SAE Aero Design
Flagstaff, AZ 86001
May 2, 2009

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Dr. John Tester:

This cover letter serves as notification that a final design solution has been developed by Team Ninja Turtles for the 2009 SAE Aero Competition. On March 6-8, 2009 the team successfully competed in Van Nuys, California. Ninja Turtles finished in 9th place out of 31 competing teams. Ten points were lost during technical inspection due to unreported changes in nominal dimensioning of the aircraft. The team was awarded 41 points on the design report submitted in January, as well as 41.9 points on the oral presentation upon arriving in Van Nuys. During flight, the airplane carried a total of 19.8 lb of payload producing a gross weight of 30.9 lb. This design performed to our analysis with a safety factor of 2 and exceeded our predicted results when safety factors were removed. We hope you enjoy this summary of hours of analysis, SOTA research, and a once in a lifetime experience which we are glad to share with you.

SAE Aero Design

Final Document

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ABSTRACT

NAU's Society of Automotive Engineers (SAE) chapter has designed and analyzed a remote control (RC) airplane for an international heavy lift competition. Some of the design specifications supplied in late September 2008 include, but are not limited to, a fixed dimensional constraint of 175 inches as the sum of length, width, and height of the aircraft and the use of a standardized OS 0.61 FX engine.

An Eppler 423 airfoil was chosen for the main wing due to its high lift capability, as well as ease of manufacturing. To account for a deficit lift coefficient in comparison with the Selig 1223 airfoil (S1223), selected by many other competing teams, a gurney flap was implemented. Winglets comprised of PSU-90-125 airfoils were used to reduce 3D drag effects. Both airfoils on the empennage of the aircraft were NACA 0012 style airfoils.

No carbon fiber or fiber glass was used on any component of the design due to other constraints given by SAE. The fuselage consisted of a bulkhead/stringer configuration constructed from balsa wood. An aluminum honeycomb backbone was implemented as the central structural component. The crafts configuration allowed a maximum predicted payload of approximately 12 pounds based off of lift/drag calculations.

NAU competed in the Aero Design West Competition March 6 – 8, 2009. Three successful flights were conducted during competition. The plane carried a maximum payload of 19.8 pounds which placed the team in the top ten out of 31 teams competing.

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Introduction

Background

Since the early 1900's many automobile manufacturers in the United States have been meeting in groups to express different ideas. One of these groups formed what we know today as the Society of Automotive Engineers, or SAE. In the year 1905, SAE membership tallied 30 engineers; this was the initial spark which started a bonfire. By 1916 SAE had grown to approximately 1800 members. Over the course of this history, many design competitions were developed to attract new engineers to various fields of automotive engineering. One such competition is SAE Aero Design, held annually at various locations throughout the world. This competition consists of aeronautical design, construction and competition of heavy-lift remote control (RC) aircraft. This year, the SAE Aero West competition was held in Van Nuys, California.

From Northern Arizona University, team Ninja Turtles was one of the groups attending. Rules and specifications for this competition are varied annually so that each successive year may inspire new and innovative designs from the competing students. These rules include payload requirements, craft dimensions, fuel and engine type, and landing and takeoff distance.

Problem Definition

Team Ninja Turtles must design and manufacture a heavy-lift aircraft for competition March 6-8, 2009 while adhering to design specifications given by the Society of Automotive Engineers and team client, Dr. John Tester.

Requirements and Specifications

Needs and Constraints

The following is a list of general needs, constraints, and refined specifications which Team Ninja Turtles has compiled for the governing of decisions made throughout the design process. The dimension specifications listed below have been set forth by SAE and are therefore general requirements for this project.

R1. The aircraft must successfully complete one 360 degree circuit of the field
R2. The aircraft must take off within 200 ft.
R3. The aircraft must land within 400 ft.
R4. The aircraft must be able to maneuver in a crosswind up to 5mph
R5. No lighter-than-air or rotary wing aircraft may compete
R6. The propeller must not be metal
R7. Carbon fiber and fiberglass are prohibited on all parts of the aircraft with exception of the propeller
R8. No fuel pump is permitted
R9. The use a gear boxes is prohibited unless the gear ratio between the engine and the propeller remains at 1:1
R10. The engine must use fuel supplied by the competition
R11. No gyroscopic stabilization is permitted
R12. The aircraft must be able to fit into a large enclosed travel trailer

R13. All tools for set up and take down of the aircraft must be able to travel with the team to the competition in the large travel trailer

R14. Must raise or find funding for product and trip

SAE Requirements

The objective of Regular Class is to design an aircraft that can lift as much weight as possible while observing the available power and aircraft dimensional requirements. Accurately predicting the lifting capacity of the aircraft is an important part of the exercise as prediction bonus points often determine the difference in placement between competing teams.

Aircraft Requirements and Restrictions

R15. *Aircraft Identification*

Team number as assigned by SAE must be visible on both the top and bottom of the wing, and on both sides of the vertical stabilizer or other vertical surface in 4-inch numbers. The University name must be clearly displayed on the wings or fuselage. The University initials may be substituted in lieu of the University name provided the initials are unique and recognizable. The assigned aircraft numbers appear next to the school name on the "Registered Teams" page of the SAE Aero Design section of the Collegiate Design Series website[1].

R16. *Name and Address*

Regular Class aircraft must be identified with the school name and address either on the outside or the inside of the aircraft.

Aircraft System Requirements

R17. *Engine Requirements*

Regular Class aircraft must be powered by a single, unmodified O.S. 0.61FX engine with E-4010 muffler. No muffler extensions or headers that fit between the engine cylinder and the muffler may be used. Muffler baffles must be installed, and must be unmodified from the factory installed configuration. No fuel pumps are allowed.

R18. *Fuel Tank*

Fuel tanks must be accessible to determine contents during inspections. Tanks may be pressurized by a stock fitting on the engine muffler only.

Payload Requirements

R19. *Payload and Payload Support*

The payload must consist of a support assembly and payload plates. All payloads carried for score must be carried within the cargo bay. The support assembly must be constructed so as to retain the weights as a homogeneous mass. There is no required configuration for the payload plates. The design of the support assembly will depend upon the configuration of the payload plates. The payload must be secured to the airframe to ensure the payload will not shift or come loose in flight. The total payload consists of the plates plus the support assembly. It is the responsibility of each team to provide its own payload plates.

R20. *Payload Distribution*

The payload cannot contribute to the structural integrity of the airframe and must be secured to the airframe within the cargo bay so as to avoid shifting while in flight.

General Requirements

R21. *Radios*

All radio transmitters must meet the FCC and Academy of Model Aeronautics 1991 standard for frequencies assigned to model aircraft.

R22. *In-Flight Battery Packs*

Regular Class aircraft must use a battery pack with no less than five hundred (500) mAh capacity.

R23. *Spinners or Safety Nuts Required*

All aircraft must utilize either a spinner or a rounded safety nut to fasten the propeller.

R24. *Control Surface Play*

Aircraft control surfaces must not feature excessive play.

R25. *Servo Sizing*

Analysis and/or testing must be described in the Design Report that demonstrates the servos are adequately sized to handle the expected aerodynamic loads during flight.

R26. *Operability*

The aircraft must be operable using standard RC controls.

R27. *Manufacturability*

The aircraft must be able to be constructed using facilities, capabilities and materials available to the NAU design team.

Specifications

After conducting state of the art review and thoroughly accounting for the rules and regulations stated by SAE for the 2009 competition, team Ninja Turtles has compiled a set of design specifications.

S1. L + W + H less than or equal to 175 inches
S2. Gross Weight less than or equal to 55 lbs
S3. Payload bay must be 5” x 5” x 10” and hold payload plates securely
S4. A standard 60 in-oz servo will be used for each of the control surfaces and throttle
S5. The aircraft must be able to take off on a runway not more than 90 ft wide
S6. The aircraft must take off within 200 ft with payload on board
S7. The aircraft must land within 400 ft with payload on board
S8. The aircraft must be able to fit into a travel sized van
S9. Dimensional constraints must match between Three Plan View and prototype.

a. Wheels thirty inches apart
b. Seven foot wing span
c. Twelve inch cord

d. Twenty-four inch horizontal stabilizer span

State of the Art (SOTA) Review

The objective of this project was to design and build an aircraft that carries a given payload. Each member of the team was assigned a specific portion of the aircraft for which to design. There are many aspects to consider which have a direct influence on how a plane flies and handles. For this reason, a physical decomposition was created based upon Ullman's method[2]. This decomposition can be found in Figure 5 below.

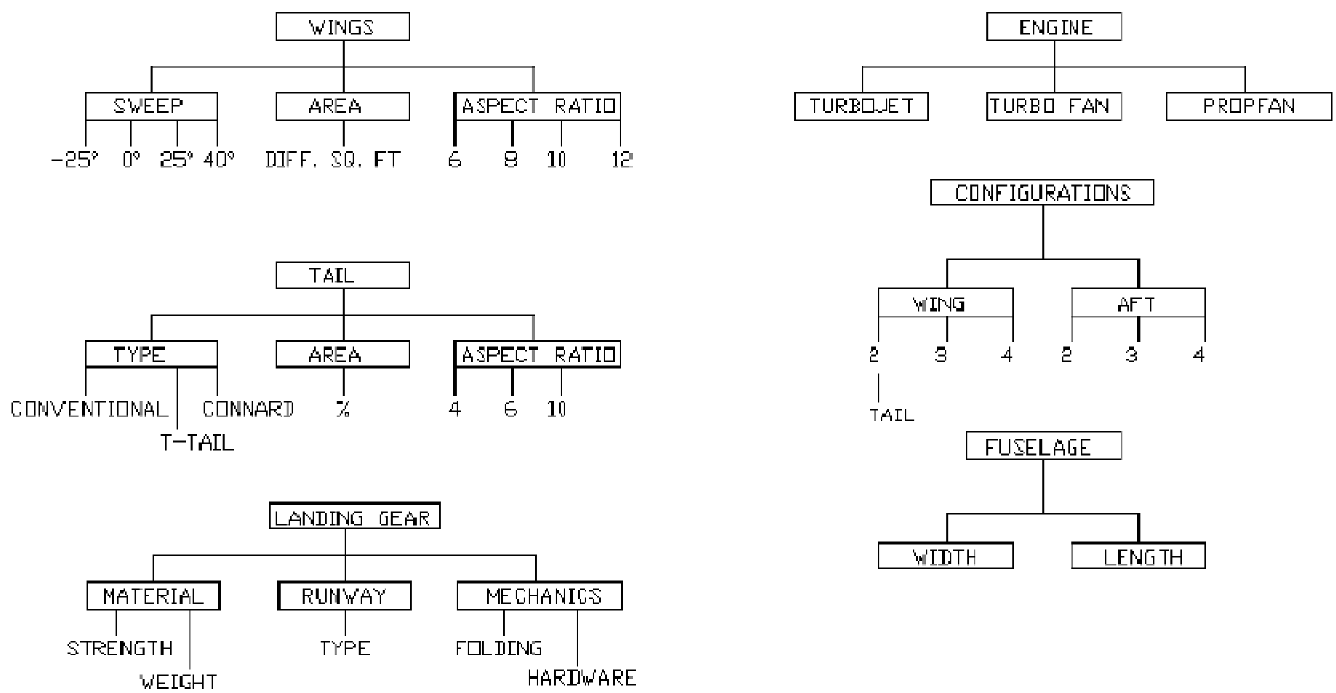

Figure 5: Physical Decomposition of Common Aircraft

The team developed a research strategy based on the physical decomposition in Figure 5. Each of the main categories above was independently researched so as to optimize team productivity. An overview of said research follows.

Wings

One of the major components in Figure 5 is the Wing. First, information on the wings was gathered. Sources of information include journal articles, websites, academic advisement, and various books. Many different wing configurations may be considered when designing an aircraft. These include, but are not limited to, the sweep angle[20], the location of wings along the fuselage[5], and angle of incidence[21] created by the airfoil. Figure 1 is an example of the sweep angle created by the wings of an aircraft.

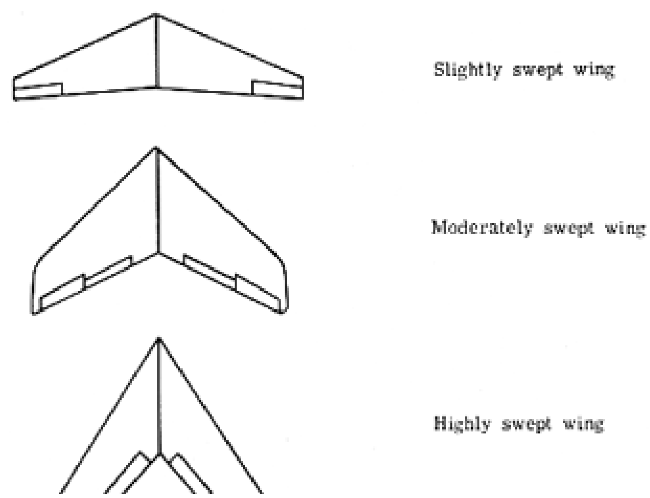

Figure 1: Various Sweep Angles[20]

The sweep angle of a wing is said to increase stability as well as maneuverability of the aircraft, but as the sweep angle increases, the lift coefficient of the wing decreases[3]. This is due to decrease in wing span, which ultimately decreases the aspect ratio, both of which adversely affect the lift coefficient.

Another aspect of wing design is something called the angle of incidence. This can be seen in Figure 2 and is not to be confused with the angle of attack.

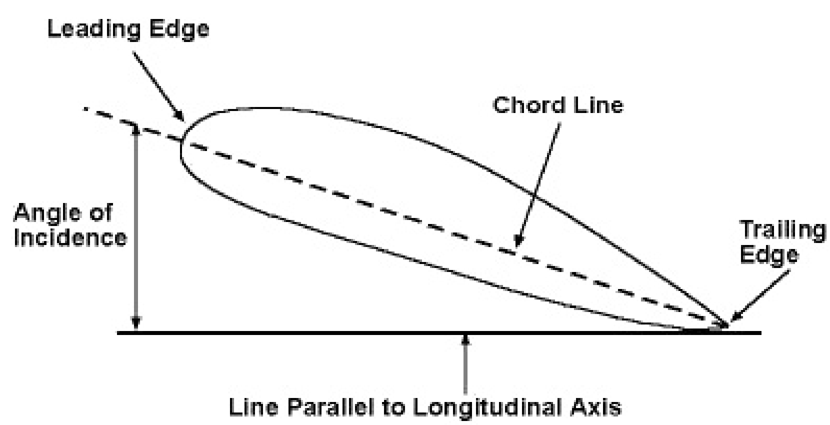

Figure 2: Angle of Incidence of an Airfoil[21]

This angle is described as the angle that the airfoil, (wing) makes with the longitudinal axis of the airplane. This induces an initial angle of attack, thus creating a larger initial lift coefficient for the wing.

Another wing configuration that was found describes the positioning of the wings along the fuselage. This positioning allows for different maneuverability and stability coefficients. Aircraft whose wings attach near the top of the fuselage travel slowly, but are more stable[12]. This is because the payload is below the wings and the airplane is not top heavy. If the wings are attached to the middle of the airplane, control may be an issue, but the craft is more maneuverable. With wings connected to the bottom of the fuselage, the airplane has better rolling capabilities; however it will be top heavy.

Lift enhancing devices specific for low Reynolds number flight, (slow moving aircraft), were also found during state of the art review. One such device is named a Gurney Flap[7]. This is a small orthogonal flap near the trailing edge of the wing approximately 1-2% the cord length. This flap increases the wings lift coefficient through shifting the point of flow separation which naturally occurs at the trailing edge of the wing back and off the wing. Since the competition is based on lifting the maximum load, this is an option which the team chose to implement. While the Gurney Flap increases the lift coefficient, an undesirable side effect is that the stall angle of the wing decreases. This is similar to what happens when the ailerons are thrown into the down position. An example of how Gurney Flaps increase lift may be seen in Figure 3.

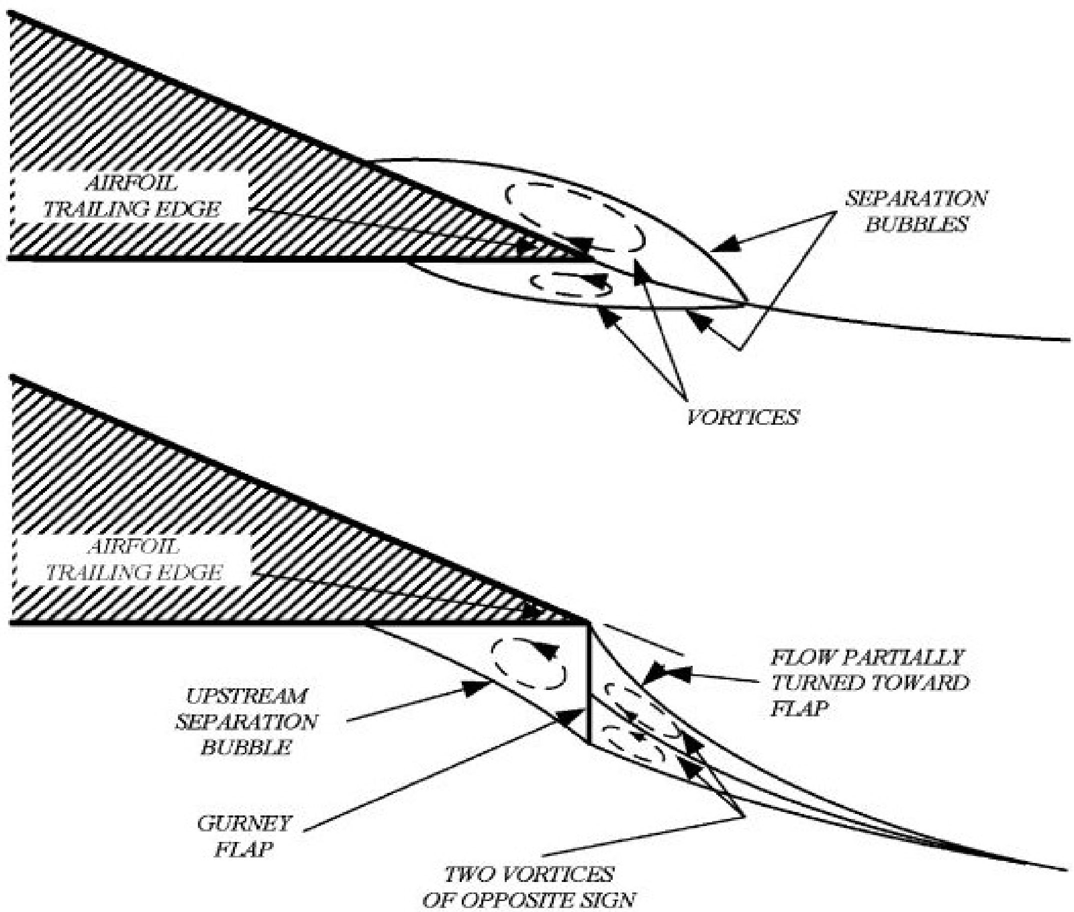

Figure 3: Flow with a Gurney Flap [7]

Not only does this flap increase the lift coefficient, it also reduces the drag coefficient according to many calculations conducted from various articles the group has obtained. Please see the bibliography for cited references associated with Gurney Flap technology.

An additional lift enhancing configuration which the team considered implements something known as tubercles. This idea was taken from analysis of fluid flow past the main fins of a humpback whale. These fins utilize rounded sinusoidal-like leading edges which ultimately increase the lift coefficient of the wing. Like the gurney flap, this change in the leading edge lowers the stall angle. These tubercles behave similarly to flow directors and off the same idea as a Venturi tube[32]. The sinusoidal configuration of the "wings" increases the velocity of the flow over the airfoil, which in turn reduces the pressure on the top surface.

Winglets

During SOTA review for the main wing of the craft, it was discovered that winglets would greatly enhance the lift and maneuvering characteristics of the airplane. Winglets can be used to prevent wingtip vortices created by the pressure differential between the upper and lower surfaces of the wing. Most winglets consist of a simple wing plate attached to the end of the airfoil; however it was found that PSU-90-125WL winglets were optimal for reducing such effects. Typically, accurate winglet analysis is conducted in a wind tunnel. The benefit of using winglets may also be found using empirical data as well as analytical relations which describe the induced angle of attack and induced drag.

Fuselage

State of the art review for a fuselage was conducted as well. The finesse ratio[16] of the fuselage describes how aerodynamic (efficient) the fuselage is. This ratio is the length of the fuselage divided by the width (diameter) of the fuselage. A finesse ratio of 3 is desired for optimal aerodynamic performance[12]. With this in mind, Figure 4 lists various fuselage design ideas.

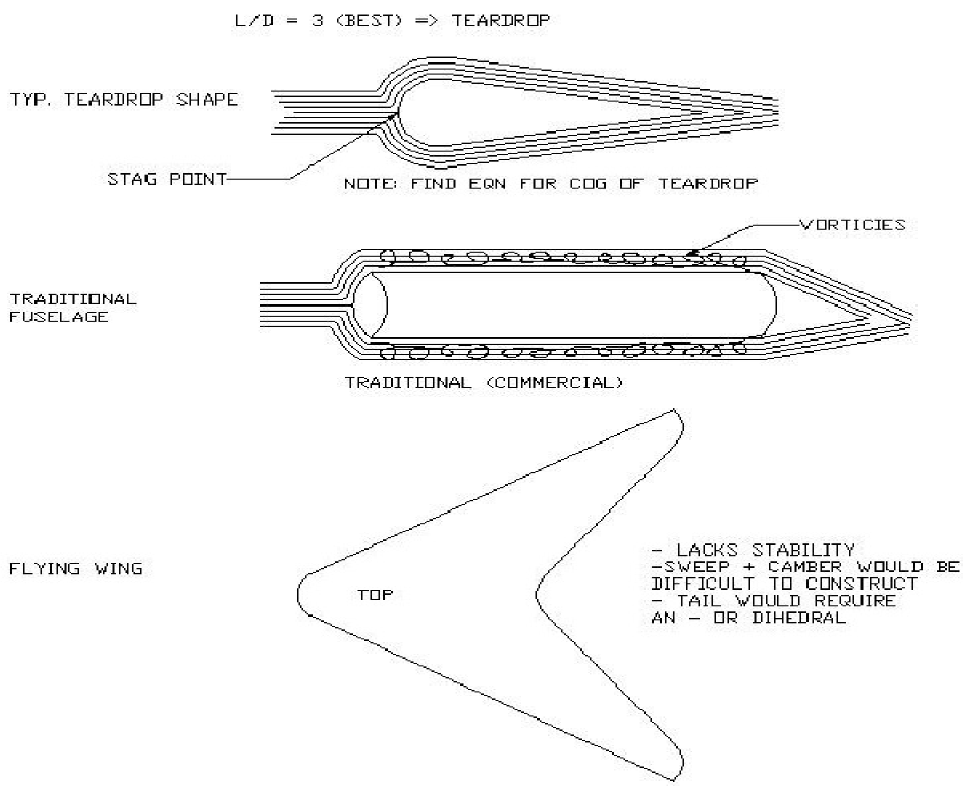

Figure 4: Fuselage Design Ideas

Three main configurations were conceptualized by the team, corresponding to those depicted in Figure 4. These include a teardrop shape, a traditional cylinder, and a flying wing design. The teardrop shape would be the best design for following the suggestion that the length-to-diameter finesse ratio be three. This would also produce laminar flow around the body[10]. The traditional design often causes turbulence around the skin of the cylinder, which makes it less efficient than the teardrop design. The flying wing design is a possibility, but little is known on how it would react to low Reynolds numbers. The flying wing would be the most efficient design for storage volume versus lifting surface area.

In order to achieve an easily constructible, yet robust fuselage, a bulkhead-stringer configuration may be used. This construction method requires that bulkheads be placed along the longitudinal axis of the craft while stringers connect the bulkheads along various diameters at longitudinal coordinates. This construction method allows the fuselage to take on a more organic and aerodynamic form.

Propellers

Various articles were found on propeller performance vs. engine size[11]. Due to the fact that the engine is already specified for this competition, choosing a propeller that will offer the maximum thrust is very important. The more thrust which can be harnessed from the engine, the more the airplane will be able to lift. For the specified engine, the O.S. 0.61FX with E-4010 muffler, propeller sizes range from 11" X 6" to 12" X 8" based on manufacturer recommendation. The propeller for this competition may be fabricated out of wood, carbon fiber, or regular plastics[1].

After a survey of the choices made by previous aero design teams, a decision was made to conduct testing on larger propellers than were recommended by the manufacturer. This testing is justified by the fact that the nature of our competition is different from traditional RC aircraft design, which may not require slow flight, heavy-lift characteristics. A description of the testing can be seen in the modeling and analysis section of this document.

Center of Gravity

The center of gravity (CG) is an important aspect of airplane design pertaining to the longitudinal stability of the aircraft[26]. The airfoil becomes more stable as CG shifts forward however the vertical maneuverability is adversely affected by this shift. This is caused by an increase in the moment needed to move the airfoil from its stable position. Ideally, the center of gravity is located between ¼ and ⅓ of the chord length.

Design Decisions

Component Selection

A summary of team decisions relating to the selected components discussed above has been developed based off of analytical data found in sections 6 and 7 of this document. During the analysis, all restrictions, specifications, and requirements were considered.

1. Rear Stabilizers

The NACA 0012 airfoil was used for the vertical and horizontal stabilizers. A conventional "T" configuration was chosen in ordinance of R26. The horizontal stabilizer was installed with an angle of incidence of six degrees to counter moments caused by the main wing and weight of the craft.

2. Landing Gear

The team decided to implement a forward-leaning single aluminum bar for the main landing gear of the aircraft. The bar was bent and angled such that the forces associated with landing and takeoff would be transmitted through a centralized point. A reinforcement gusset was used to maintain the approximate 45° angle which each transverse bar makes with the horizontal.

A tail gear was implemented in our design in order to take maximum advantage of the angle of attack during takeoff. This tail dragging configuration allowed for the majority of the gross aircraft weight to be concentrated through the two main front wheels. This decision moves away from the three-gear tricycle configuration which is common in standard RC aircraft. The rear "tail dragging" wheel was incorporated into the airplane maneuverability system using a rigid linkage which connects to the bottom of the rudder, allowing the wheel to be turned at the same time as the rudder. This also saved the weight of incorporating an additional servo. An example of this setup may be found in Appendix A.

3. Servos

For benefits such as static balance and direct control transfer, Team Ninja Turtles chose to use remotely located servos to interact with the ailerons, elevator, rudder, and throttle. This implies that the craft will have five servos in various parts of the configuration. Servo sizing guides indicate that two 60 in-oz servos will be required for aileron control to the main wing. These servos were also used in other locations as well. Appendix B contains methods for determining servo sizes.

4. Fuselage

The fuselage was four and one half feet in length with a blended boom. This was originally designed at 5 feet in length, however an error in manufacturing lead to the production of a shorter fuselage than was designed. This design alteration did not result in a problem due to the angle of incidence built into the horizontal stabilizer discussed in Section 1 of Component Selection. The team attempted to adhere to the teardrop design using a bulkhead-stringer configuration. The payload assembly was attached to an aluminum honeycomb backbone, as were the landing gear and the wing. This allowed most of the significant dynamic forces to be directed through the backbone rather than through the fuselage. This design allowed the fuselage to be designed and manufactured with less material. The payload carriage was designed to be completely modular and in no way enhanced the structural integrity of the airframe. The payload weights were inserted from underneath the fuselage and the fuel tank was accessed from the top. The batteries were located in the boom of the fuselage during initial testing, however during redesign, the fuel, batteries, and receiver were relocated to the nose of the craft to shift the CG forward.

Originally, the CG was designed further aft than the standard window of recommendation, at approximately ½ chord length. This created problems during prototype testing. After redesign, the center of gravity was shifted forward to approximately ⅓ the chord length. SolidWorks assembly files were used to calculate the center of gravity as seen in section 7.

5. Engine

The engine, as specified by SAE, was an OS 0.61FX engine. The engine weighed 24.75 oz and was capable of producing 1.9hp at 16000 rpm. Its operating range was from 2000 rpm to 17000 rpm.

6. Propeller

An aromatic polymer composite (APC) propeller with a diameter of 14 inches and a pitch of 4 was selected based on thrust calculations detailed in Section 6.

Wing Planform Design

Due to specification S1, the overall dimensions were decided early in the design process. The wingspan was 85” with a tolerance of +/- 0.5”. The wingspan is the measurement from tip to tip of each winglet. The cord length was chosen to be 1 foot in length. Maximizing the span leads to a more efficient lifting surface and aspect ratio as discussed in Airfoil Selection.

Airfoil Selection

Airfoil selection for the main wings was based on the need for high-lift, while still residing in the low Reynolds number (Re) regime. For this reason, Dr. Selig’s S1223 high-lift airfoil and the Eppler 423 were considered. After much consideration, the Eppler 423 was chosen due to requirement R26 and the time constraints given. According to empirical data from the Selig Database[28], the S1223 airfoil has a larger lift coefficient than the Eppler 423 by 0.2 near Re = 200,000 at zero angle of attack. Despite this minor setback, the Eppler 423 was chosen for the purpose of manufacturability. The Selig 1223 would be difficult to manufacture with balsa while maintaining appropriate tolerances due to its extremely thin trailing edge. The team chose to manufacture the wing out of balsa wood, rather than foam and glass/epoxy for two reasons: The inherent strength associated with a balsa wing was a desirable design attribute, and also, the team wanted to perform a large part of the manufacturing process. In order to amend the deficit in lift coefficient between the Eppler 423 (E423) and Selig 1223 airfoils, a gurney flap was implemented. On average, a properly-implemented gurney flap raises the lift coefficient approximately 0.2[7] for low Re numbers. The suggested 0.02c[7] (2% chord) length was used for the gurney flap.

The airfoil selection for the winglets was based off the knowledge of how winglets, not *wing plates*, work. In order to have a beneficial winglet, the wingtips must have an appropriate camber[31]. Accordingly, the team chose to use the PSU-90-125 airfoil from which to construct the winglets. Not only will the winglets offer some lift, but they will maximize the reduction of three dimensional drag effects (discussed later).

Taper ratio

The taper ratio is the slope of the wings from root to tip. Normally wing tapers are used in order to reduce 3D drag effects, such as wingtip vortices and skin friction. These effects are also reduced through the implementation of winglets; therefore a wing taper was not included in this design. This adheres to requirement R26 and also increases the lifting surface available with the constraints given.

Dihedral

The dihedral of an aircraft is the angle the wings make with a horizontal datum. The dihedral increases stability and rolling characteristics however it also reduces the crafts maneuverability.   A three degree dihedral has been selected based on standard practices[12]. This is expected to increase a few degrees while in flight due to the load placed on the wings.

Aspect ratio

Aspect ratio is defined as the ratio of the large dimension to the small dimension of an object. In application to avionics, the aspect ratio is the span length divided by the chord length of a wing. The team chose an aspect ratio of seven for the craft. This number was not only derived from specification S1, but also from the analysis seen in Section 6. While determining the aspect ratio of the wings, several equations were used to find the induced angle of attack (loss of angle of attack due to wingtip vortices), induced drag, and lift slope using Prandtl's lifting line theory[23]. Equation 1 below was used in determining the induced angle of attack.

$$\alpha_i = \frac{C_L^2}{\pi * AR} \tag{1}$$

In this equation, C_L is the lift coefficient and AR indicates aspect ratio.

Equation 2 was used to calculate induced drag on a general wing.

$$C_{D,i} = \frac{C_L^2}{\pi * e * AR} \tag{2}$$

The e in this equation indicates wing efficiency based on the taper ratio.

In addition to these equations, the lift slope for a high aspect ratio (AR > 4) un-swept wing may be found using Equation 3 below.

$$a = \frac{a_0}{1 + \frac{a_0}{\pi * AR}} \tag{3}$$

In this equation, a_0 represents the initial lifting slope of the airfoil.

Using these equations, and an aspect ratio of 7, the induced angle of attack was found to be 2.35° for the E423 airfoil during flight. This means that without the use of winglets, an angle of attack of 4° is reduced to 1.65°. The initial lift slope was found to be 5.73 rad^{-1} from empirical data[28] which is reasonable when compared with the theoretical value of $\frac{\pi}{2}$. Applying this AR and using the equation above, the lift slope was found to be 5.70 rad^{-1}. The induced drag will be discussed in the analysis section of this document.

Modeling/ Analysis

Mathematical

Drag Analysis

When designing an aircraft, is very important[23] to accurately predict what 3D drag effects may be acting thereon. For this reason, the major components of drag were considered and analyzed theoretically. These components include viscous drag (skin friction) and induced drag (due to vortices). The overall coefficient of drag (Equation 4) was found using Dr. Leland M. Nicolai's equation provided for use by SAE competitors[16].

$$C_D = C_{Dmin} + (K' + K") * (C_L - C_{Lmin})^2 \tag{4}$$

In this equation, C_D represents the total drag coefficient, C_{Dmin} is the summation of pressure and skin drag for all components, K' is the induced drag factor, K'' is the viscous factor, C_L is the coefficient of lift, and C_{Lmin} is the coefficient of lift at minimum drag.

The aircraft components and corresponding dimensions can be found in Table 1 below.

Table 1: Aircraft Component Dimensions

Component	Planform Area(ft^2)	Wetted Area(ft^2)	Characteristic Length(ft)
Wing	7	15.08	1
Horizontal Stabilizer	2	4.72	1
Vertical Stabilizer	2	4.6	1
Fuselage	1	5.25	2

The equation used to calculate the minimum drag coefficient for the various components of the craft is represented in Equation 5 below.

$$C_{Dmin} = \frac{FF * C_f * S_{wet}}{S_{ref}} \tag{5}$$

In Equation 5, FF represents the form factor, C_f is the skin friction coefficient, S_{wet} is the wetted area, and S_{ref} is the reference area of the components.

Please note that the skin friction coefficient was found using an approximation for that of a flat plate in turbulent and/or laminar flow[23]. Equations 6 and 7 represent this coefficient.

$$C_f = \frac{1.328}{\sqrt{Re}} \quad Laminar\ Flow \tag{6}$$

$$C_f = \frac{0.074}{Re^{\frac{1}{5}}} \quad Turbulent\ Flow \tag{7}$$

Using Equations 5, 6, and 7 the drag coefficient was calculated for each component of the craft. This accounts for both pressure drag, and form drag. Each component's contribution to drag as well as coefficient of skin friction may be found in Table 2 below.

Table 2: Drag Coefficients for Aircraft Components

Component	CDmin Laminar	CDmin Turbulent	Cf Laminar	Cf Turbulent
Wing	0.0128	0.0316	0.0048	0.0118
Horizontal Stabilizer	0.0039	0.0097	0.0048	0.0118

Vertical Stabilizer	0.0038	0.0095	0.0048	0.0118
Fuselage	0.0133	0.0405	0.0067	0.0205
Landing Gear	N/A	0.0060	N/A	N/A
Engine	N/A	0.0020	N/A	N/A
Total	0.0338	0.0993	N/A	N/A

The induced drag factor K' is found using the equation 1/ (π AR e), where e is the wingspan efficiency and AR is the aspect ratio. e can also be defined below in Equation 8[23]:

$$e = \frac{1}{1+\delta} \tag{8}$$

In this equation δ is a dimensionless constant which is a function of taper ratio and can be found in Figure 6 below. Since an aspect ratio of seven was chosen and the taper ratio is one, the δ constant equals approximately 0.07. This yields a wing efficiency of 0.93.

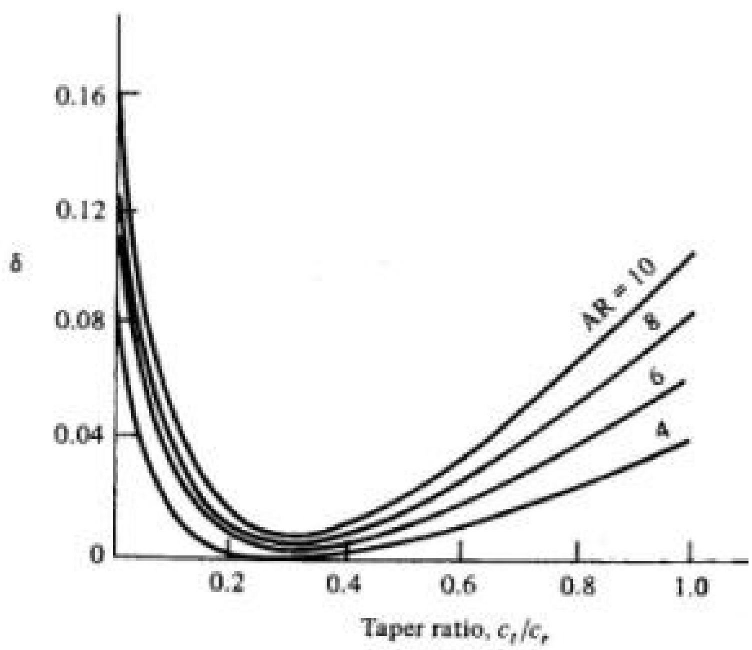

Figure 6: δ vs. Taper Ratio

For an aspect ratio of seven and a wing efficiency of 0.93, the K' value for the wing was found to equal 0.048 times the value for K". The K" value was assumed to be 0.4 and therefore K' is 0.019.

The minimum coefficient of lift was found using a program named Profili 2.21[24]. Profili 2.21 is based off of an airfoil design freeware named Xfoil, which was created by Dr. Mark Drela from the Massachusetts Institute of Technology. With this program, one is able to plot drag polars for different airfoils. Figure 7 contains the drag polar for the E423 airfoil at various Reynolds numbers. The minimum coefficient of lift was found to be 0.92. These values were checked with a vortex panel method developed by members of Team Ninja Turtles as seen in Appendix C.

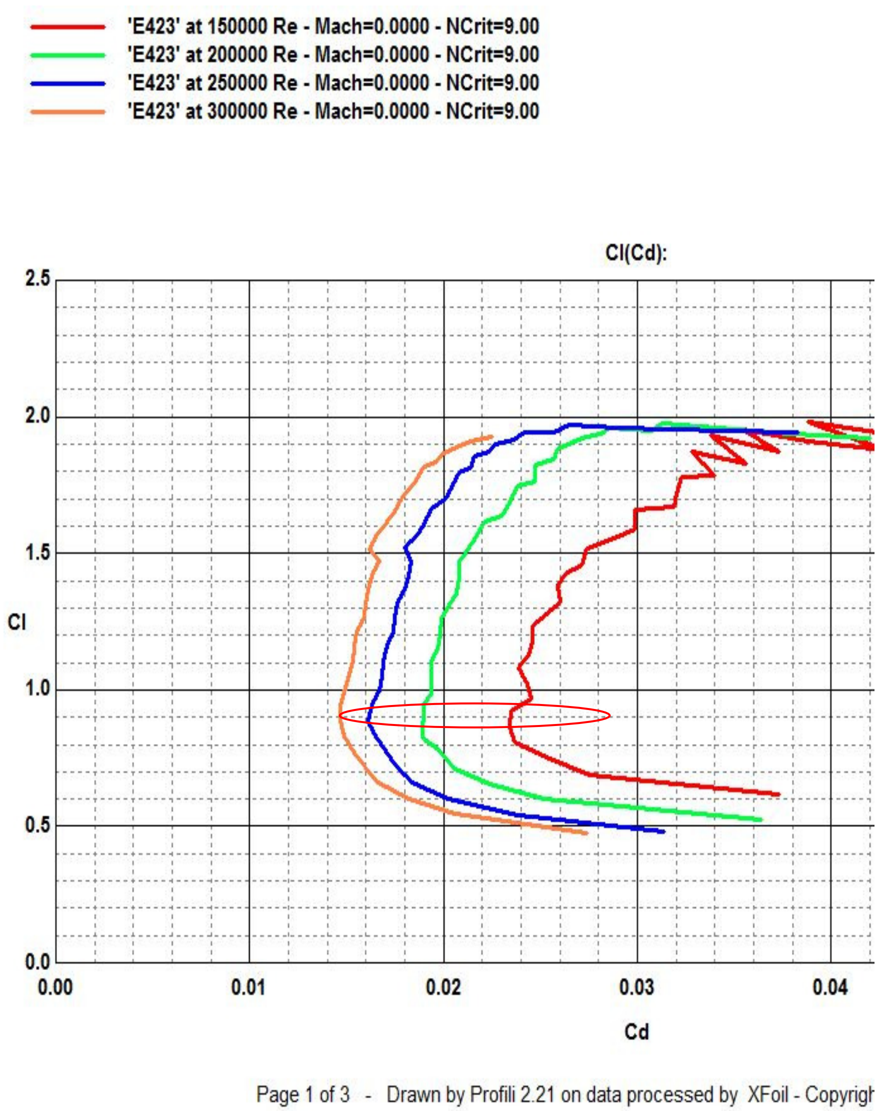

Figure 7: C_L vs. C_d for E423

Using this data, the total drag for turbulent flow may be represented by Equation 9 below. A similar representation of the total drag for laminar flow appears in Equation 10.

$$C_D = 0.0965 + 0.068(C_L - 0.92)^2 \tag{9}$$

$$C_D = 0.0410 + 0.068(C_L - 0.92)^2 \tag{10}$$

The total drag coefficient of the craft during steady flight (α = 0, C_L = 0.95, and velocity = 36-50 ft/s) is equal to 0.0965 in a turbulent flow and 0.0410 in a laminar flow.

Plotting this data yields the optimal flight angle of attack for the aircraft. The optimal conditions occur at the maximum L/D ratio and are shown in Figures 8 and 9 to be 6° and 3° for turbulent and laminar flow respectively. The calculations and their respective values which were discussed in this section have been programmed into a spreadsheet which the team developed as a design aid. Said spreadsheet is programmed to evaluate individual craft components as well as overall aircraft integrity and can be found in Appendix D.

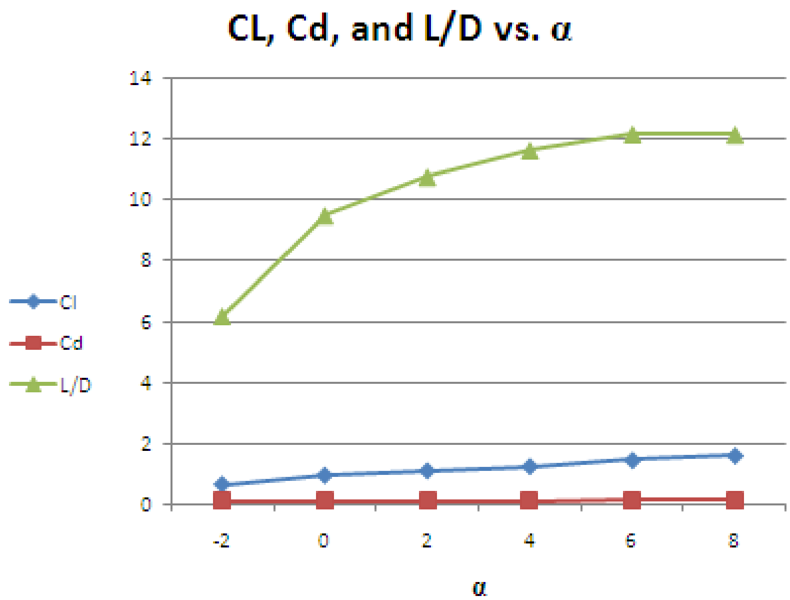

Figure 8: Optimal Angle of Attack for Turbulent Flow

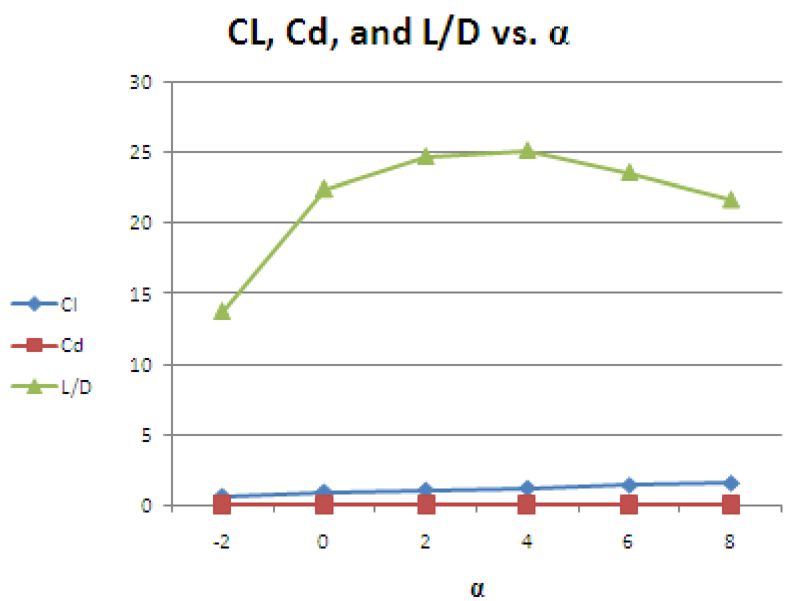

Figure 9: Optimal Angle of Attack for Laminar Flow

Winglets

As stated before, winglets were implemented into the design of the aircraft. Many calculations were considered when choosing whether or not winglets would be beneficial. In summary, the weight of the winglets would require an increase in the lift coefficient of 0.0151 to support their implementation without proving an inconsequential appendage. Using Equation 1 and others previously-mentioned, the team determined that the absence of winglets would reduce the lift coefficient by 0.25. Said reduction is obviously a consequence of previously-mentioned flow anomalies such as wingtip vortices. This increase in induced drag and decrease in lift coefficient in the absence of winglets amply justifies their implementation. The hand calculations for this consideration may be found Appendix E.

The above calculations are limited to determining the induced drag. In addition, skin friction drag was also calculated for the winglets using Equation 11.

$$D_{Skin} = 2C_f * q_\infty * A \qquad (11)$$

In this equation, C_f represents the skin friction coefficient, q_∞ is the dynamic pressure, and A is the surface area of the winglet.

This drag was calculated for two different cases to determine the most efficient size and shape of the winglets. The first case derived the drag for un-tapered winglets, and the second for tapered winglets.

Drag savings between un-tapered and tapered winglets was found to be 0.002186, 0.00732, and 0.0158 pounds for speeds of 10, 20, and 30 ft/s respectively in favor of tapered winglets. Since the predicted cruise velocity would be most closely related the 30 ft/s scenario, a tapered winglet was implemented. This not only protects the craft from the induced drag, but also minimizes the skin friction drag by more than 0.0158 lb.

Stability and Control

Tail sizing

When selecting a tail size, the team decided to go with a 3.5 to 1 wing to tail ratio. This provides that the span of the horizontal tail is two feet in length. The horizontal tail has a cord length of 12 inches, which yields an aspect ratio of two. It was made with the NACA 0012 airfoil. This airfoil will offer no lift in a horizontal freestream and will only act as an aerodynamic stabilizer in flight. Similarly, the vertical tail will be constructed with a tapered NACA 0012 airfoil to reduce drag and counter adverse yaw. The vertical stabilizer will have a one foot span and twelve inch cord length.

Wing Moment and Tail Configuration

Using the program Profili 2.21[24], the quarter cord moment coefficient (Cm) for the E423 airfoil was plotted at various angles of attack. As shown in Figure 10, during steady flight the moment coefficient was found to equal -0.24.

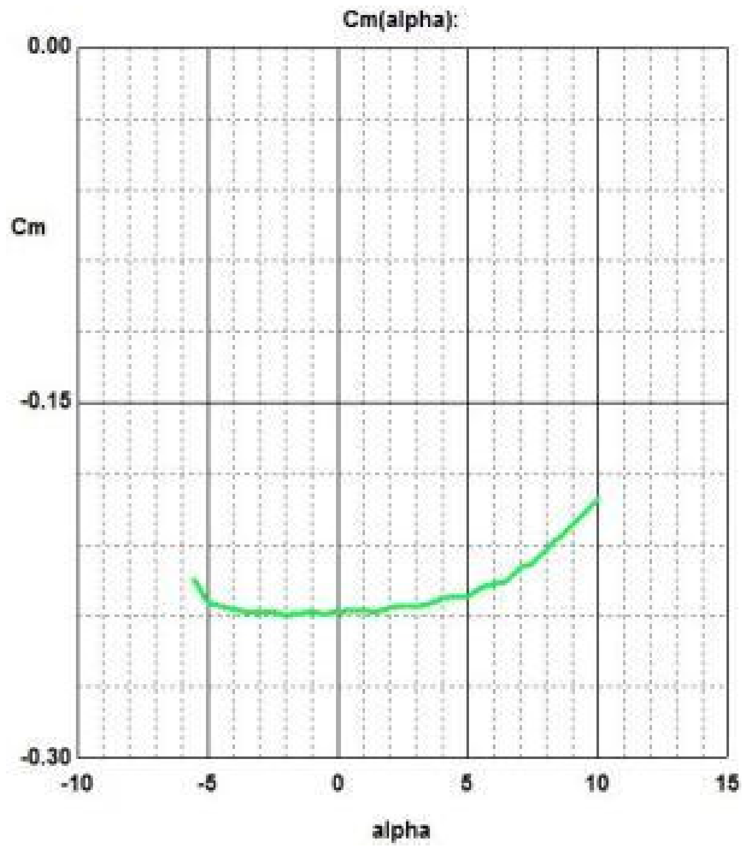

Figure 10: Cm vs. Alpha

This indicates that an angle of incidence is required for the tail to counter this moment during flight. The quarter cord moment is found using Equation 12[23]:

$$C_m = \frac{M}{q_\infty * A * C} \tag{12}$$

In this equation, C_m represents the moment coefficient, q_∞ is the dynamic pressure at cruising velocity, A is the planform area, C is the chord length and M is the moment formed.

The moment induced from the wing is approximately -2.25 ft-lb with an empty cargo bay and -4.49 ft-lb at projected payload. This moment is added to the moment which the weight of the aircraft (11.2 pounds empty and 22.4 pounds at projected payload) causes about the center of pressure.

The standard lifting slope for the NACA 0012 airfoil is 2π. Therefore, the horizontal stabilizer should be installed at an angle of incidence of 22.78° for an empty craft and 9.5° for a full craft. The difference of angles is due to the variation in takeoff velocity for the respective payloads. The moment which a designed angle of attack into the tail provides, should counter the adverse moment of the craft and result in a level flight. Due to the fact that an angle of attack measuring 22.7 degrees is unreasonable, a 6 degree angle will be used. Although 22.7 degrees is recommended, a empty-payload flight with velocity larger than 36.5 ft/s is obtainable reducing the need for a higher angle of attack. If a takeoff velocity of 51.6 ft/s is obtained during empty flight, the angle of incidence required decreases to 6.3

degrees. As the weight is increased, the moment increases which will result in oscillatory motion during flight. The increased angle of attack will create an increased lift from the tail as long as the tail is not in the stall region.

Ailerons, Rudder, and Elevator

Ailerons are implemented in the design of the aircraft to help make it more maneuverable. Aircraft absent of ailerons are known as “sail planes” and make use of a rudder as the only means of maneuvering. Based upon sizing standards[26], the length of the ailerons should be 30% of the wingspan for each side (fourteen inches). The width of the ailerons should be at least two and a half inches. The recommended aileron width should be 25% of the chord length corresponding to three inches, however, the team could not procure three inch aileron stock, and therefore implemented two and a half inch ailerons.

The vertical stabilizer (rudder) assembly is sized to be fourteen inches at the root and six inches at the tip. The tapered design will help alleviate some parasitic drag. A design rudder length of four inches will help counteract any adverse yaw created by the ailerons as well as create a large control service with which to increase the maneuverability of the airplane.

Engine Performance

Theoretical Static Thrust

The theoretical static thrust for a propeller driven airplane is found by assuming a control volume around the propeller in question. In the case of static thrust the airplane is not moving. The mass flow rate leaving the control volume creates the forward thrust. Equation 13 is used to find the thrust (F) of the propeller.

$$F = (0.5(\dot{m}_e * \ V_e) - \ (0.5(\dot{m}_o * V_o)) \tag{13}$$

In this equation, $\dot{m}_e = \ \rho * A_{cv} * V_e$, $\dot{m}_e$ is the outgoing mass flow rate, $\dot{m}_0$ is the incoming mass flow rate, V_e is the outgoing velocity, V_0 is the incoming velocity, ρ is the air density, A_{cv} is the area of the control surface, and V_f is the final velocity.

For static thrust, the incoming velocity is minimal due to the fact the propeller’s intake is from stagnant air. In order to calculate V_e, the propeller rpm is multiplied by the propeller pitch. Of course, with an increase in elevation, as is the case in Flagstaff Arizona, this static thrust decreases. Because of this, another equation was derived to account for the effect which elevation has on static thrust.

Modifying an equation found from the AMA magazine in October of 1986 produced Equation 14, which allows for the calculation of different theoretical static thrusts at various elevations.

$$T_{Static} = 2.83 * 10^{-12} * RPM^2 * D^4 * 1.11 * \left(\frac{P_{el}}{P_{sea}}\right) \tag{14}$$

In Equation 14, D represents the propeller diameter in inches, RPM is the propeller rotation rate, is the air pressure at theoretical elevation, and is the sea level air pressure as an elevation datum.

A summary of thrust results was obtained from this equation which was then used to calculate the dynamic thrust at takeoff.

Theoretical Dynamic Thrust

In order to calculate the theoretical dynamic thrust at takeoff, theoretical static thrusts were necessary at various elevations. This data was then inputted into an equation derived from a graph given by Dr. Leland M. Nicolai's white paper on page nine. The relationship between static and dynamic thrust is represented in Equation 15 below.

$$T_{Dynamic} = (-8.77 * 10^{-3}x + 1) * T_{Static} \quad (15)$$

In this equation, x represents the plane's takeoff velocity (mph). Each of the static thrusts which were calculated has a corresponding dynamic thrust at each elevation.

Solid Modeling

In addition to the mathematical modeling conducted by the team, SolidWorks was used as a design tool to physically model the entire aircraft. This allowed the team to locate a theoretical CG before construction. The model also gave the team a visual representation of what the plane would look like. This is important because sometimes there is a discrepancy between theory and manufacturability. Figures 11 & 12 show some of the solid modeling as rendered by SolidWorks.

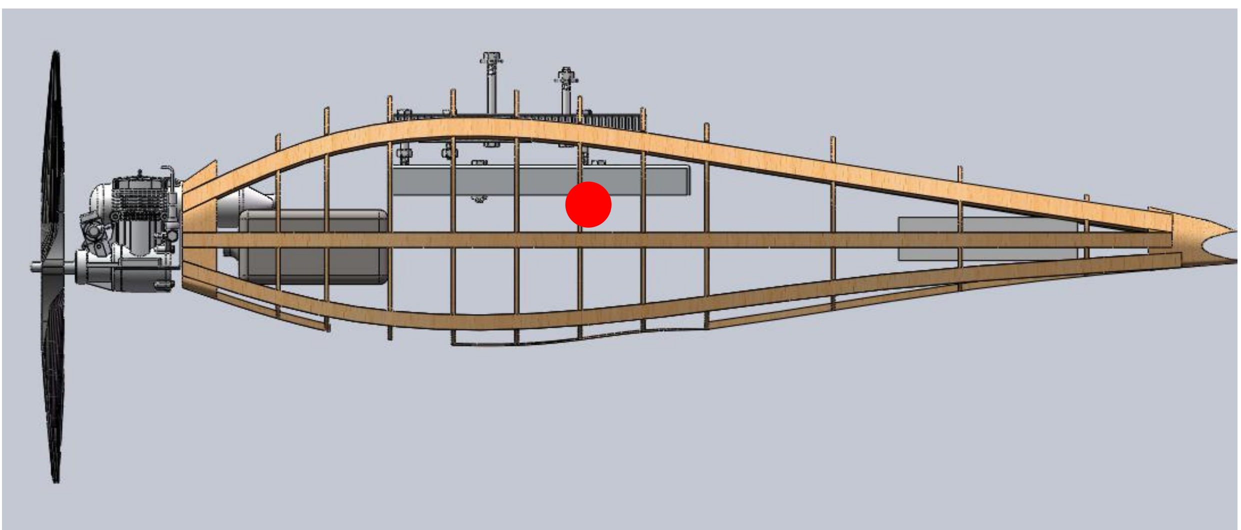

Figure 11 – Fuselage Assembly and Original COG

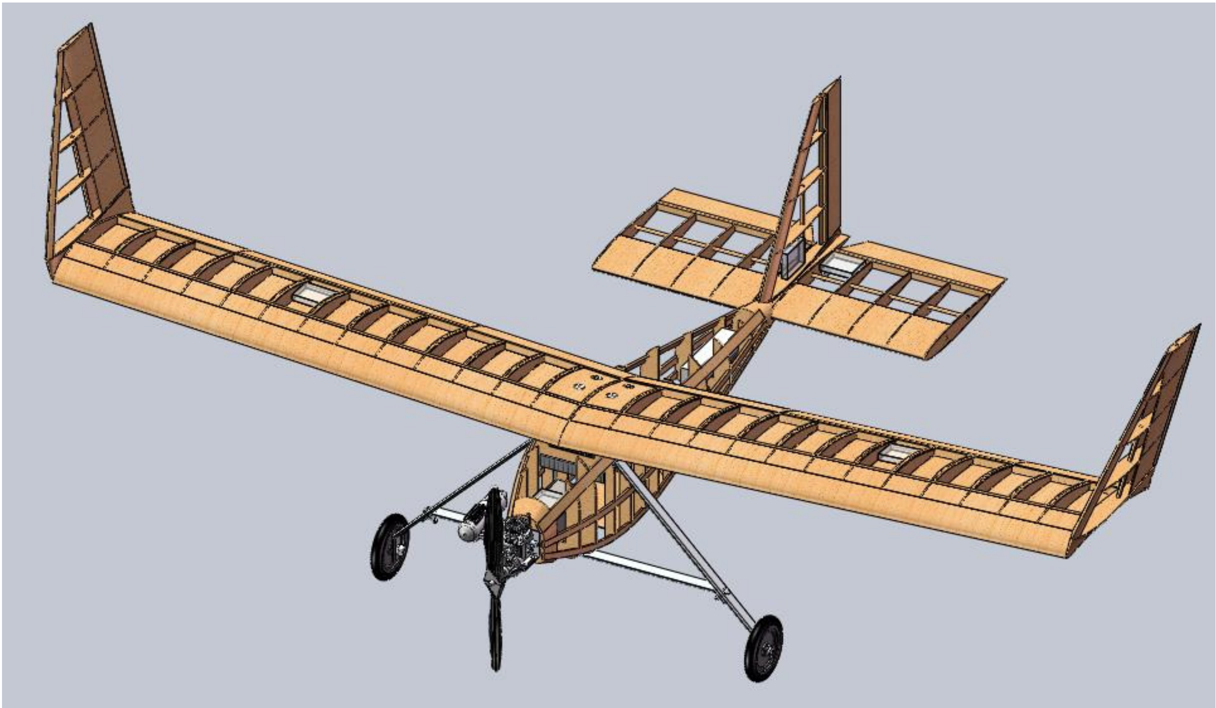

Figure 12 – Complete Digital Prototype

Stress/Weight Analysis

In order to determine the displacement (flex) of the wings under a gross weight of 31 pounds, COSMOSWorks was used to apply a point load at the wingtips. Only one wing was analyzed to reduce computation time. It was determined that the result of such loading would cause a deflection of 1.2 inches. In addition to this deflection, the FEA results presented a 1500 psi stress point near the root of the wings. This can be seen in Figure 13 below. This high stress may be due to a stress concentration at the rib/panel interface. Because of this high stress near the root, extra caution was taken when designing a method for the manufacture of the joint where the two halves of the wing connect. Reinforcement was added to the root interface by means of a Kevlar wrap and a short aluminum spar.

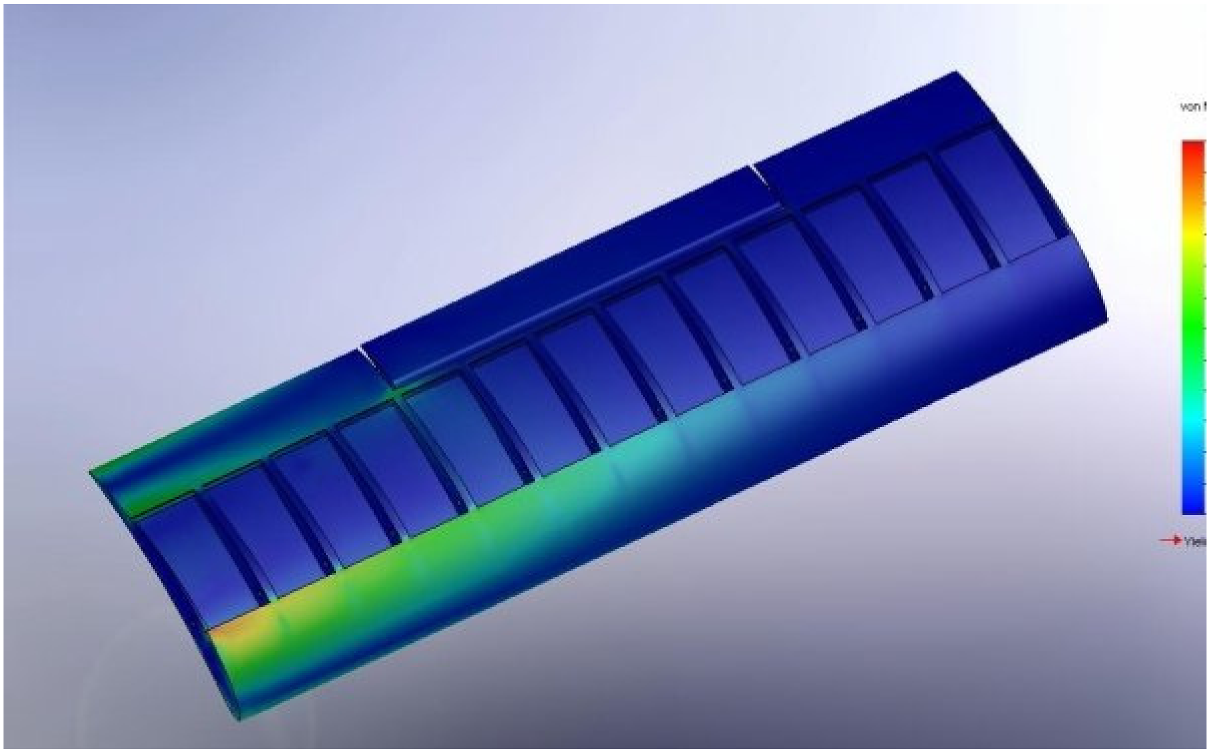

Figure 13: Wing Stresses as Rendered by COSMOSWorks

Of course, in actual flight, the wings will not experience point loading at any time but rather a distributed load over the lifting surface. This Finite Element Analysis fails to account for design modifications like the Kevlar wrap used to fix each half of the wing to one another and a half inch diameter thin-walled aluminum pipe embedded in the root. To verify the findings of the FEA, a fully constructed prototype was lifted at the wingtips with 20 pounds of lead in the cargo bay. The wings indeed deflected however this deflection was significantly less that predicted due to the stress distribution offered by the Kevlar wrap and embedded pipe.

Testing

Engine/Thrust Testing

To verify the theoretical static thrust equation listed above, a thrust test apparatus was constructed (Figure 8) allowing Team Ninja Turtles to measure the static thrust generated by the engine.

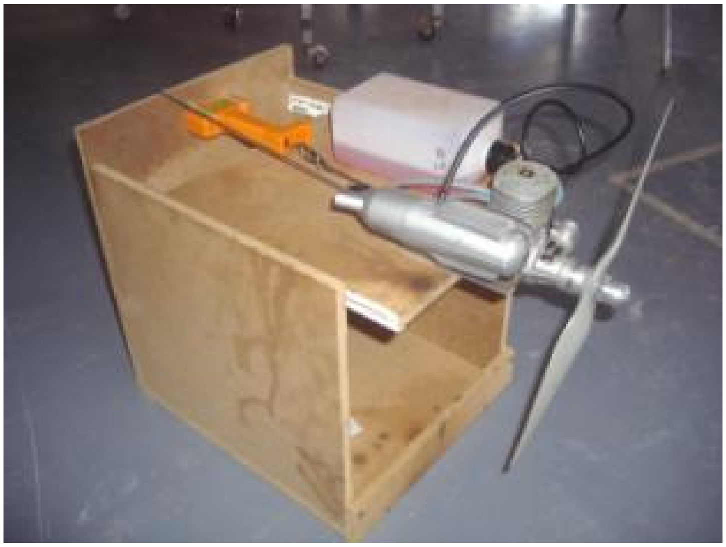

Figure 14: Thrust Test Apparatus

Two propellers were tested at an altitude of approximately 1100ft. The results of the tests are listed in Table 3.

Table 3: Thrust Data for 1100ft elevation

Diameter	Pitch	Max RPM	Theoretical Thrust	Measured Thrust
13in	6in	10500	9.5lb	9.5lb
14in	4in	9900	11.4lb	10.5lb

The results for the theoretical thrust were calculated using the static thrust equation listed above at an air pressure corresponding to test elevation. For the thirteen inch propeller the theoretical value was the same as the measured value. There is variation between the data for the fourteen inch propeller. Upon reevaluating the test setup, a large ding was found in the fourteen inch propeller most likely causing the observed variation in data.

Prototype One Operational Testing

On February 27, 2009, the team traveled from Flagstaff, AZ to Lake Havasu, AZ. The purpose of this trip was to test the first fully-constricted prototype aircraft at an elevation and temperature similar to Van Nuys, California. On the 27th, the team scouted a few possible locations where the first flight could take place. Depending on variations in wind velocity, the first flight could take place at an old construction site or an actual RC airfield designed and built for use by a local flyers club.

The next morning the team began early in an attempt to beat the wind which was quite significant. After many suggestions were made by the local aeronautics club at the airfield, the team decided to change some design aspects of the craft. These changes include a need to add downward thrust, modification of the center of gravity and modifying the size/throw of the control surfaces. After these changes were made, the wind was blowing at approximately 15 knots. The team decided to test fly the craft regardless of the wind conditions.

The airplane lifted off the ground in approximately 10 feet carrying about half the maximum predicted payload. Once in the air, the pilot lost control and crashed the plane into the ground due to stalling and going into an unrecoverable spiral. Figure 15 is an image taken right before the plane crashed into the ground. Aftermath of the crash required a re-fabrication of the landing gear and fuselage, the engine needed to be tested, new axels needed to be cut, labels had to be added to the plane, a new payload carriage needed to be developed and manufactured, and the vertical stabilizer needed to be reconstructed. This bill of repairs does not include the reapplication of monokot inherent in said component reconstruction. The main wings experienced only minor damage comprising of one aileron which needed repairs and a hole on the bottom side which needed patching.

The team quickly hurried back to Flagstaff and arrived around 8:30 PM and worked until 4:00 AM on Saturday night. During that morning, most of the work mentioned above was accomplished. The following Sunday, the fuselage was assembled and monokoted.

Figure 15: Destructive Prototype Testing

While the crash of the airplane in such close proximity to the design competition seemed disconcerting, the phase of design prototype testing had served its purpose in informing the team of flaws which should be assessed. The team determined that the crash of the airplane was due to both a major problem with the center or gravity and a lack of adequate surface area on the control surfaces. In addition to the fatal flaws in the original design other small issues were noticed in the testing which were changed in the second prototype and can be seen in the list below.

- The center of gravity was changed by shifting the payload carriage 2.5 inches forward (original position can be seen in the three view drawing in Appendix G)
- The landing gear was angled 30 degrees forward to prevent nose tip landings
- A tension member was added in between the landing gear
- The rear landing gear used a new stiffer configuration
- The rudder chord length was increased by 1.5 inches (from 2.5 to 4in)

Schedule

At the beginning of the project a schedule was created in Microsoft Project. Through the course of the project slight changes were made to the projected timeline of some of the tasks in the Gantt chart however the team was mostly on schedule for the entire project. This is an accomplishment given that the timeline requiring that a design be ready for the competition was so accelerated. The Gantt chart can be seen in Appendix F.

During the first semester, Team Ninja Turtles developed most of the analytical solutions and acquired most elementary knowledge and data. The team met approximately two times a week to discuss design decisions and to complete various tasks given in addition to the design assignment. Approximately 300 total man-hours were spent on the SAE Aero Design project during the first semester. This led to the successful completion of our first milestone; finishing our preliminary design by December 12th.

The team continued on schedule through winter break with the construction of the main wing. This took most of the break and proved to be the most time-consuming part of the aircraft construction process. In addition to construction roles, Kevin took the role of lead CAD designer, Joel became the sponsor liaison, and Nick the report drafter for the SAE design report which was due on January 22. Sean spent most of his time in the shop gluing and cutting pieces for the main wing. An estimated 138 cumulative hours were spent by the team over winter break to get a head start on the construction of the craft.

The team finished the fuselage and rest of the craft by February 11th. This included the construction of the rest of the wings, the fuselage, landing gear, and tail. A cumulative 400 man-hours was spent during the second semester from January 12th to the 11th of February. As can be seen in the Gantt chart, the original completion date was January 25th, however due to lack of wanting to flight test in Flagstaff the team was still on schedule for the remainder of the project. The team decided to wait a week to complete finite adjustments to the craft before testing it on February 28th. After testing, the airplane was rebuilt in 48 hours (80 man-hours) leaving only minor fixes during the week before competition.

On March 5th, the team drove from Flagstaff, Arizona to Van Nuys, California. On the 6th the team was required to pass a technical inspection and present a mandatory oral report. The following day consisted of flight competition. Due to the travel time multiplied by all members, an approximate cumulative time spent from February 11th to March 31st on project related activities was found to be 1006 hours.

Bill of Materials

The following is an annotated list of all materials consumed by the team in construction of the aircraft. These parts consist not only of fabricated parts which the team had to cut and manufacture; they include the commercial off-the-shelf parts as well. Drawings associated with all manufactured parts may be found on the submission CD in the folder named "2D Plan Views of Manufactured Parts." Also on this CD is a complete file containing all of the team's solid modeling.

<u>Wing</u>

- Winglet ¼” Dowell Long: 13”
- Winglet ¼” Dowell Short: 7.5”
- Fabricated End Loft between Eppler 425 and NACA 00112 is from a 2” x 2” x 12.5” Solid Block
- Winglet Trailing Edge is a piece $\frac{1}{16}$” x 4.5” x 12” and fitted to the 0012 shape
- Wing Underside Paneling is $\frac{1}{16}$” x 6” x 39” and fitted to the Eppler 425
- Spar Material (as per drawing)
- Rib Material for Airfoil and Winglets (as per associated drawings)
- COTS ¼” Bolts and Washers for fastening to the body: 2 @ 4 ½” and 2 @ 3 ½”
- Aileron Stock: 2 pieces @ 18”

<u>Fuselage</u>

- 4 Stringers ¼” x ½” x 36” to be formed as is necessary to meet the bulkheads
- 2 Stringers ¼” x ¾” x 36” to be formed as is necessary to meet the bulkheads
- 1 Stringer ¼” x 1” x 36” to be formed as is necessary to meet the bulkheads
- Three variously-cut-to-fit panels which are to be shaped to fit covering the bays
- Tail and Nose Pieces need to be manufactured from bass wood and are highly susceptible to change. They need to be worked as symmetrically as possible and then adapted to intercept with the stringers.
- Bulkhead Material: (as per drawings): $\frac{3}{16}$” thick

<u>Tail</u>

- Custom manufactured base block to fit
- 3 Trailing Spars: ¼” x ½” x 12”
- 4 Sheets for leading edge paneling: $\frac{1}{16}$” x 4” x 12”
- 4 Dowels for Horiz. Stabilizer: ¼” x 13”
- 3 Pieces Aileron Stock: 12”
- 2 panels for Vert. Leading Edge: $\frac{1}{16}$” x 1” x 12”
- Rib Material for Horiz. And Vert. Ribs: (as per associated drawings)

<u>Landing Gear</u>

- COTS Wheels: 2
- Landing Gear Gusset (as per drawing): 1
- Landing Gear Bar (as per drawing): 1
- COTS ¼” Bolts, Lock Washers, Washers, and Nuts: 2 @ 1 ½” and 2 @ 1”
- COTS Tail Gear kit

<u>Electronic Components</u>

- Servos
  - Aileron and Stabilizer Servos
  - Throttle Servo
- Connecting Wires: various lengths as needed

- Battery Pack
- Receiver
- Antennae
- Radio Controller

Fuel Line Components

- Fuel Tank
- Fuel Line
- Foam Vibration Insulator

Engine and Propeller

- 0.61 in^3 OS Engine (as per regulations)
- Engine Mount
- 14-4 Propeller

Miscellaneous:

CA Glue for Balsa Wood

Wood Glue 2000 psi Rating

Budget

Because our project is not funded by a particular company, sponsors were needed to cover the costs of the construction of the airplane as well as the expenses associated with travel and competition during the project. After much time was spent meeting with potential sponsors, a number of companies donated money to our team. Purina offered a very generous $1000 which paid for numerous construction supplies. Moon Valley Media supplied the team with $300 which went toward a travel tool kit for competition. In addition, Sean Varga's grandfather donated $100 for supplies. Gary Smith, Vice President of Unisource Energy Services, has extended a verbal offer for $2500 which the team has yet to receive. As of March 31st, 2009, a summary of the team's actual budget can be seen in Figure 16 and estimated budget summary in Figure 17. For an itemized description of the budget see Appendix H.

Actual Expenses to Date	
Travel Expenses	
Lodging	1084.09
Van rental	0
Fuel	320
Summary	1404.09
Competition Expenses	
Registration	450
T-Shirts	0
AMA membership	20
Report Printing / Binding	0
Summary	470
Building Supplies	
Balsa/wood	314
Glue	32
Covering	45
Nuts/bolts/screws	25
Glow Plugs	35
Radio / Controller	0
Servos	75
Wheels	47
Aluminum	38
Propellers	79
Engine/Muffler	0
Fuel	0
Flight Simulator	0
Spinners	0
Toolbox extras	152
Battery	25
Connectors	15
Linkages	15
Modeling tools	0
12V starter	0
Miscellaneous	296
Summary	1193
Grand Total	3067.09

Figure 16: Actual Budget

Estimated Budget	
Travel Expenses	
Lodging	1200
Van rental	700
Fuel	550
Summary	2450
Competition Expenses	
Registration	450
T-Shirts	175
AMA membership	58
Report Printing / Binding	130
Summary	813
Building Supplies	
Balsa/wood	100
Glue	60
Covering	50
Nuts/bolts/screws	15
Glow Plugs	8
Radio / Controller	290
Servos	220
Wheels	15
Aluminum	10
Propellers	60
Engine/Muffler	270
Fuel	20
Flight Simulator	210
Spinners	15
Toolbox extras	100
Battery	50
Connectors	40
Linkages	35
Modeling tools	50
12V starter	65
Miscellaneous	200
Summary	1883
Grand Total	5146

Figure 17: Estimated Budget

Conclusions

In conclusion, Team Ninja Turtles researched, designed, constructed and successfully competed with a heavy lift remote control aircraft. The final design is state of the art and incorporates innovative features which ultimately led to the team placing in the top ten of their class. The team spent over 1000 hours on the project, including the large amount of time it took to rebuild the craft after a catastrophic crash, the time spent traveling to and from the competition, and competing with the plane. A vast amount of experience was gained as well as knowledge that will be useful to the team in future endeavors.

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