than brushed motors. There are two main types of brushless motors, outrunner and inrunner configuration. Outrunner motors tend to displace more torque due to its rotating outer cylinder. Inrunner motors have a higher power output and tend to be more efficient than outrunner motors.
- **Propeller Types** – There are two major manufacturers of model airplane propellers. Each with its own advantages. APC manufactures propellers that are designed for efficiency in top speed and maximum thrust. These propellers tend to have better climb performance. Master Airscrew propellers are more durable and have a wider blade chord for better braking characteristics. APC propellers are more desired due to the nature of the competition.
- **Motor Mounting Location** – There are three main propulsion configurations with relation to how the motors are mounted: tractor, pusher, and push-pull. In the tractor configuration, the motor is mounted facing forward with the propeller directing thrust towards the rear of the airplane. In pusher configuration, the opposite is true. Push-pull configuration is a combination of both tractor and pusher with dual motors mounted on the same axis.
- **Drive-train** – There are two drive trains that are possible: direct drive and gear driven. Direct drive consists of a propeller mounted directly to the motor output shaft—the

propeller spins at the same revolution as the motor shaft. Gear driven system consists of using gears to increase or decrease the rate at which the propeller spins in relation to the motor output shaft. The main advantage to using a gear drive is the ability to spin a larger diameter propeller at a lower amperage draw so as to improve climbing characteristics of the airplane at the expense of speed. Gear driven systems are mechanically complex and require extra maintenance.



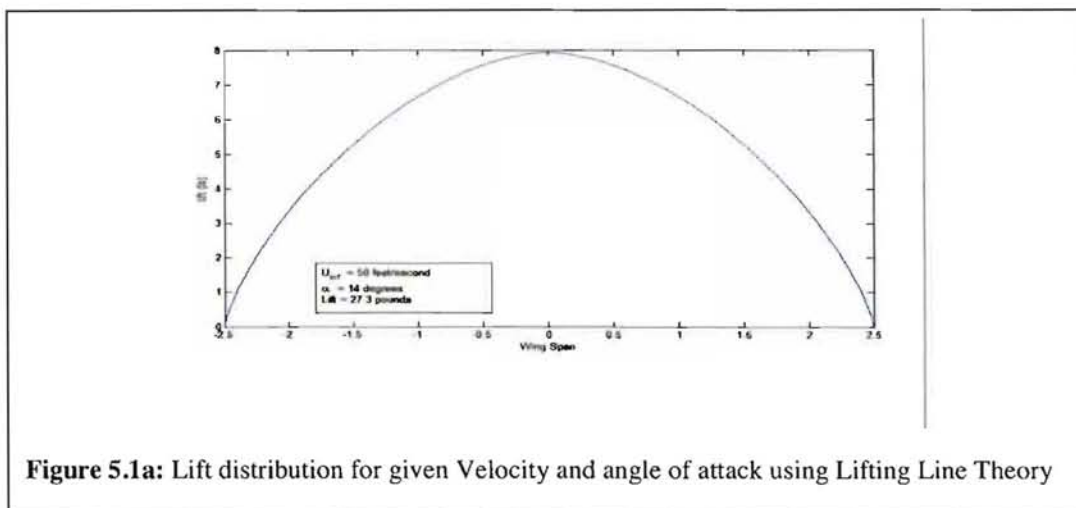
## 5.0 Detailed Design

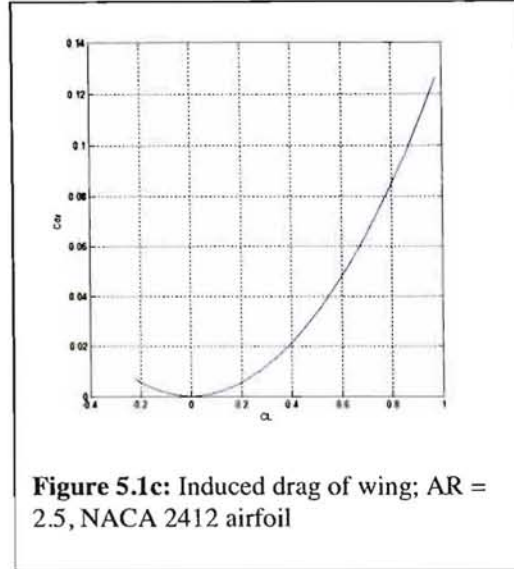
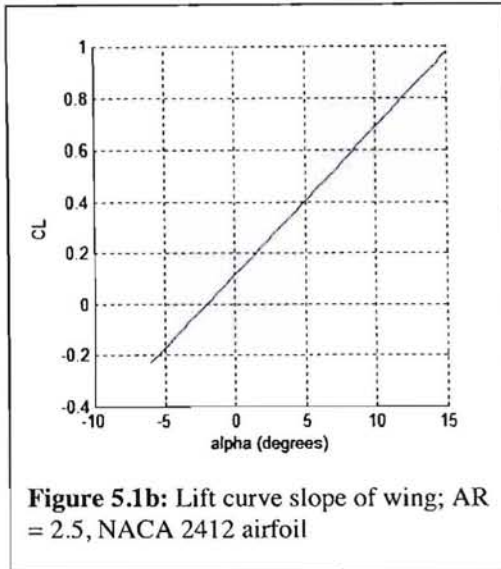
### 5.1 Aerodynamics

A detailed aerodynamic analysis was done on the wing and tail sections. The entire model was not analyzed; however, piecemeal analyses were done on the wing using two aerodynamic theories. The first analysis was done using the lifting line theory. This theory has the advantages of being applicable for a straight wing, being simple to setup, and providing accurate results without being a computer intensive process. The results from this analysis are corroborated with the second analysis which was based on the Vortex Lattice Method (VLM). The VLM code returned the pressure distribution over the wing allowing for a more accurate analysis for the structural setup of the plane.

#### 5.1.1 Lifting line theory

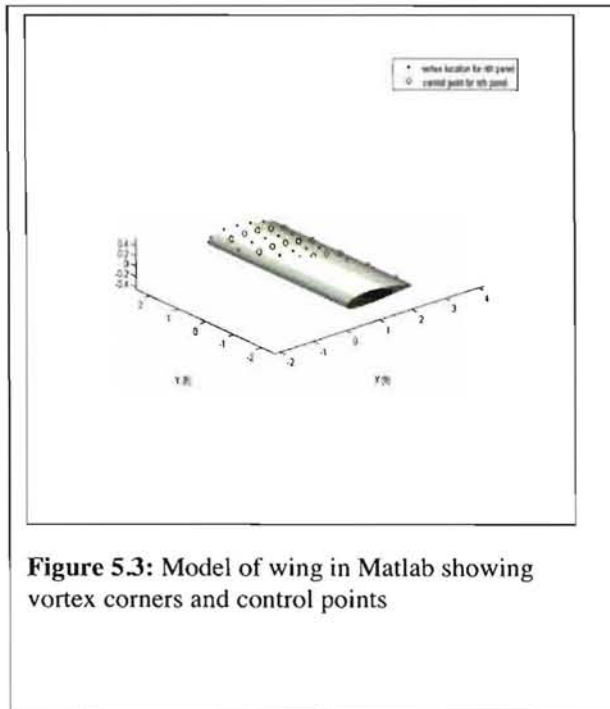
Lifting line theory returns coefficients of lift, coefficients of drag, downwash, and lift distribution across the span of a finite wing. However, to get reliable data, the wing must be unswept, straight, and have an aspect ratio greater than 4.0. The aspect ratio of the wing being tested was 2.5. However, the data was still assumed to be reasonably accurate since the Reynold's number regime was not high, which is where the lifting line theory fails. The results are shown in Figure 5.1a-c. The equation generated using the lifting line theory is used to perform the structural analysis on the wing.



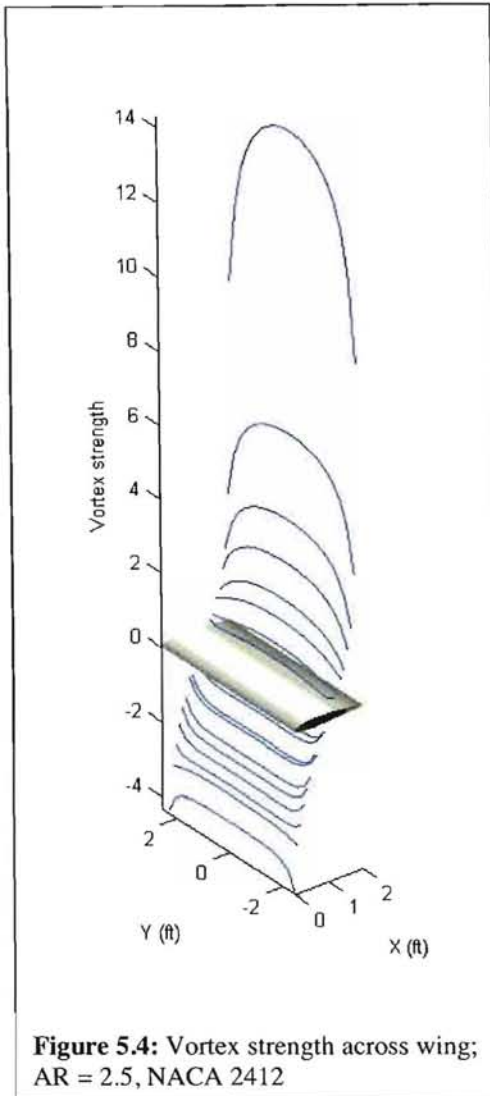


### 5.1.2 Vortex Lattice Method

A vortex lattice method using Matlab was used to find a more detailed analysis of the wing and tail. Currently only an analysis for the wing has been done. **Figure 5.3** shows the panels and their corresponding control points. The coding of this program was an involved process. All control points lay on the surface of the wing. The vortices were located at 0.25 mark from the front of each panel and the control points were located at 0.75 mark from the front of each panel. The results of the analysis can be found in Figure 5.3. This data was modified to find a more detailed pressure







distribution across the wing. The shape of the lift distribution for the VLM model was the same shape found from the lifting line theory. In addition, the model will be verified by test data collected from the final model. Once this is done, stability of the plane can be optimized using the VLM method by adding side slip to the model.

## 5.2 Weight estimate

The weight estimate was done by adding the components of all of the pieces broken down into four categories: wing, tail assembly, fuselage, and payload. The two main components that are used in the construction are balsa wood and carbon fiber.

Balsa wood has a density that varies from  $6.5 \text{ lb/ft}^3$  to  $12 \text{ lb/ft}^3$ . A density of  $8 \text{ lb/ft}^3$  will be used. We searched for the lightest balsa possible; however,  $8 \text{ lb/ft}^3$  is used due to the probability of not getting the lightest balsa on the market. The main purpose of the balsa is as a former for the carbon fiber, and due to the strength of the balsa compared to the strength of carbon fiber all efforts are done to decrease the amount of balsa used by

drilling holes or using thinner pieces.

The weight of carbon fiber per unit area varies depends on the resin and weave used. The carbon fiber used in the construction of the plane is a 3k weave with a thickness of 0.005 inches. The resin used is a polyvinyl ester. This has a weight of  $1.18 \text{ g/cc}$ . The final weight per unit area of a finished carbon fiber piece is  $0.0123 \text{ lb/ft}^2$ . Due to the stiffness of carbon fiber, only one

layer is used for most of the plane and layers are added where more stiffness is required based on the structural analysis done.

The motor used is an AXIS 5330-F3A, which has a weight of 23 oz. The battery weight is 3 pounds. The servos used weigh 1.5 oz. A weight of 0.1 pounds was added to each of the four sections of the plane. This is done to account for additional weight such as glue or excess resin. The summary of the weight of the plane can be found in Table 5.1.

**Table 5.1:** Detailed weight of the plane

	Wing		Fuselage		Payload		Tail	
	area/volume	weight	area/volume	weight	area/volume	weight	area	weight
Carbon Fiber(A)	3782.3	0.322	1907.8	0.163			842.11	0.072
Balsa(V)	58	0.269	23	0.106	47.77	0.221	2.09	0.01
Payload						7.1		
Motor				1.438				
batteries				3				
servos			1	0.094			2	0.188
radio equipment				0.125				
other		0.1		0.1		0.1		0.1
sub total		0.691		5.025		7.421		0.369
<b>GRAND TOTAL</b>	with payload		13.506	lb	Without payload		6.085	lb
Area weight of Carbon Fiber			0.01227	lb/ft <sup>2</sup>				
Density of Balsa			8	lb/ft <sup>3</sup>				

### 5.3 Airfoil choice

Several criteria went into choosing the airfoil. Key parameters that were to be decided were the camber and the thickness of the airfoil. Several airfoil thicknesses were compared and twelve percent produced the most lift independent of camber. Due to the strict seventy-five foot takeoff distance, an airfoil with a thickness of twelve percent was chosen. Next to be chosen was the camber. Camber affects the zero angle of attack lift for the wing, so high camber would allow for minimum drag and mitigate the rolling resistance due to takeoff. However, the advantage would be negated because the wing would have to be mounted at a negative angle of attack for steady level flight or the plane would have to fly at a negative angle of attack. Flying at a negative angle of attack would increase the drag of the plane during flight which will consist of about 95 percent of the flight time. There a camber was chosen that would provide enough lift at zero angle of attack to allow for the least amount of drag for the duration of the flight. Figure 5.5

compares the polar for three NACA airfoils: 1412, 2412, and 3412. The NACA 1412 has a  $C_l$  of 0.12 at zero angle of attack and with a speed of 100 ft/sec a lift of about 15 pounds is produced. The NACA 2412 has a  $C_l$  of .25 at zero and of attack which will produce a lift of 25 pounds at 100 ft/sec. Taking the affect of aspect ratio into consideration the coefficient of lift will be reduced. In this case the NACA 1412 will have to be mounted at a positive angle of attack and the NACA 2412 will have to be mounted at a negative angle of attack. However, the NACA 2412 has a slightly higher  $C_l$  max than the NACA 1412. Due to these conditions, the NACA 2412 was chosen to as the airfoil to be used.

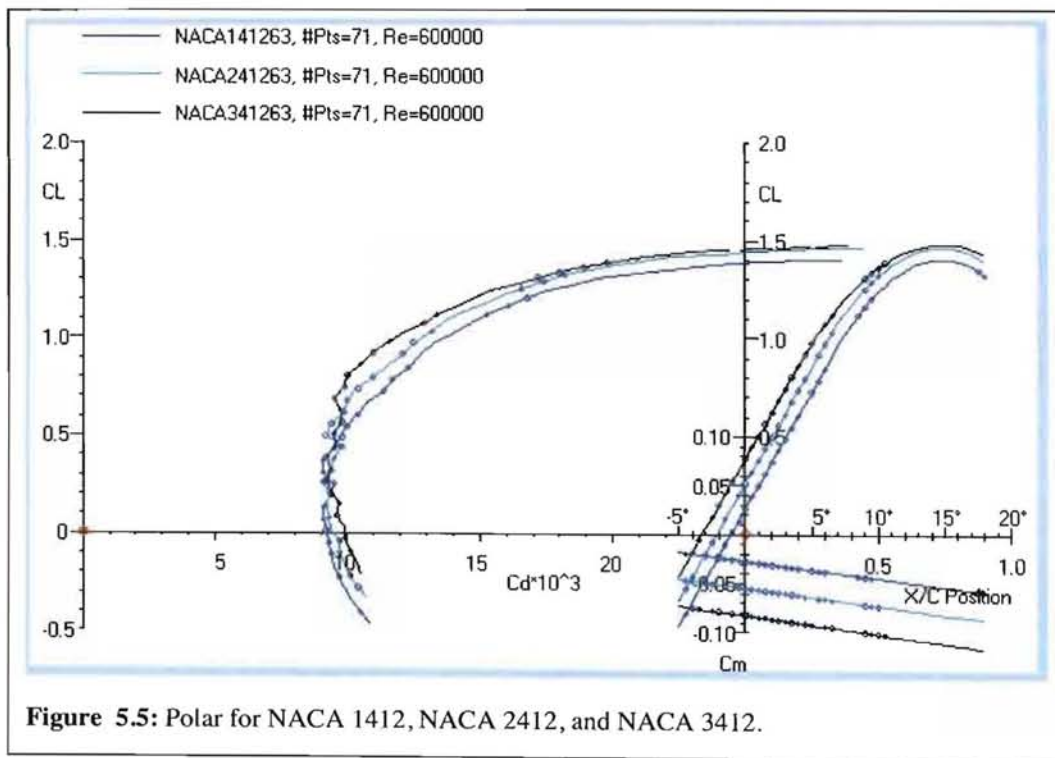


Figure 5.5: Polar for NACA 1412, NACA 2412, and NACA 3412.

#### 5.4 Propulsion Selection

The factors taken into account during the initial selection of the propulsion system were: motor and propeller weight, battery weight, top speed, flight time, and take off distance.



Because the requirements of the competition limited many factors of the propulsion system, these were further analyzed using data provided by the motor manufacturers.

In determining what propulsion system would be used for the airplane, the first step taken was narrowing down the large selection pool of motors available in the commercial industry into small pool placed in three main subcategories: small, medium, and large class motors. Motors that can propel the airplane by itself were placed in the large class. Motors that required at least two motors to properly propel the airplane were placed in the medium class. If it takes four or more motors to attain the necessary thrust required, the motors were placed in the small class. The motors that were chosen had to achieve a minimum thrust required for the plane to takeoff in 75 feet. The motors that were selected for each category were chosen based on manufacturer's posted weight and performance data. Table 5.2 shows the motor selection. This data gave a general idea on the performance expectations from the motors.

**Table 5.2: Motor Selection**

Motor	Class	Estimated # of Motors Required
AXI 5330-F3A	Large	1
E-Flite Park 25	Medium	2
E-Flite Park 15	Medium	2
E-Flite Park 480	Small	4
Little Screammers	Small	4

### 5.5 Further Propulsion Analysis

The next step in the analysis involved utilizing a commercially available electric flight performance prediction software called MotoCalc to determine the initial propulsion requirements for the airplane. The program allows the user to input parameters of the airplane and also allows the input of specific parts such as motor type and brand, propeller characteristics, drive system, speed control, batteries, and more. The program was used to determine the performance of each motor based on different combinations of speed controller, battery specifications, and propeller dimensions. The goal is to pair the motors with the propeller and

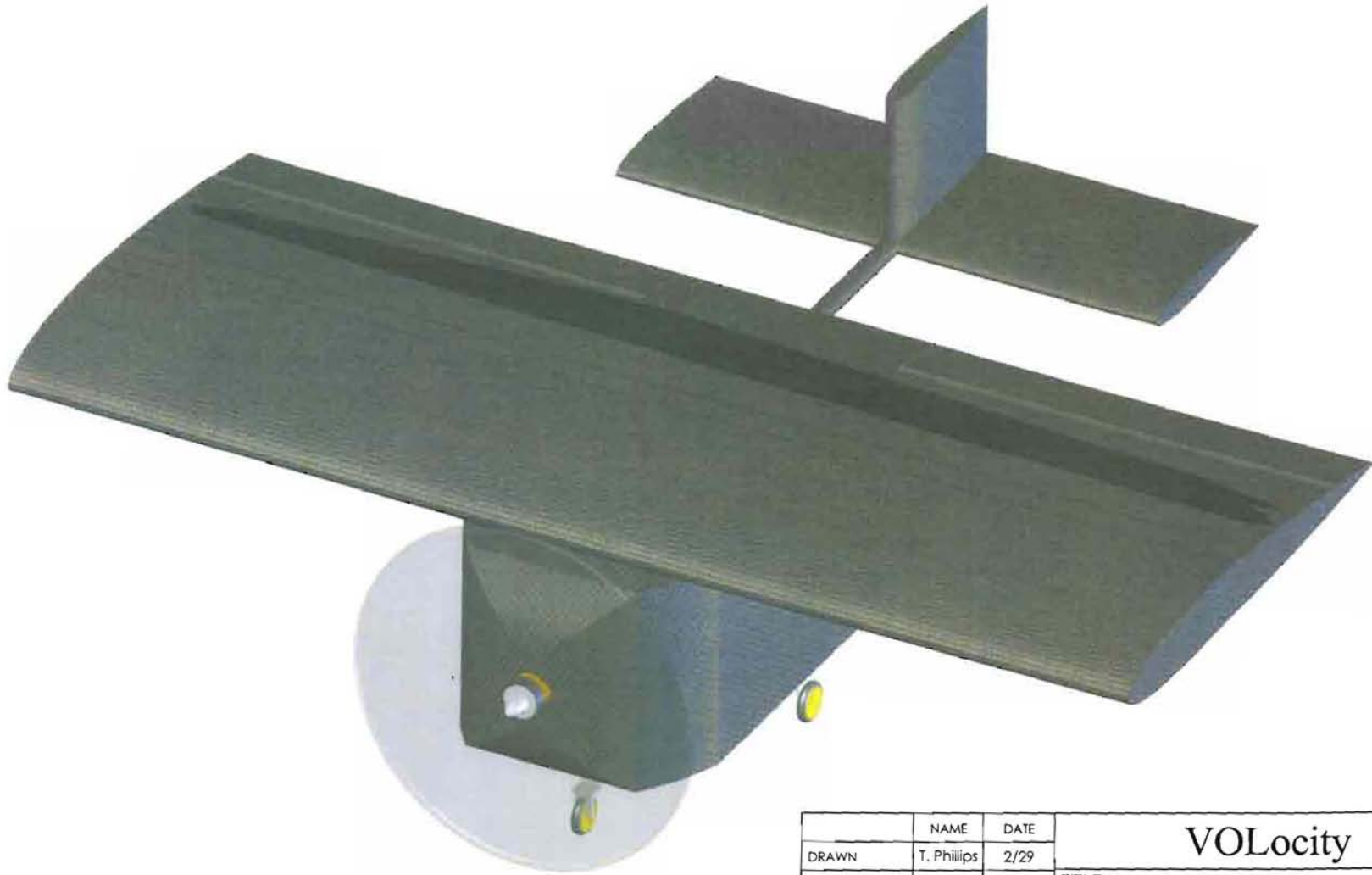
battery cells that would allow the motors to run as efficiently as possible yet minimizing the weight of the propulsion system.

**Table 5.3: MotoCalc Predicted Results**

Motor	Class	Estimated # of Motors Required	Predicted Thrust Output (oz)
<i>AXI 5330-F3A</i>	Large	1	203.6
<i>E-Flite Power 25</i>	Medium	2	60.6
<i>E-Flite Power 15</i>	Medium	2	55.4
<i>E-Flite Park 480</i>	Small	4	44.4
<i>Little Screammers</i>	Small	4	21.3

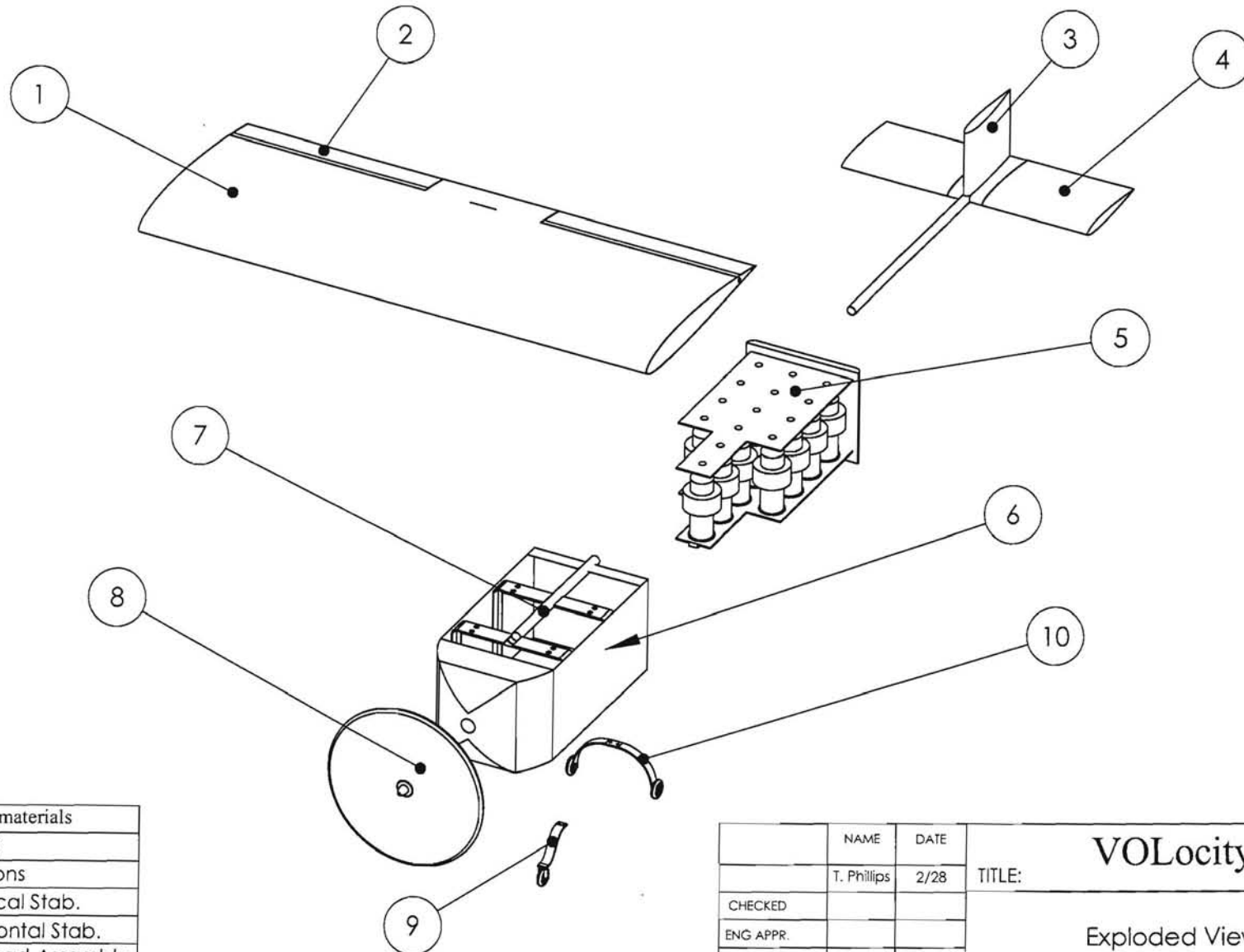
To test the reliability of the analysis and manufacturer specifications, a run of each motor will be done using a thrust stand.





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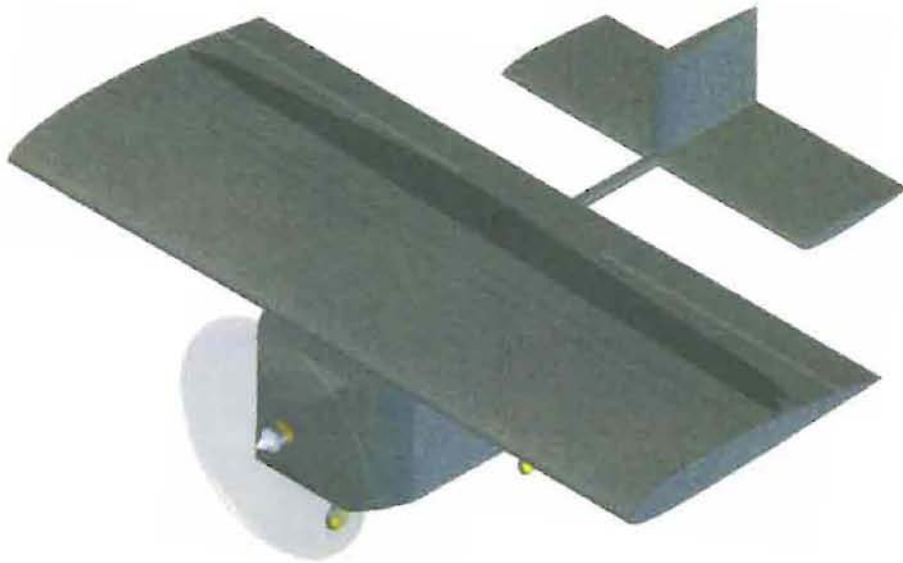
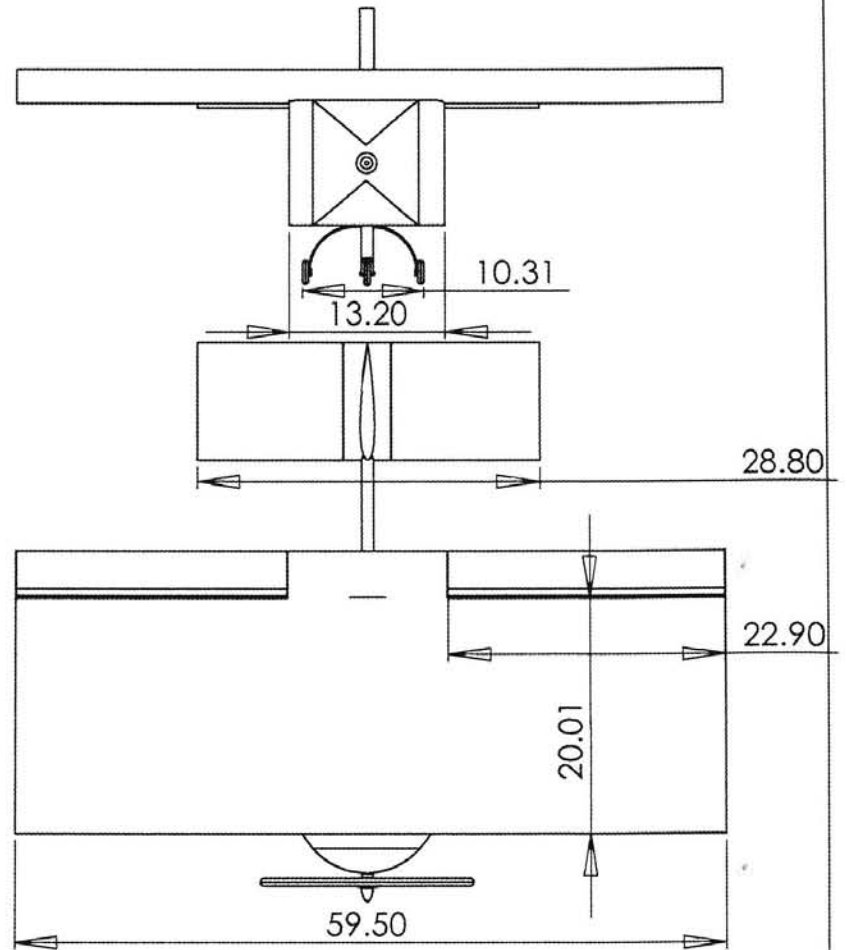
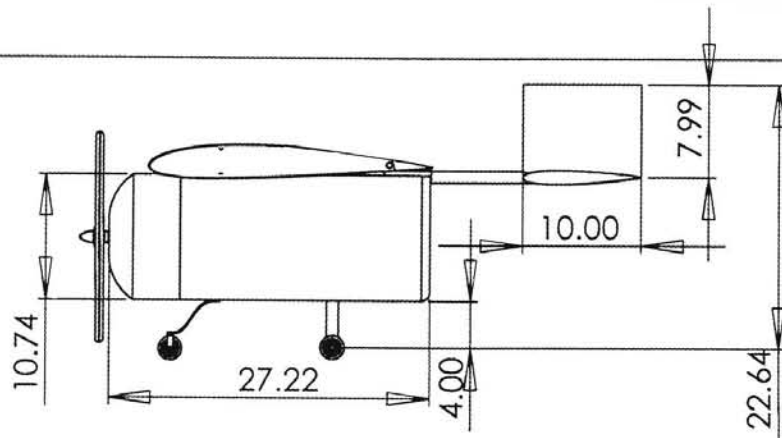
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Bill of materials	
1	Wing
2	Ailerons
3	Vertical Stab.
4	Horizontal Stab.
5	Payload Assembly
6	Fuselage
7	Boom Sheath
8	AXIS 5330-F3A
9	Front Landing Gear

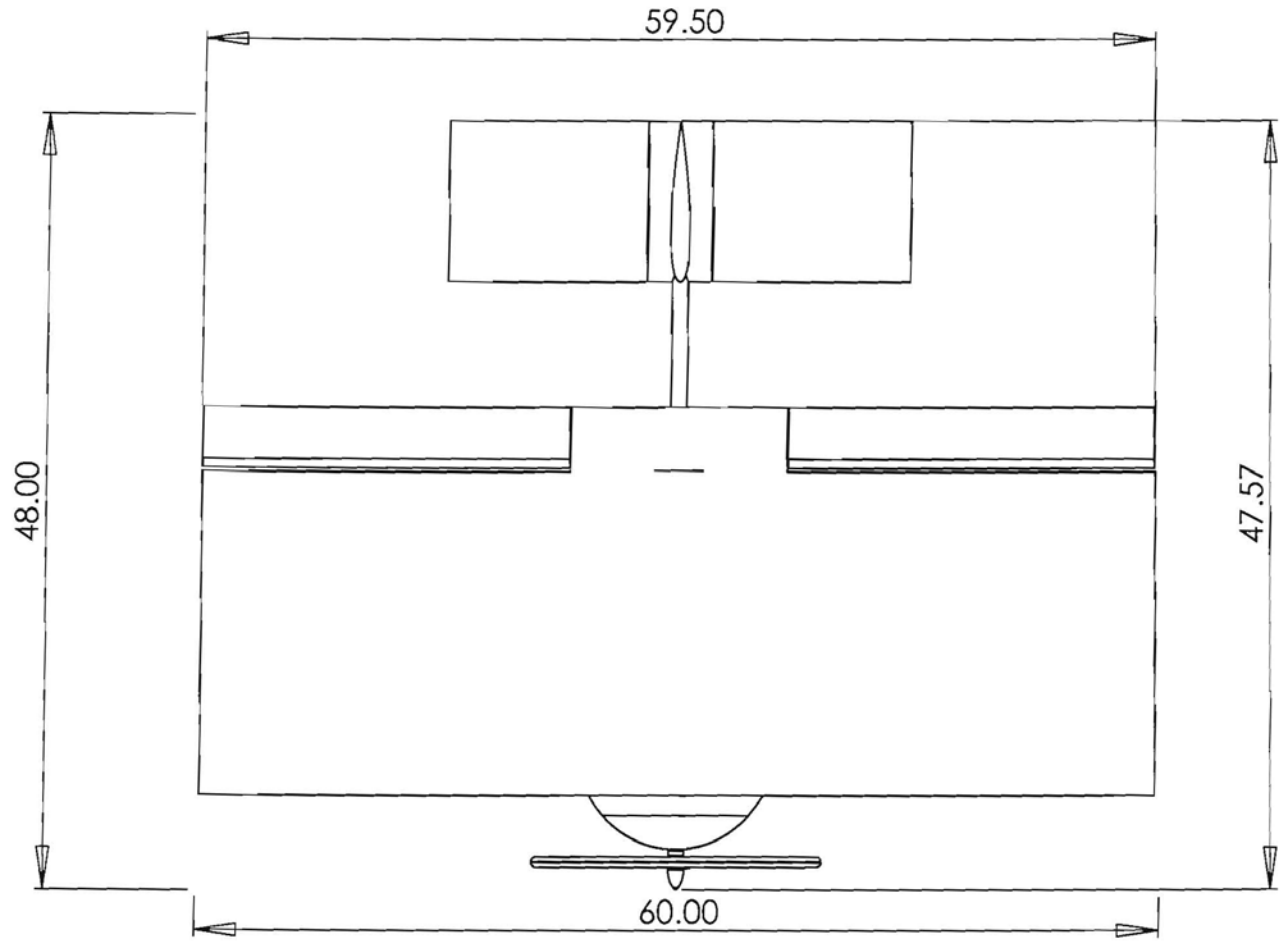
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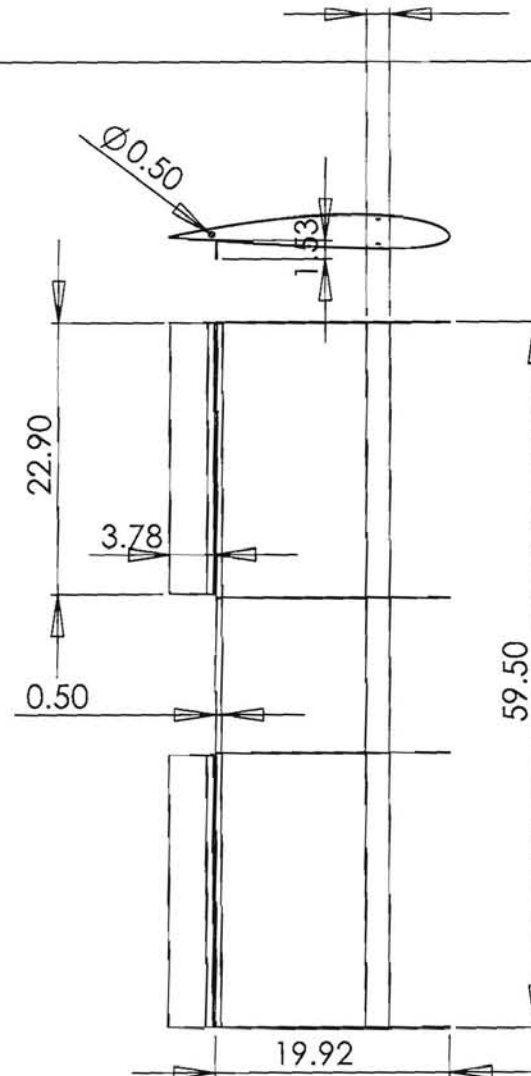
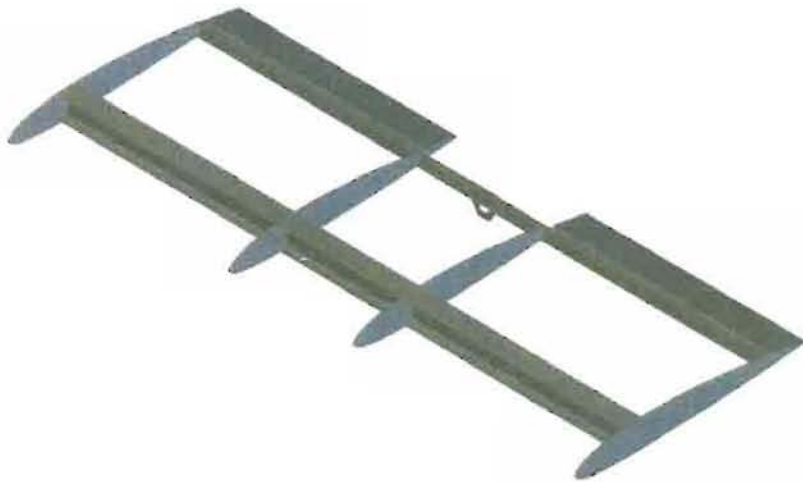
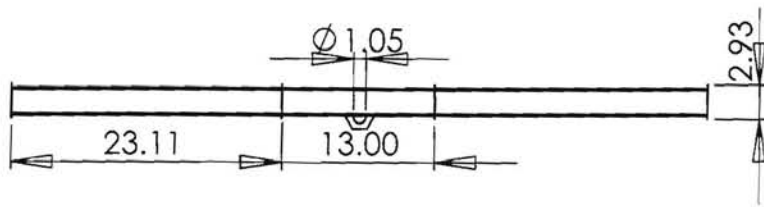
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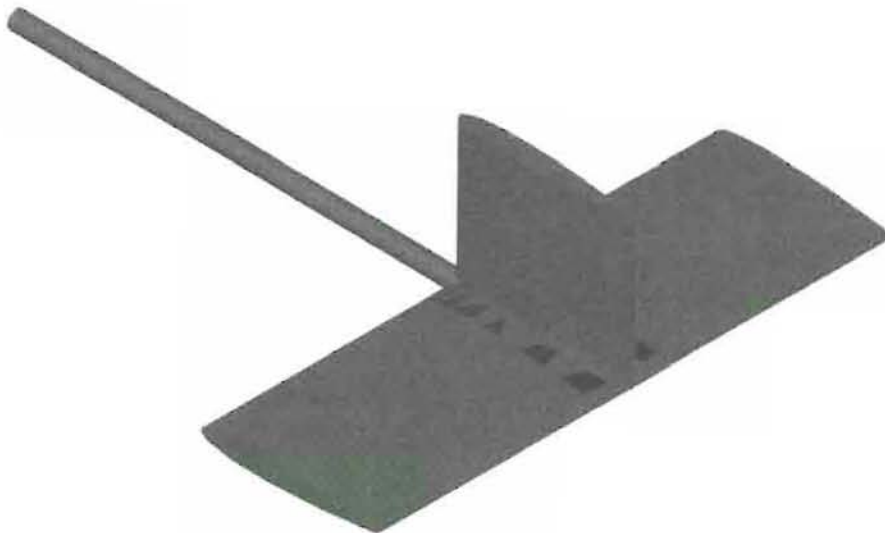
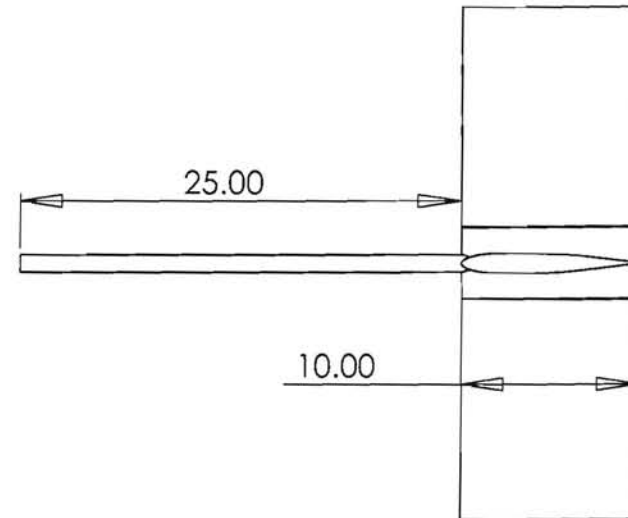
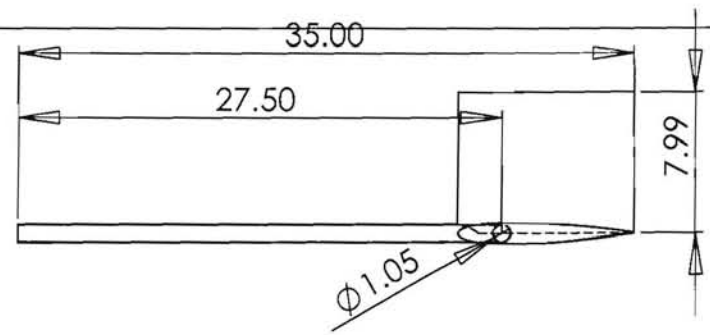
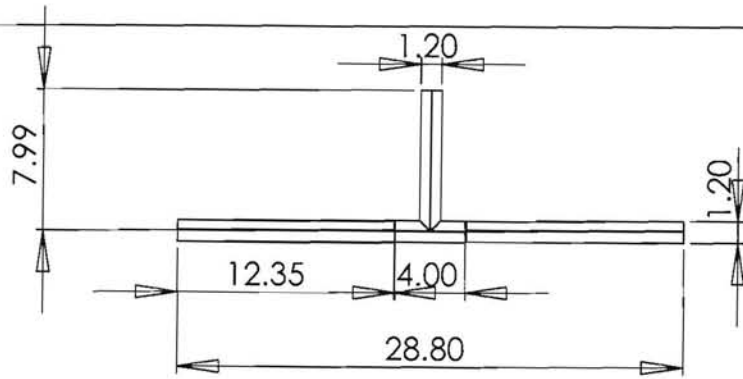
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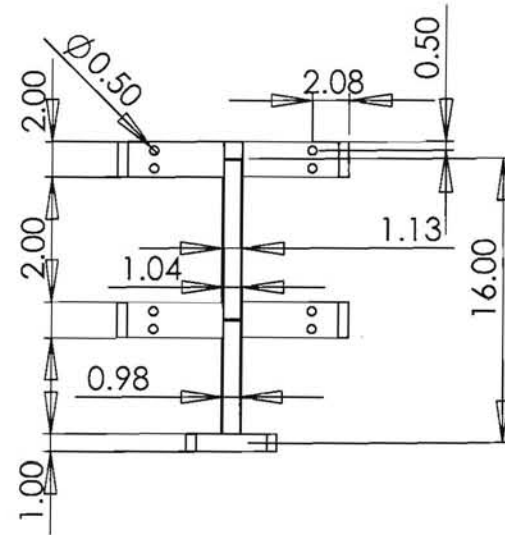
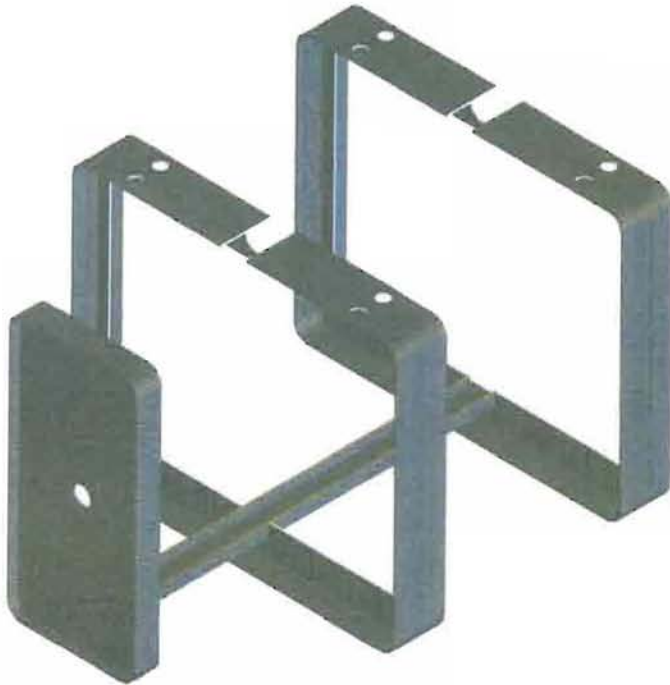
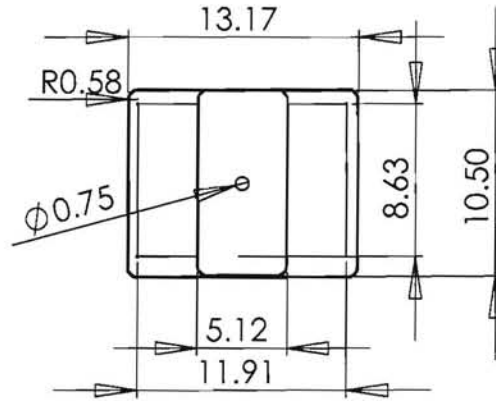
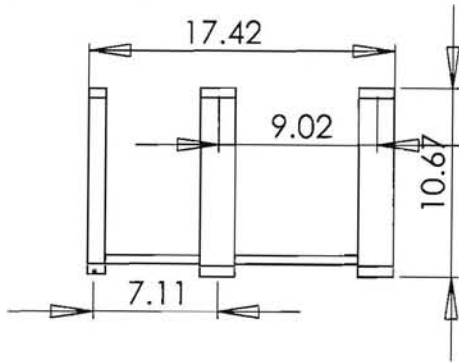
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 TOLERANCES:  
 FRACTIONAL  $\pm$   
 ANGULAR: MACH  $\pm$  BEND  $\pm$   
 TWO PLACE DECIMAL  $\pm$   
 THREE PLACE DECIMAL  $\pm$



		NAME	DATE	VOLocity		
DRAWN		T. Phillips	2/28			TITLE:
CHECKED				Fuselage frame		
ENG APPR.						
MFG APPR.						
Q.A.						
COMMENTS:				SIZE	DWG. NO.	REV
				A		
				SCALE:1:10	WEIGHT:	SHEET 7 OF 8

DIMENSIONS ARE IN INCHES  
 TOLERANCES:  
 FRACTIONAL ±  
 ANGULAR: MACH ± BEND ±  
 TWO PLACE DECIMAL ±  
 THREE PLACE DECIMAL ±



## 7.0 Manufacturing Plan

The airplane construction was broken up into three individual parts: fuselage, wing, and empennage. All the parts were designed with the ability to be taken apart for shipping and storage purposes and then assembled together. There were many things to consider in the manufacturing plan, including the material selection and construction methods.

### 7.1 *Material Selection*

The criteria for the materials included: strength, weight, ease of manufacturing, and price. After completing research on modern building materials suitable for use in model airplanes, it was found that the most common are balsa wood, plastic, alloys such as aluminum, and composites such as carbon fiber and fiberglass. All of these materials have specific attributes that make them suitable for specific applications, and these attributes had to be taken into consideration to make a decision.

- **Balsa wood** is found in most model aircraft today due to its inexpensive cost and large availability. Balsa wood is a very low density material that is frequently used to build the structural frame of the fuselage and wing. Unlike metals and some composites, balsa wood is relatively easy to shape as is desired. It is also very strong in tension, but does not perform as well in compression. When utilized by itself to build an aircraft structure, it needs to be built with a truss system for structural support. Such a construction is meticulous and is often time intensive.
- **Plastic** is used primarily for small components such as fasteners and control systems in model aircraft. It can be used for both internal and external airplane structures, but since it has a high density and manufacturing processes involving it are complicated, plastic is not a desired material of choice. However, in most balsa frame model airplanes, thin plastic films are used for the skin structure.
- **Alloys** are mainly utilized for structure on larger model and full scale aircraft. An alloy, such as aluminum, contains properties that allow it to be very light yet extremely strong in both torsion and bending. This material can be best utilized in high stress areas such as the wing spar and tail boom. However, alloys such as aluminum still have a relatively high density compared to non-metals, and if the

emphasis is on weight reduction, a high grade of alloy must be used. This requirement makes aluminum parts very expensive. Metals require specific tools to machine, which makes it very difficult to quickly change design or repair a damaged part.

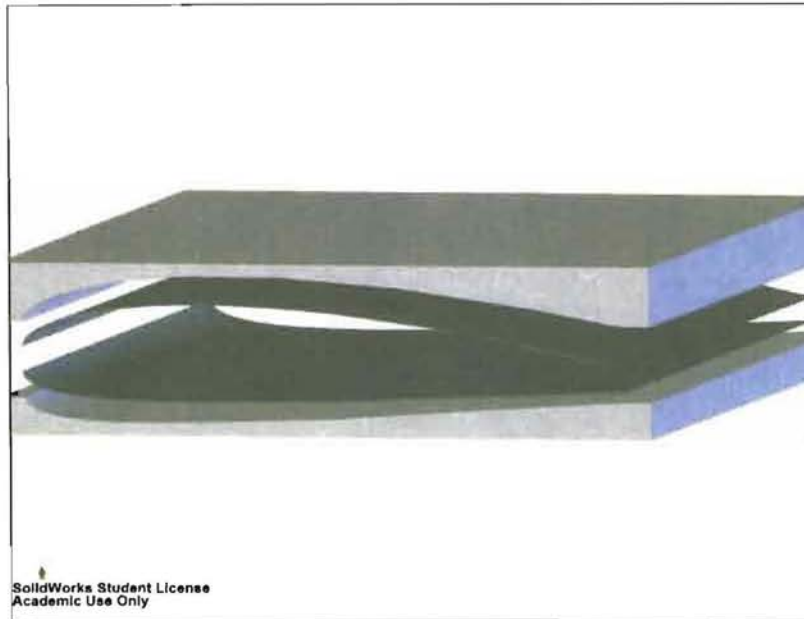
- **Composite** materials require time consuming planning and processes, yet can allow for considerable weight savings without compromising strength and safety. Composite materials are typically strong in one specific direction thus requiring additional analysis of the structure to plan for compensating the stress that develops in the direction counter to the composites strengths. These materials are typically strongest in the direction that the fiber strands are in tension. For this reason, composites are set up in layers and then a very strong resin is applied to bond the layers together. The most common types of composites are fiberglass and carbon fiber. The difference between the two types is in strength and weight. Carbon fiber can hold up to far more stresses than fiberglass. It is very important that no metal should touch the carbon fiber material so as to prevent radio interference.

## **7.2 Manufacturing Process**

The carbon fiber cloth (without epoxy) will be laid into a mold of each part required for building. The layers being placed will have specific orientation; this orientation will be determined by analyzing the structure. Once the layers have been placed into the mold, the epoxy will be added and the entire part will be vacuum bagged to rid the epoxy and fabric of any excess air which could weaken the material. Once the epoxy has set, the part can be sanded and is then ready for flight.

There were two different types of manufacturing processes that were used. The different types were referred to as Type I and Type II construction methods. Type I construction, shown in Figure 7.1, was used to make shell components such as the fuselage and wing skins. Type II construction, shown in Figure 7.2, was used to make the internal structure of the airplane that included beams and ribs.



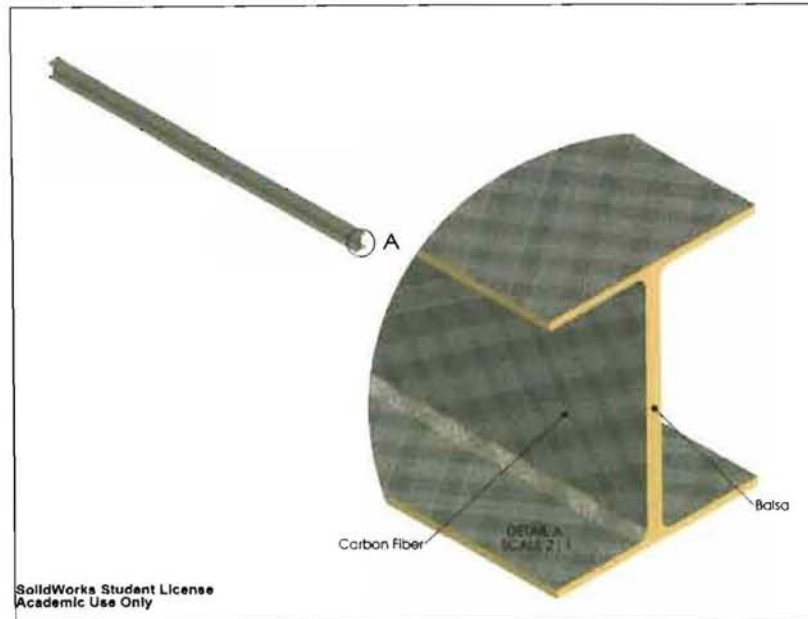


**Figure 7.1:** Shell Construction (Type I)

#### *7.2.1 Type I Construction Process*

In the Type I construction process, the shape of the airplane components was sculpted from foam blocks. These foam parts, referred to as “masters”, were used to make the plaster molds as shown in Figure 7.1. Only the “shell” components of the airplane structure needed these masters to form the shape of the mold. The molds were used to lay the carbon fiber cloth, which in turn will be soaked in a Polyvinyl Ester resin and left to cure in a vacuum bag system overnight.

The clam-shell technique was used for assembling the shells. The top and bottom sides of the wing were made separately and were glued together in the final assembly. The seams were filled and sanded to ensure a smooth surface.



**Figure 7.2:** Beam and Rib Construction (Type II)

### 7.2.2 Type II Construction Process

The Type II construction process was used to make the beams and ribs as shown in Figure 7.2. These were manufactured from molds, referred to as “tools”, manufactured from wood. The tools were designed to form the shape of the components and apply even pressure to the material as it cures to ensure reproducible results. The shape of the pieces was made using one-sixteenth inch thick balsa wood that was sandwiched with the carbon fiber material. The tools were applied to the outside surface and the assemblies were left to cure overnight in a vacuum bag system.

The vacuum bag system combined with the mold and tools ensured that any excess resin would seep away from the components. Doing so will produce a lightweight and reproducible part.

Tolerances were set for the final components produced so that different parts will interlock with each other. For all components, a sixteenth of an inch tolerance was set.

- **Fuselage** – The internal structure consist of three formers, which are similar to ribs, held together with dowel rods that run through the entire length of the fuselage. This was then covered with the carbon fiber skin.
- **Wing** – Four ribs make up the internal structure of the wing, which were attached to two spars that transfer load from the wings to the fuselage. The wing was attached to the fuselage using bolts that hold the spars to the formers in the fuselage.
- **Empennage** – This was built using the same process as the wing. It were attached to the fuselage with a tail boom.

**7.4 Manufacturing schedule**

The manufacturing process required the help of the entire team, both seniors and underclassmen. The team received advice from model aircraft enthusiasts who helped the group plan the most effective and efficient way of constructing the plane. Figure 7.3 details the manufacturing plans of the group.

Task	February				March					April		
	3	10	17	24	2	9	16	23	30	6	13	20
<b>Wing Construction</b>												
Wing template construction												
Creating master wings												
Mold design and construction												
Spar and rib tool assembly												
Wing Assembly												
<b>Fuselage Construction</b>												
Base Assembly												
Fuselage structure ring constr.												
Payload construction												
Assembly												
<b>Tail Construction</b>												
Tail template												
Creating master tail												
Mold design and construction												
Tail Assembly												
<b>Total Assembly</b>												
<b>Competition</b>												

**Figure 7.3:** Manufacturing plan and timeline

## **8.0 Testing Analysis**

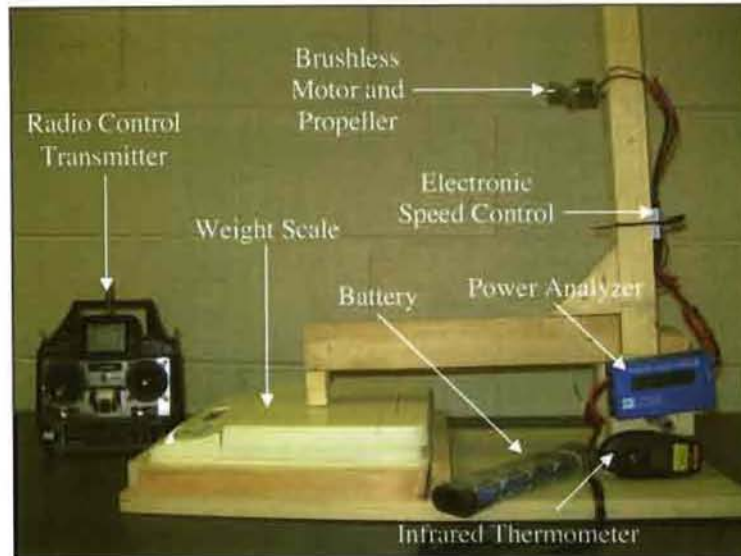
Before flying at the competition, there are several tests that need to be conducted on flight systems. Some of the testing involves flying the actual model through simulated courses and allowing the ground crew more time to practice loading the payloads. However, a key subsystem that needs testing before and after the actual airplane has been constructed is the propulsion system. Many of the analysis for the propulsion system are derived directly from these tests, and thus an extensive testing plan was created. Results from these tests were implemented in the final design of the team's airplane.

### **8.1 *Propulsion Testing***

The objective of the propulsion tests was to determine the best motor, propeller, and battery combination to achieve the optimum thrust, efficiency, and low system weight.

A thrust stand was designed and built to examine each of the motors and propeller combinations in an exposed environment. Both static and dynamic thrust output from the motor systems was measured. The exposed environment of the dynamic thrust analysis consisted of the surrounding air properties with the thrust stand mounted on top of an automobile. The test stand as shown on Figure 8.1 consists of a motor mount connected to a moment arm that directs the horizontal force from the motor system to a vertical force that presses on a digital weight scale. The following measurements were taken during each test run: thrust using the weight scale, motor current draw using an ammeter, motor voltage draw using a voltmeter, propeller revolutions per minute (RPM) using a tachometer, temperatures of the motors and batteries, and incoming air speed using a wind speed indicator. The data was then used to evaluate the motor and propeller efficiencies, power draw of the motor system, and maximum thrust of the various system combinations.





**Figure 8.1:** Thrust Stand Setup

The first step in the motor test analysis process was the calibration of the thrust stand. To test the accuracy of the commercially purchased scale, precision weights were used and any bias measurement errors found will be corrected during the analysis process. In order to accurately measure the thrust provided at certain speeds, the drag force of the motor and thrust stand must be found at those speeds. This will be done by placing the motor without the propeller on the thrust stand and running the platform up to the necessary wind speed. Because of the inaccuracies of current automobile speed indicators and the variable wind around the platform body, the airspeed indicator mounted near the thrust stand will be used to measure the air speed “seen” by the thrust stand. The drag force produced by the thrust stand, including motor, will be added to the thrust found by the stand when ran with a propeller.

## 8.2 Propulsion Test Results

Table 8.1 shows the brushless motors that were tested and analyzed. This data will be used to determine the best motor and battery configuration in order to increase efficiency thus reducing battery size and overall system weight. The overall airplane weight below includes the motor system and batteries along with the airplane including payload with an assumed weight of 12 pounds. The number of motors required was found by determining how many motors were needed to achieve a thrust of 7.5 pounds or



more, which is a thrust-to-weight ratio above 0.50. This minimum thrust is set based on the necessary amount of thrust required for the plane to takeoff in 75 feet.

**Table 8.1:** Brushless Motors Test Results

Motors	# of Motors Required	Max Thrust per motor (oz)	Motor System Weight (oz)	Battery Weight (oz)	Overall Airplane Weight (oz)	Thrust-to-Weight Ratio
AXI 5330-F3A	1	240	24	48	264	0.91
E-Flite Power 25	2	88	15	28	235	0.75
E-Flite Power 15	2	60	12	24	228	0.53
E-Flite Park 480	4	36	16	24	232	0.62
Little Screammers	5	24	10	24	226	0.53