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Designing a Remote-Control Airplane for the SAE Aero Design Competition

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Abstract

The project objective is to design and build an electric remote-control fixed-wing aircraft that maximizes payload capacity for the 2023 Society of Automotive Engineers (SAE) Aero Design West Competition in Fort Worth, Texas. The team placed 24th out of 63 teams at the SAE Aero Design West Competition. The SAE Aero Design competition is a yearly regional competition that “provides students with real-world engineering experience through aircraft design challenges”. The team designed a remote-control aircraft with a 12-foot wingspan utilizing a tapered cylindrical fuselage, Clark Y airfoils for the wing, and NACA 0012 airfoils for the horizontal and vertical stabilizers with the goal of minimizing aircraft weight while maximizing potential payload capacity. During development, design decisions were made based on SolidWorks fluid flow simulation to optimize and verify the aircraft design. The aircraft was manufactured utilizing carefully selected materials to increase performance.

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Name	Variable	Unit
Fuselage Length	l_{fuse}	m
Nose Length	l_{nose}	m
Tail Length	l_{tail}	m
Wing Area	A_{wing}	m^2
Wing Length	l_{wing}	m
Wing Chord Length	l_{wc}	m
Lift	L	N
Drag	D	N
Takeoff Lift	$L_{takeoff}$	N
Takeoff Drag	$D_{takeoff}$	N
Angle of Attack	α	degrees
Coefficient of Lift	C_L	unitless
Coefficient of Drag	C_D	unitless
Velocity	V	m/s
Air Density	ρ_{air}	kg/m^3
Gross Aircraft Weight	W	N
Aircraft Mass	m	kg
Acceleration Due to Gravity	g	m/s^2

Designing a Remote-Control Airplane

1 Introduction

The SAE Aero Design competition is a yearly regional competition hosted by the Society of Automotive Engineers to “provide students with real-world engineering experience through aircraft design challenges.” [1] Remote-control (RC) fixed wing aircraft are designed, built, and flown by up to 75 teams following the guidelines released by SAE. In the following report, aircraft design and analysis has been completed for the University of Southern Indiana’s airplane shown in Figure 1 that competed in the 2023 SAE Aero Design Competition.

Figure 1: Final Constructed Aircraft

Objective Statement

The objective of our project is to design and build a remote-control fixed-wing aircraft that maximizes payload capacity for the 2023 SAE Aero Design West Competition in Fort Worth, Texas.

1.1 Deliverables

The deliverables of our project are the following:

- Constructed Remote-Control Aircraft for SAE Aero Design Competition
- SolidWorks Aerodynamic and Stress Analysis

- SolidWorks Models of Aircraft
- Senior Design Presentation
- Senior Design Report
- Senior Design Poster

In the following sections of the report, background information on our project as well as a review of previous designs will be completed including lessons to be applied in our design. Concepts considered during the initial design phase will be discussed. Design choices, calculations, and the performance of the aircraft at the competition are discussed. Appendices include a system hierarchy, schedule, budget, weight table, failure modes and effects analyses (FMEA).

2 Background

The SAE Aero Design West Competition is a yearly competition where students design, build, and test remote control fixed wing airplanes given design restraints. For this year, the goal for regular-class airplanes is to carry the largest payload as a ratio of weight given many strict design requirements.

At the competition, test flights must be completed. Two team members will line the airplane up at the starting line. The third member will go to the pilot station. The airplane will take off before the Take-Off line at 100 ft. The airplane will fly to the 400 ft marker and turn around. The airplane will head towards the starting line. Once the airplane passes the starting line, it will turn to face the same direction it took off. The airplane will land in the designated 400 ft range. A diagram of this process can be seen in Figure 2. For a flight to be considered successful, the full course must be flown, and the plane must land in the landing zone without losing any parts.

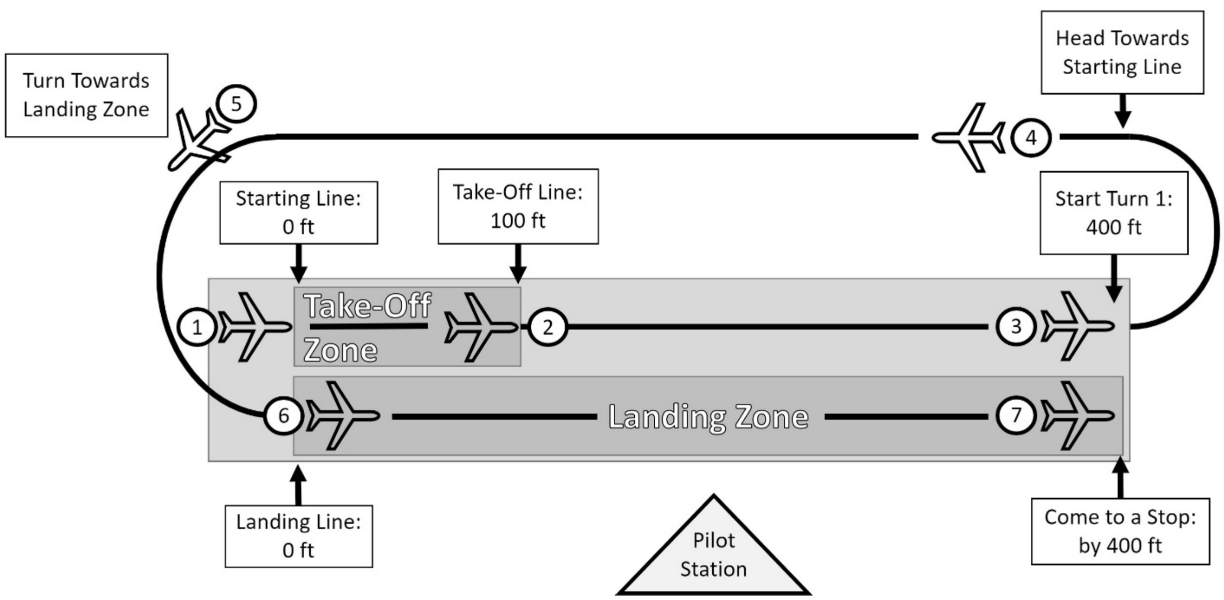

Figure 2: Concept of Operations

Key requirements and rules outlined in the SAE rulebook [1] are listed as follows.

The aircraft shall:

1. weigh less than 50 lbs. including payload
2. take flight in less than 100 ft
3. land in the designated 400 ft area
4. use the competition standard Electronic Speed Controller (ESC) power limiter
5. have controllable landing gear
6. have a wingspan between 10 and 18 ft
7. not have any parts that measure more than 4 feet in length
8. be a typical fixed wing aircraft, not a helicopter or quadcopter
9. have a verified center of gravity marker
10. not use rubber bands
11. not use fiber-reinforced plastic
12. be powered by a singular electric motor
13. have a propeller rotating at the same rpm as the motor
14. be powered using a commercially available 6 cell 22.2-volt lithium polymer battery pack
15. not allow cargo to be exposed to the airstream
16. not use gyroscopic stabilizers
17. have a radio control system operating at 2.4 GHz
18. automatically kill power if the aircraft loses radio control (working fail-safe)

2.1 Literature Review

2.1.1 Worcester Polytechnic Institute (WPI) [3]

In the 2018 SAE Aero Design Competition, the team from Worcester Polytechnic Institute (WPI) was able to take flight using a complete foam insulation board and steel rod construction [3]. Their completed aircraft can be seen below in Figure 33.

Figure 3: Worcester Polytechnic Institute Aircraft [3]

To increase the durability of their aircraft, the WPI team opted to create a solid fuselage as opposed to a lighter frame and skin design from balsa wood. They also claim that their design uses a tricycle style landing gear that would significantly exceed their expected landing loads. As seen in Figure 4 below, the team did not account for potential loads experienced during crash landings and damaged their fuselage as a result.

Figure 4: WPI Damaged Landing Gear [3]

The WPI team also claims to have not considered enough of a weight margin when designing each aircraft component. Manufacturing methods were not kept consistent between teammates, causing difficulty during construction. They also had issues locating the center of gravity of the aircraft for stability when using a solid fuselage design. The team constructed their aircraft primarily out of foam and aluminum to maximize structural efficiency. The choice of adhesives, such as Gorilla Glue, was not strong enough as the aircraft broke several times during testing. The foam was constructed as a single piece and reinforced with aluminum rods.

2.1.2 Florida Agricultural Mechanical University (FAMU) [4]

The SAE Aero Design team from Florida Agricultural Manufacturing University (FAMU) shows, through their design, the importance of modularity [4]. The team struggled to implement lightweight PLA because it is difficult to calibrate 3D printers for consistent prints. Scale issues were also present while printing parts. While interesting, the report makes no mention of test flights but does make a case for utilizing 3D printed models in competition.

The most useful bit of information taken from this report was the method applied for constructing modular wings. To hold their wing segments together, the team used aluminum rods that span the full length of the wing internally. Bolts are used at the ends of the rods to sandwich the separate panels together.

2.1.3 Northern Arizona University (NAU) Skyjacks [5]

After reading the report from the Northern Arizona University Skyjacks, it was clear to see that material selection can have one of the largest impacts on the performance of the aircraft [5]. The Northern Arizona University team ran into problems with aluminum bolts shearing off and aluminum plates bending unexpectedly, because they were not reinforced. Any plane designed needs to be built while considering necessary crash repairs.

While the NAU Skyjacks were able to complete successful test flights, they were not able to carry their expected payload. After construction, the team found that their center of gravity was not in the desired quarter cord length from the leading edge of the wings. To correct the center of gravity, weight was added to the nose of the plane, reducing the margin intended to be used for payload. The team believes that the increase in weight was from the Monokote shrink wrap film they used to skin their wings. As seen in Figure 5 below, to use the shrink wrap, many support ribs are needed within the wings.

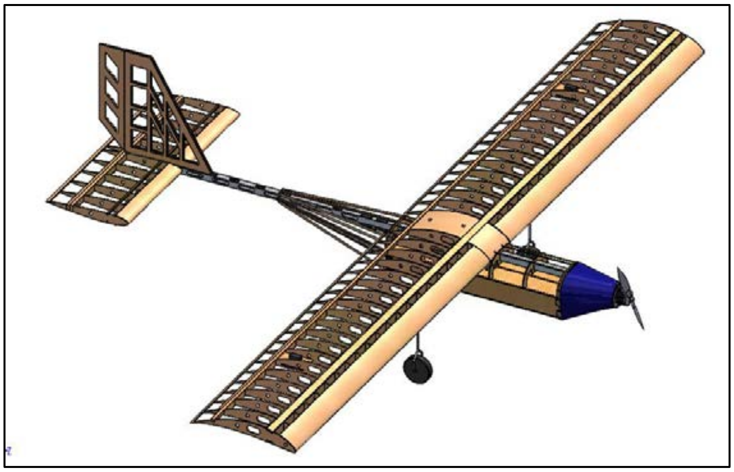

Figure 5: NAU Skyjacks Aircraft Model [5]

The NAU Skyjacks report also suggests placing control rods above control surfaces so that they act as "pull" rods and not "push" rods for better control. Landing gear can also be designed so that it acts as a spring on landing to absorb load, instead of a rigid shaft that will buckle during impact.

Northern Arizona University had a team compete in the SAE Aero Design West competition in 2013 [6]. The team implemented curved ribs on the inside of the wing with the hope that the curvature of the wing will distribute the weight better. Because the airfoil was not fully enclosed, the wings did not create enough lift force to get the aircraft off the ground.

2.1.4 Flight Vehicle Design [15]

Flight Vehicle Design by Andrew Ning [15] describes in detail the equations necessary to design different kinds of aircraft: remote-control aircraft, unmanned aircraft, fighter aircraft etc. The textbook provides the calculations that can be used to find the free stream velocity. After finding free stream velocity, other equations listed were used to determine the lift and drag forces. Simulation free stream velocity results in computer generated lift and drag forces. The lift and drag forces can be applied to a deflection simulation that will show the stress concentrations. *Flight Vehicle Design* provides general aircraft dimensional relationships that were used to determine dimensions.

3 Aircraft Design and Construction

During the design portion of the project, each team member was tasked with a system to focus their respective design efforts. For the safety of all SAE Aero members, it must be insured that no part of the aircraft shall fall off during flight. A high-level view of these systems can be seen in the system hierarchy included in Appendix A. In Appendix F, an overview of the components used in the plane is shown.

Three primary factors drove our design process. The plane needed to be easy to manufacture so that we could make spare parts, it needed to be quick to assemble so that we can be ready for quick take-off at the airfield, and it had to be easy to transport so that we could travel to the competition site at Fort Worth, Texas, with the plane. Many compromises had to be made during the design process as many requirements directly compete with each other. For example, we want to maximize aerodynamics while maximizing cargo space, we want to minimize weight while maximizing payload, and we want to maximize lift while minimizing drag.

Very aerodynamic planes typically have small passenger compartments, where large cargo planes are typically less aerodynamic and compensate for this with larger motors. Minimizing weight makes constructing a fuselage capable of withstanding forces exerted by a large payload difficult due to less desirable material properties. Carbon fiber composites would have been useful for many of these components, but competition rules prevent the use of fiber reinforced plastics. Maximizing lift while minimizing drag is also difficult as drag is required to generate lift.

3.1 Fuselage Design & Construction

For our plane, a Clark Y Airfoil shape with a 12 ft wingspan is being used. Chuck Cunningham's *R/C Design Made Easy* from RCM Magazine [6] is used for basic model plane geometry. The article states that for an RC aircraft, the fuselage length should be approximately 80% of the wingspan length, the nose should be 21% of the fuselage length, and the tail should be 55% of the fuselage length. The resulting length calculations can be seen in the following equations.

$$l_{fuse} = 0.8 * l_{wing} \quad [6] \tag{1}$$

$$l_{fuse} = 0.8 * 12\ ft$$

$$l_{fuse} = 9.6\ ft$$

$$l_{nose} = 0.21 * l_{fuse} \quad [6] \tag{2}$$

$$l_{nose} = 0.21 * 9.3\ ft$$

$$l_{nose} = 2.016\ ft$$

$$l_{tail} = 0.55 * l_{fuse} \quad [6] \tag{3}$$

$$l_{tail} = 0.55 * 9.6\ ft$$

$$l_{tail} = 5.28\ ft$$

7

In Figure 66 below, the full model generated from these dimensions can be seen. Neglecting the vertical elevator, the fuselage has an overall length of 8.79 feet. When the elevator is included, the full aircraft length is 9.74 feet.

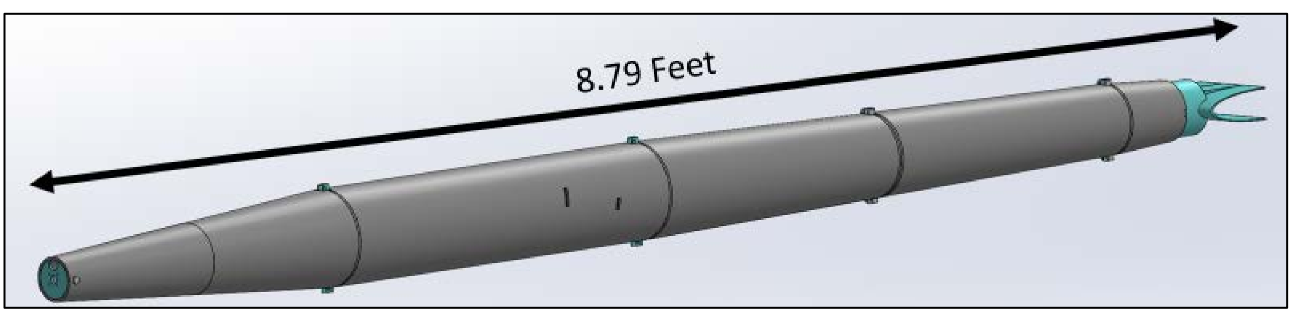

Figure 6: Full Fuselage Model

The nose of the fuselage can be seen below in Figure 7. On the front of the nose, a rib is included that will be the mounting location for the motor that will provide thrust for our RC airplane. It has an overall length of 2.03 feet.

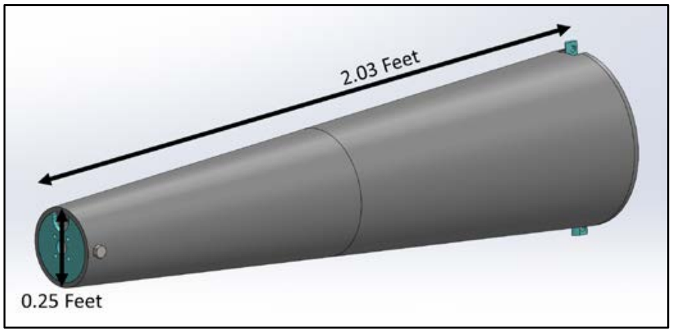

Figure 7: Fuselage Nose

The tail of the aircraft was split into three sections to comply with the competition requirements as shown in Figure 8. SAE Aero competition rules [1] indicate that no individual section of the aircraft is longer than 4 feet. Another limitation in building the fuselage was the dimensions of the foam board used to make it. This yielded two segments 1.76 feet in length, and a coupler to the 3d printed elevator mounts that was 0.94 feet long.

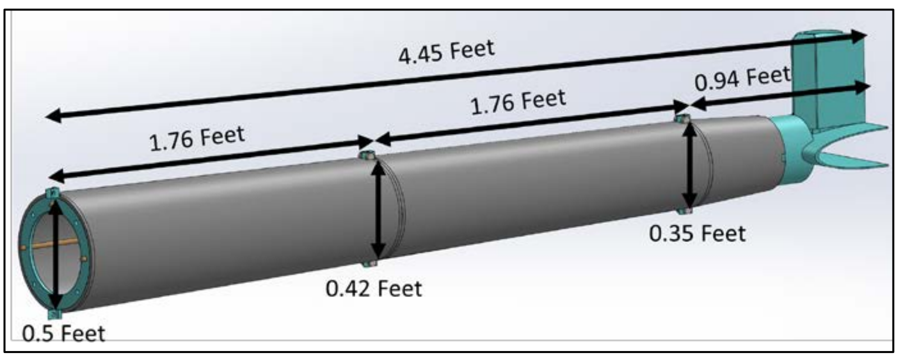

Figure 8: Fuselage Tail

For the wings to pass through the center of the fuselage, cuts are made in both sides of the skin. The skeleton of the wings passes through the thicker ribs and the skeleton is glued into place. Both ribs and wing cuts can be seen below in Figure 99.

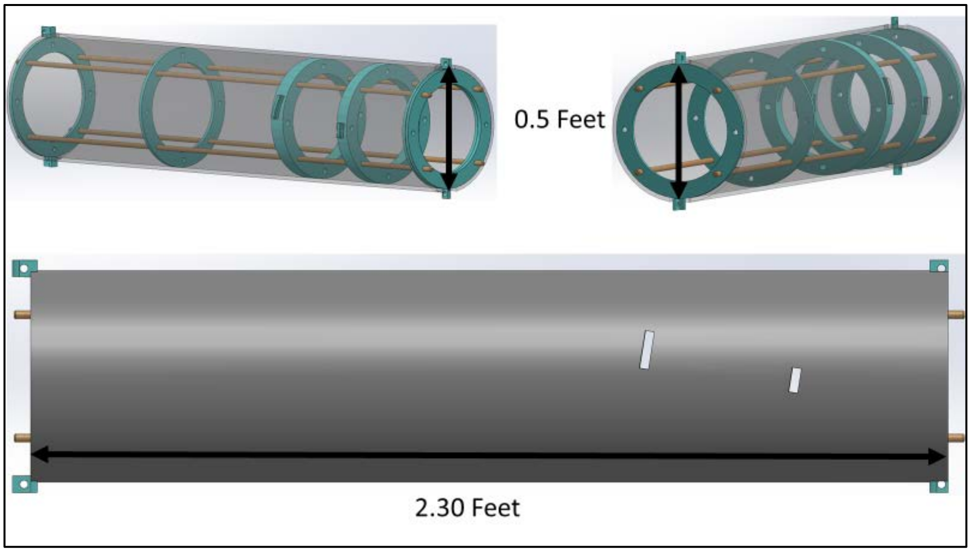

Figure 9: Fuselage Center Section

To construct the fuselage, Readi-Board foam board was used to make the skin, as it is commonly available and can be cut with a hobby knife. The boards are also extremely lightweight. After cutting multiple 2-centimeter by 2-centimeter pieces and measuring them on a balance, they had an average mass of 0.0525 kg. These measurements yield a density of only 27.56 kg/m^3.

3D Printed PLA ribs were utilized with pine wood dowel rods to reinforce the foam skin. Initially, foam ribs were going to be used with wire stringers, but after construction began the foam ribs were not able to support anticipated load values. Ribs are evenly spaced in the fuselage and spaced 1 foot from the end of any segment. In the nose, the front rib will be utilized as a motor mounting plate. Each rib has 8 holes patterned on them for stringers to pass through. The dowel rod stringers are placed in a square pattern that alternates between each segment. This alternating method was utilized to comply with the 4-foot part length limit and to allow for the replacement of parts in the event of a crash.

Craig Russel's *Flat Top Cone Calculator* [7] was used to find the measurements needed to take the flat board and roll it into the tapered fuselage shape. After experimenting with the calculator, it was found that adding 5 percent to each measurement accounted for the thickness of the foam board. These measurements were modeled in SolidWorks, then tangent lines were drawn equally spaced from each curve. An example of this drawing is seen in Figure 1010.

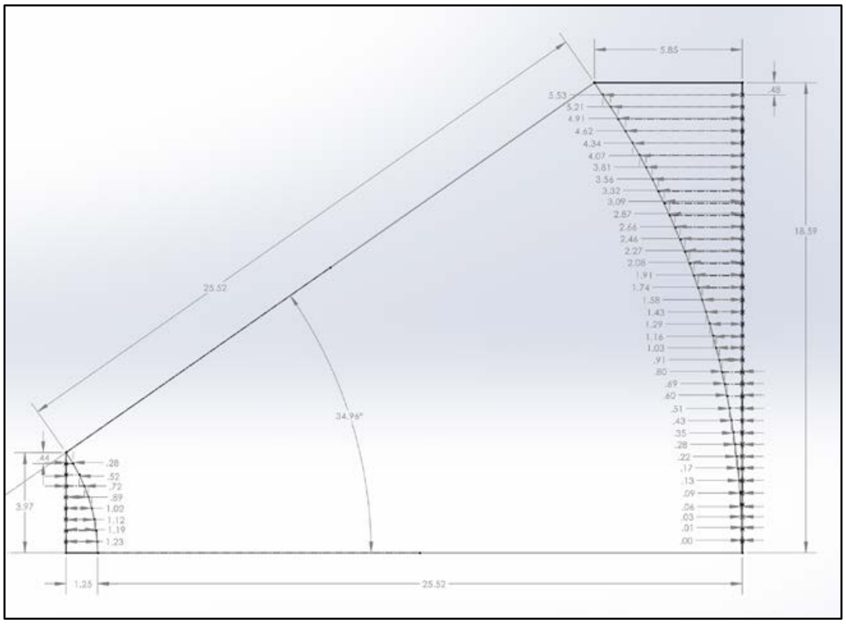

Figure 10: SolidWorks Skin Drawing

Once the cones were drawn in SolidWorks, the measurements were transferred to foam board and cut out using a hobby knife shown in Figure 111. Calipers were used to exact measurements to 4 decimal places. There was inherent inaccuracy in this measurement method due to the thickness of pencil lead and hand drafting.

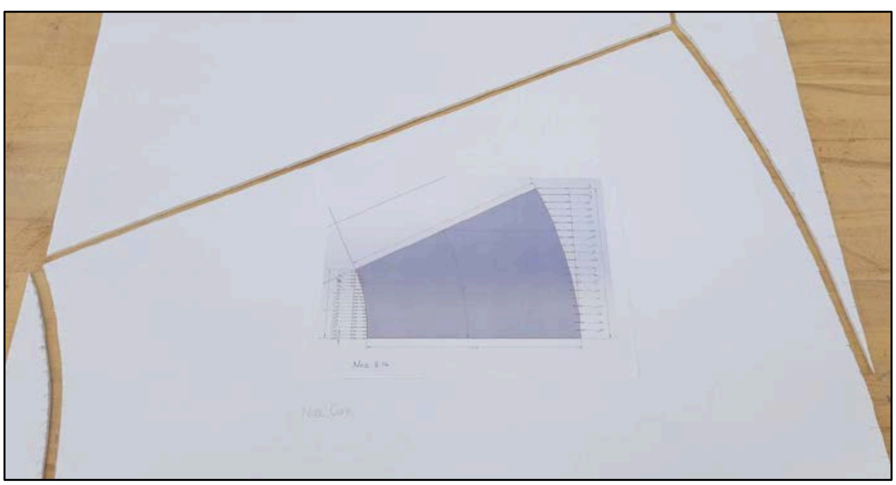

Figure 11: Cut Flat Foam Board

After cutting the boards, they needed to be scored so that they would bend without snapping, as foam board is typically very brittle. A press brake was used to score the foam board at equal intervals to maintain a constant bend radius shown in Figure 122. Initially, this process was completed by using flat stock steel and hitting the steel with a hammer. The press was able to score the boards more consistently and with far less effort.

Figure 12: Skin in press brake

Once scored, the skin was glued along the remaining seam to finalize the cone shape. Next, the skin had to be relief cut for the rib connection tabs and each rib was glued with Gorilla Glue into place. Temporary stringers were used to align each rib. The glued ribs can be seen in Figure 133. After each component that needs to be included in the fuselage, such as the battery tray and cargo bay, are mounted, stringers are cut to appropriate lengths and hot glued into each fuselage section.

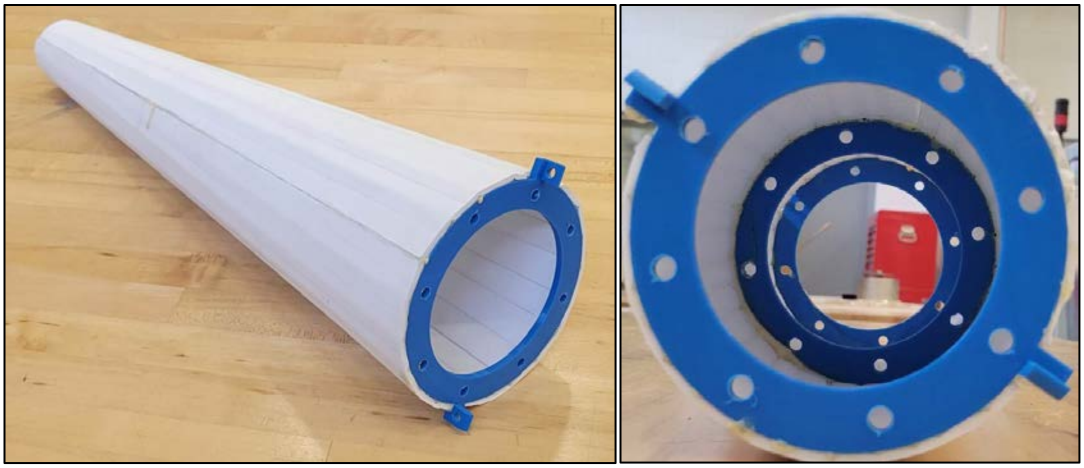

Figure 13: Rolled skin with fixed ribs.

While this process was expected to be difficult, there were unexpected complications that arose. Initially, hot glue was going to be used to hold the ribs in the skin due to its quick drying time. The hot glue would not adhere to the PLA ribs, so expanding gorilla glue was used in place of hot glue. The gorilla glue had approximately a 24-hour drying time and required the fuselage sections to be clamped together until the glue had completely cured to avoid the foam board returning to its naturally flat state. The height of the bolt connector tabs on the ribs also needed to be made taller to avoid interference between tools and the skin.

Knowing that approximately 20 pounds of lift will be generated when the plane is flying at an expected velocity of 40 mph, SolidWorks static analysis was used to verify the fuselage design. Because the aircraft has a 12-foot wingspan with 6 feet exposed either side of the fuselage, the 20 pounds of lift can be approximated as a 60 pound point load acting on both sides of the skin. This is completed by taking the 20-pound distributed load multiplied by the 3 foot moment arm as the cross section of the wing is constant. For this simulation, the rib connection tabs are held as fixed points.

In Figure 14, the maximum von mises stress value seen after mesh refinement is $2.339*10^7$ N/m^2. This stress occurs in the connector tab, which has an ultimate tensile strength of $6.29*10^7$ N/m^2 yielding a safety factor of 2.69. While planes typically operate on very narrow margins of safety, modeling 3D printed material can be difficult and requires increased margins. The node shown in Figure 14 shows a $4.38*10^5$ N/m^2 stress acting on the foam skin of the plane. Compared to the ultimate strength of $5.50*10^6$ N/m^2, a safety factor of 12.56 is calculated. This value suggests that more of the load could have been applied to the skin, but the wing mounting changed late in the project and there was not enough time remaining to redistribute load to the fuselage skin from the internal ribs.

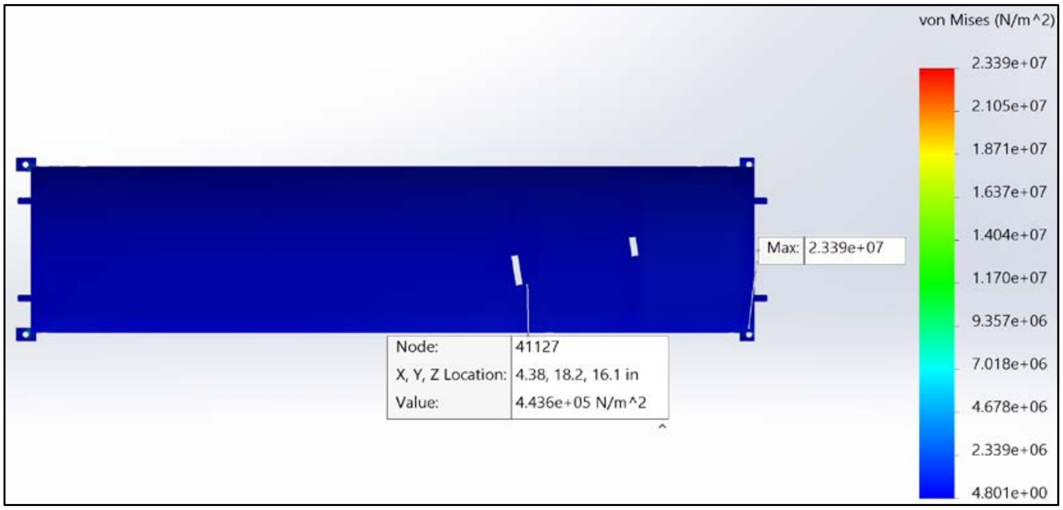

Figure 14: Solid body analysis on fuselage

Ribs must be included in the fuselage to prevent the fuselage from buckling during flight [8]. In Figure 15 below, a rib in the center section of the fuselage can be seen. Considering a worst-case stress condition where the full 120-pound lift force is acting on a single rib, there is negligible deflection, and at the maximum stress point, there is a factor of safety of 12.05. In contrast, a similarly sized square fuselage experienced a stress that was more than a factor of 10 larger than the yield stress and would fail.

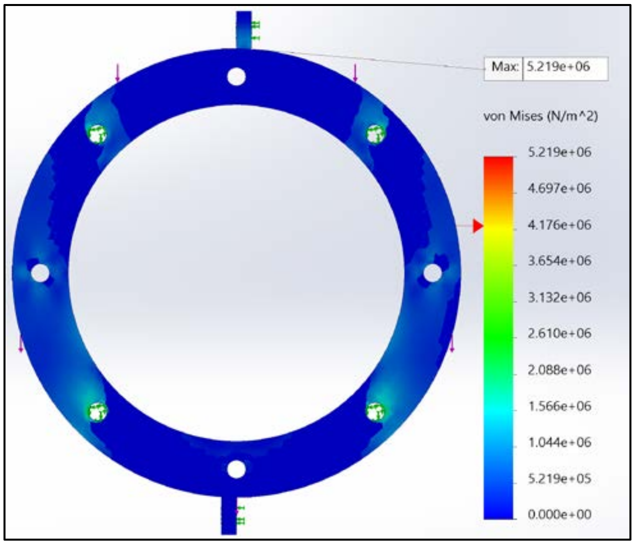

Figure 15: Fuselage Rib Stress Analysis

3.2 Wing Design & Construction

The wingspan chosen was 12 feet in length, constructed into 5 sections to keep the parts under 48 inches. Figure 16 shows the final wing design with the desired specifications. The center section will be fixed into the fuselage. The chord is 12 inches long, and the ailerons have an area of 2 ft x 4.25 in. Each aileron is powered by a servo motor with a torque of 20 kg*cm. There are eight 3D-printed connectors in total, with two connectors between each piece. Insulation foam board is cut to the Clark Y airfoil shape and placed across two beams constructed out of yard sticks. This design allows for each piece to be easily replaced if any parts are damaged during flight or landing.

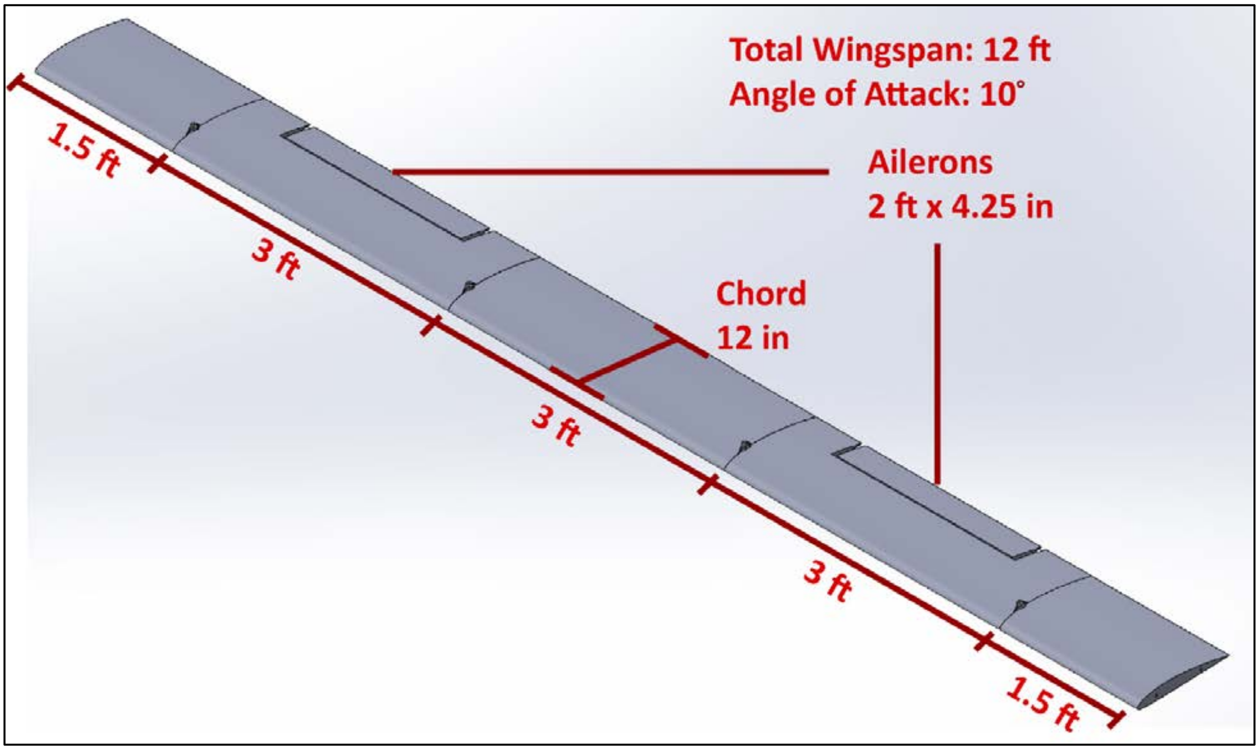

Figure 16: Final Wing Design

The wings undergo a maximum lift force of 40 lbs across the entire wingspan shown in Figure 17. The lift force comes from a SolidWorks flow simulation described in Section 3.6.

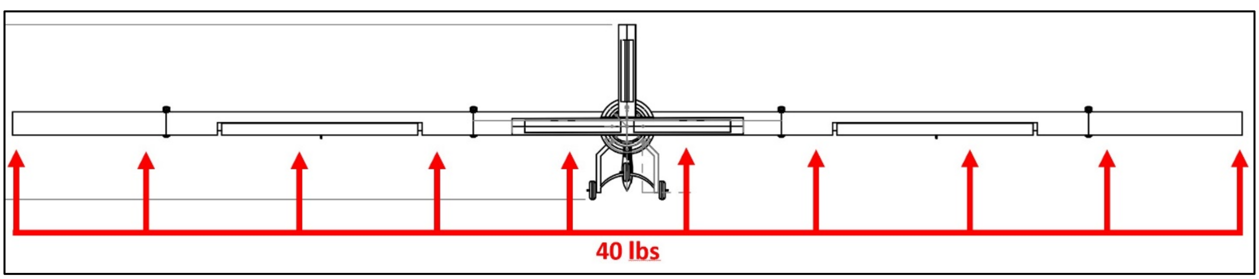

Figure 17: 40 lbs of Lift Applied to Entire Wingspan

The force diagram on the wings can be simplified so that 20 lbs is applied to the wing 3 ft away from the center of the wings as seen in Figure 18.

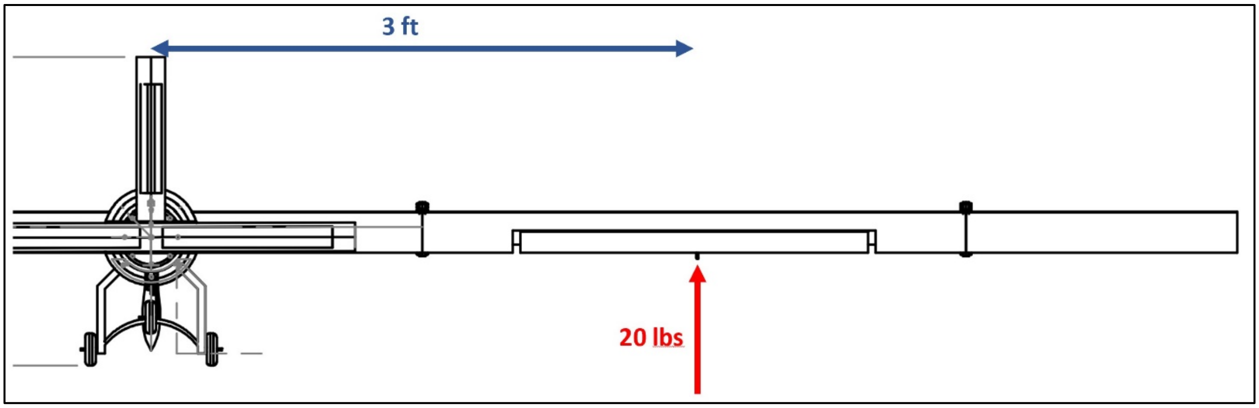

Figure 18: Simplified for Solving Deflection and Stress

The internal structure of the wings, shown in Figure 19, utilizes meter sticks set vertically to maximize the moment of inertia to decrease the overall deflection of the wings. The dimension of the larger beam is 0.25 x 1.12 in., and the dimension of the smaller beam is 0.25 x 0.72 in.

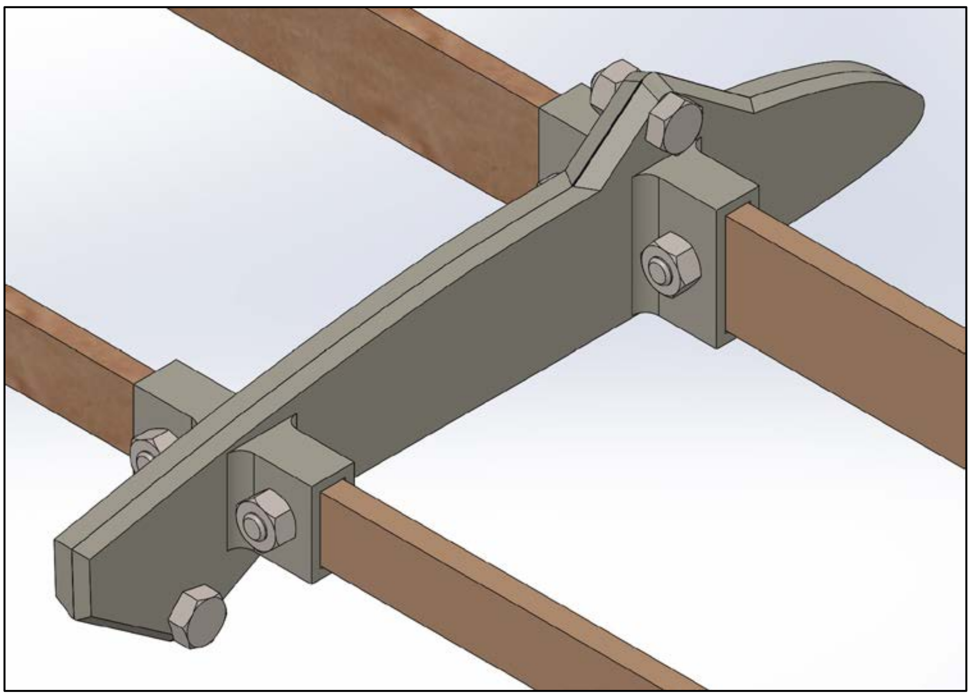

Figure 19: Wing Internal Structure

The moment of inertia is found using Equation 4. The total moment of inertia is combined and solved as a single beam.

$$I = \frac{bh^3}{12} \tag{4}$$

$$I_{small} = 0.007776\ in^4$$

$$I_{large} = 0.02927\ in^4$$

$$\sum I = 0.03705\ in^4$$

The meter stick is made of pine wood ($E = 1.45\ mpsi$). The total deflection of the wings is calculated using Equation 5.

$$\delta = \frac{FL^3}{3EI} \tag{5}$$

$$\delta = \frac{(20)(36)^3}{3(1.45 * 10^6)(0.03705)}$$

$$\delta = 5.79\ in$$

The analytical deflection of the wing tips is 5.79 in at each end. Using SolidWorks to simulate a distributed load of 40 lbs. across the wings, demonstrated in Figure 20, yields a deflection of 9.828 in. The simulation treats the two beams as separate entities and accounts for the plastic connectors. Because the load of 40 lbs. is applied upward, the downward deflection will not cause any dragging of the wings on takeoff.

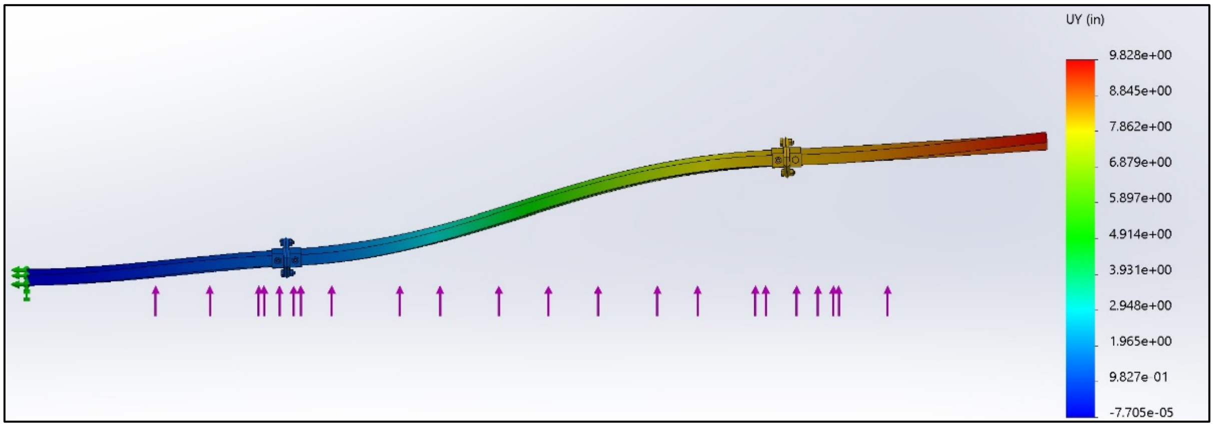

Figure 20: Simulated Deflection of Wing Skeleton

The stress of the beams is calculated using Equation 5. The SolidWorks stress analysis is 15,170 psi, and the analytically calculated stress is 10,883 psi which is significantly less than yield strength of the pine wood yard sticks. The moment of maximum stress occurs at the fixed end of the wings which are placed into the center of the fuselage.

$$\sigma = \frac{FLc}{I} \tag{5}$$

$$\sigma = \frac{(20)(36)\left(\frac{1.12}{2}\right)}{0.03705}$$

$$\sigma = 10{,}883\ psi$$

The 3D printed connectors are designed to have tabs that stick out of the foam for easy connection points. The meter sticks are cut into three 3 ft sections and two 1.5 ft sections, with the larger beam cut to 0.25 x 1.12 in., and the smaller beam cut to 0.25 x 0.72 in. The wooden sticks are also cut with holes that line up with the holes of the extruded 3D printed connectors. The wooden sticks are placed into the extruded connector and bolted into place, shown in Figure 21.

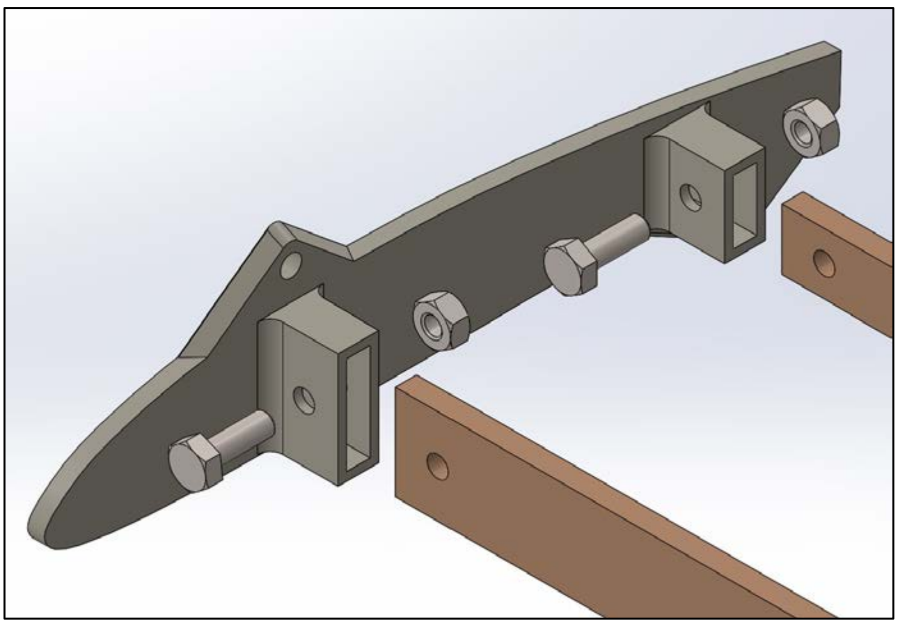

Figure 21: Place Wood Sticks into Slots and Bolt Together

The same steps are taken with another 3D printed connector that is designed and mirrored the exact opposite of the connector shown in Figure 22. Each set of connectors is then bolted together on the top and bottom with their matching pair, shown in Figure 22.

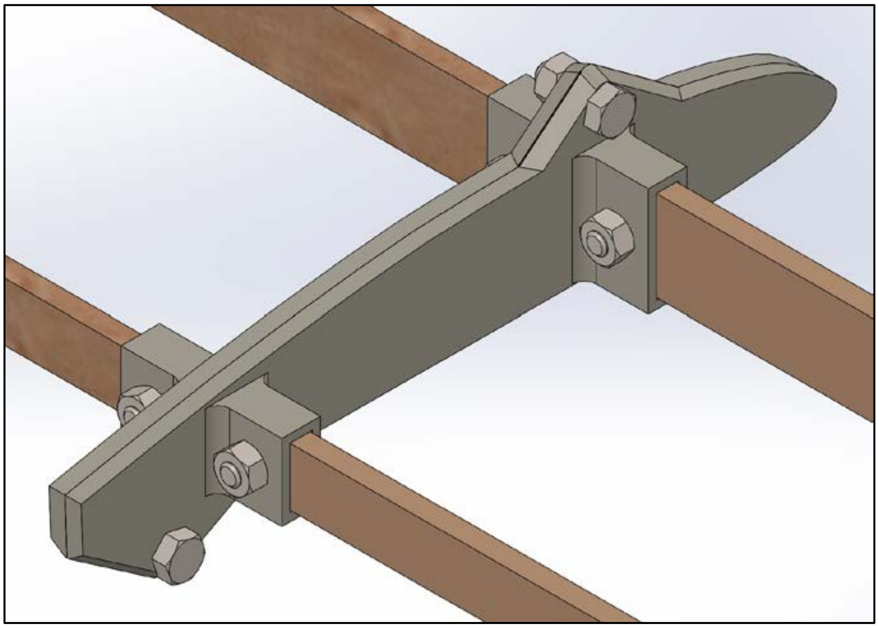

Figure 22: Bolt the Other Sections Together

These steps are repeated, placing the 3 ft beams together and the 1.5 ft beams on each end, shown in Figure 23.

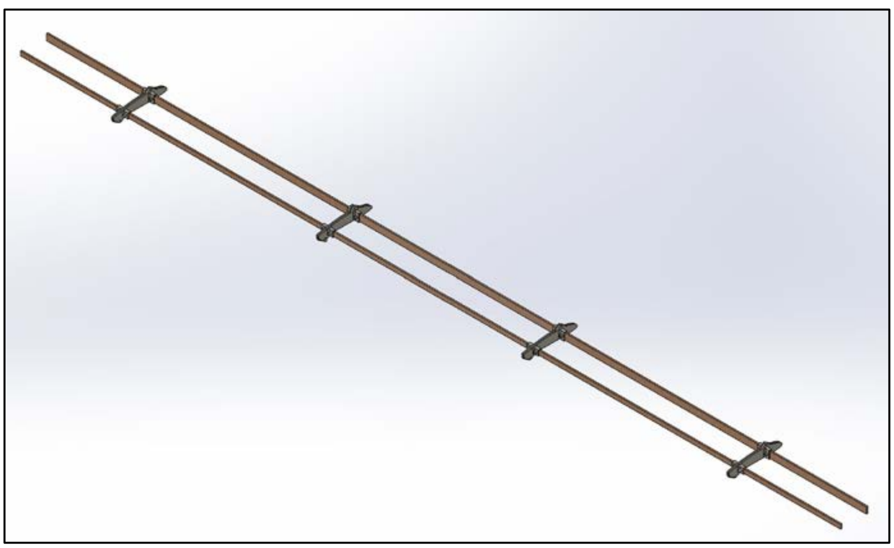

Figure 23: Repeat for Each Section of the Wing

The insulation foam board with dimensions 8 ft x 4 ft x 2 in is cut down into 1 ft x 13 in x 2 in pieces using the table saw. The boards are cut into smaller sections to be formed by the band saw which only allows for a cutting thickness up to 1 ft. An acrylic template of the Clark Y airfoil with the slots for the wooden beams is placed on top of the foam, and then it is traced with a marker. Next, the traced shape is cut using the band saw. The cutout part of the foam is then glued over the plastic connector and wooden sticks, shown in Figure 24.

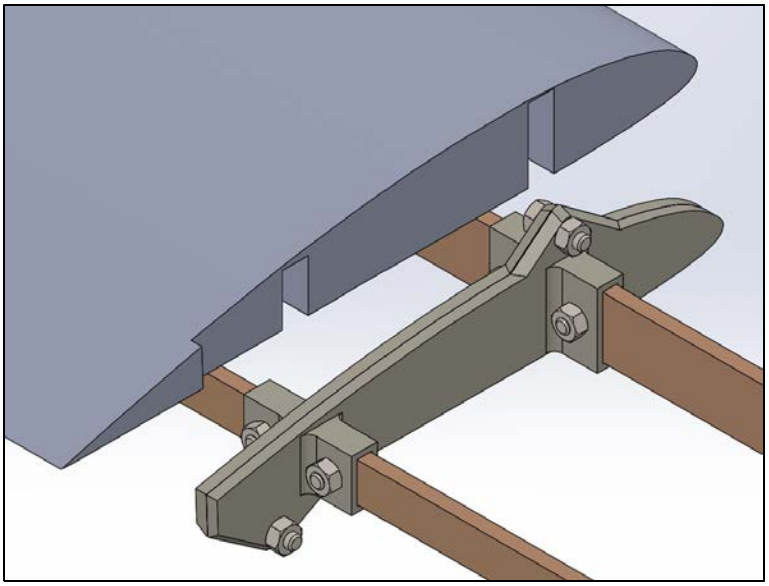

Figure 24: Place Cutout Part of Foam Around Plastic Connector

Figures 25 and 26 show the bottom and top view of the completed model of the connections. The foam sections are designed to be friction fit and secured using gorilla glue.

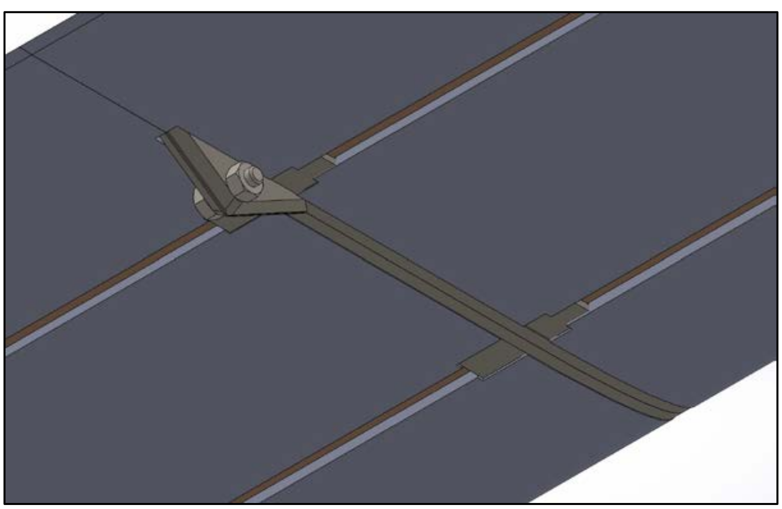

Figure 25: Bottom View of Completed Connection

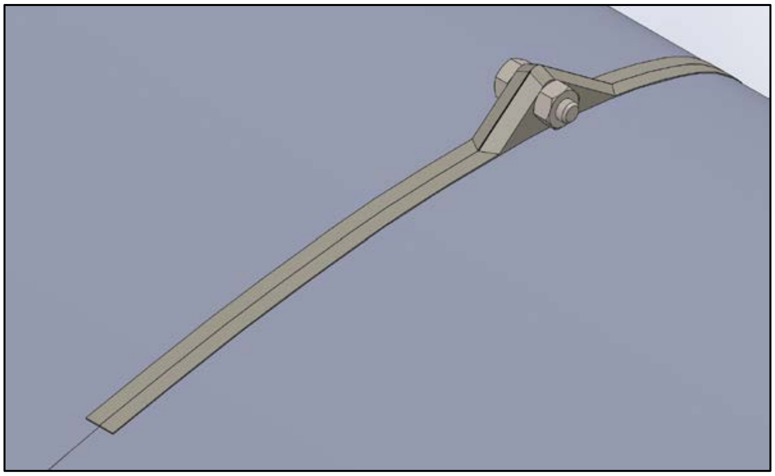

Figure 26: Top View of Completed Connections

Figure 27 is the final construction of a 3 ft section of wing. The aileron sections are cut out of the 3 ft sections into 24 in x 4.25 in pieces. The inner edges of the ailerons are cut at an angle for maximum vertical displacement. After the foam was glued to the wooden sticks, the wings are covered in packaging tape and spray paint. On the pieces with the ailerons, a hole is carved out for the servo motor to decrease the protrusion and decrease drag. Slits were also cut into the foam to secure the 3 pin wires of the servo motor.

Figure 27: Final Construction of a 3 ft Section

3.3 Tail Design & Construction

After understanding the different types of tail configurations, a conventional tail was selected to be considered as a final design. A conventional tail was the first to be considered because it is the most common tail. In addition, a conventional tail provides stability and control with limited added mass since we are aiming for a lightweight airplane. This type of tail is also easy to manufacture and adequate to the design. A finalized tail model can be seen in Figure 28. This model consists of 7 parts including the 2 airfoils. These parts are a rib, tapered circular section, a cylinder section, and two 3D printed components that will hold the two airfoils. The different parts of the tail can be seen in Figure 29 and are described in the same order in the figure from left to right.

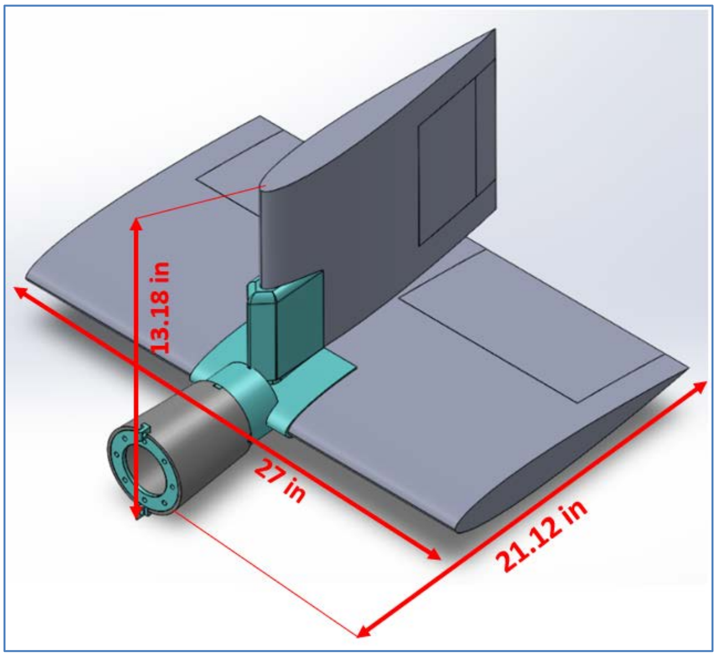

Figure 28: Tail Model

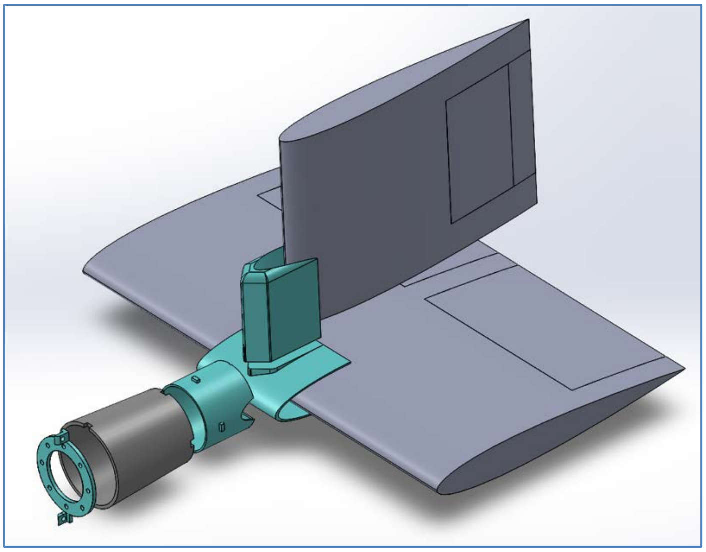

Figure 29: Tail Components Expanded

The rib has an outer diameter of 4.26 in and inner diameter of 2.76 in. The tapered section is 5.12 in long and 4.26 in tall on the left side and 3.62 in on the right side. The circular section is 3.12 in long with an outer diameter of 3.62 in and has an opening on the right side with the shape of the airfoil selected, NACA 0012, for the horizontal stabilizer. The dimensions of that opening are 1.92 in tall and 4.89 in long. One of the 3D printed parts will hold the horizontal stabilizer, and it is shaped to the NACA 0012 airfoil up to its max thickness. The dimensions of this part are 5 in tall, 1.82 in wide, and 4.13 in long. The vertical piece, a 3D printed part, has a triangular shape to allow the smooth flow of air, and it also has the shape of the NACA 0012. The horizontal stabilizer area is 25% of the wing area, and the vertical stabilizer area is 10% of the wing area.

The rib, the cylindrical sections, and the elevator and stabilizer connectors are 3D printed. Foam was used for the tapered section and for the two airfoils. The rib is the connector between the tail and the rest of the fuselage. It is secured using bolts and nuts and is also glued using

Gorilla glue to the foam tapered section. The PLA circular section is glued to the tapered section. The PLA horizontal section is glued to the opening in the circular part, and the horizontal stabilizer is glued to the PLA horizontal section. The PLA vertical section is glued on top of the horizontal piece and the upper section of the circular part, and the vertical stabilizer is glued to the vertical section which sits on top of the horizontal stabilizer.

The horizontal stabilizer has two connected elevators connected to a servo motor, and the vertical stabilizer has one rudder. The decision to use two elevators was made to avoid the conflict of motion of the elevator with the vertical stabilizer.

Stress and displacement analysis were performed on the tail structure with and without the horizontal and vertical stabilizers to compare where the stresses will be concentrated on each and compare the results. The results for these analyses are shown in Figure 30-33.

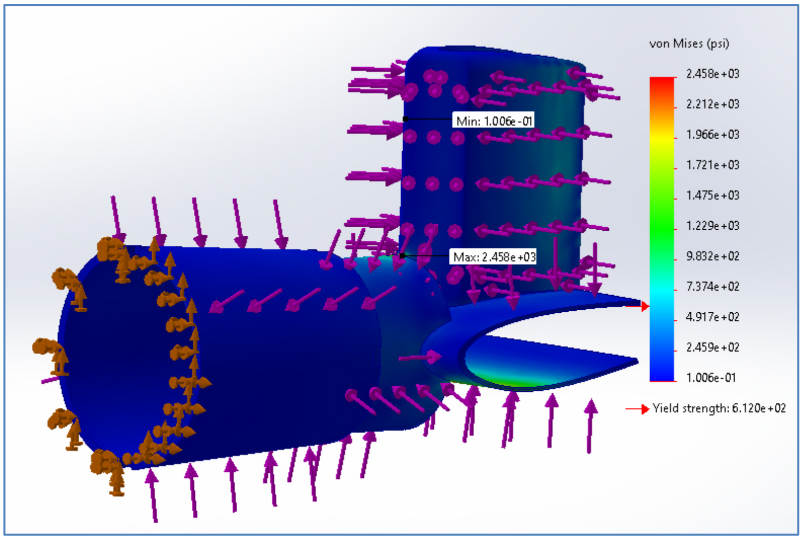

Figure 30: Stress Analysis of Tail Without Airfoils

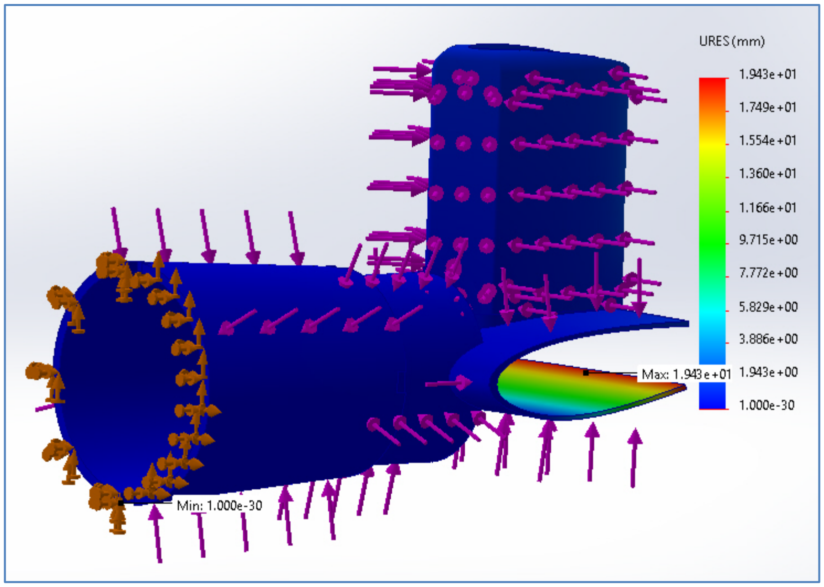

Figure 31: Displacement Analysis of Tail Without Airfoils

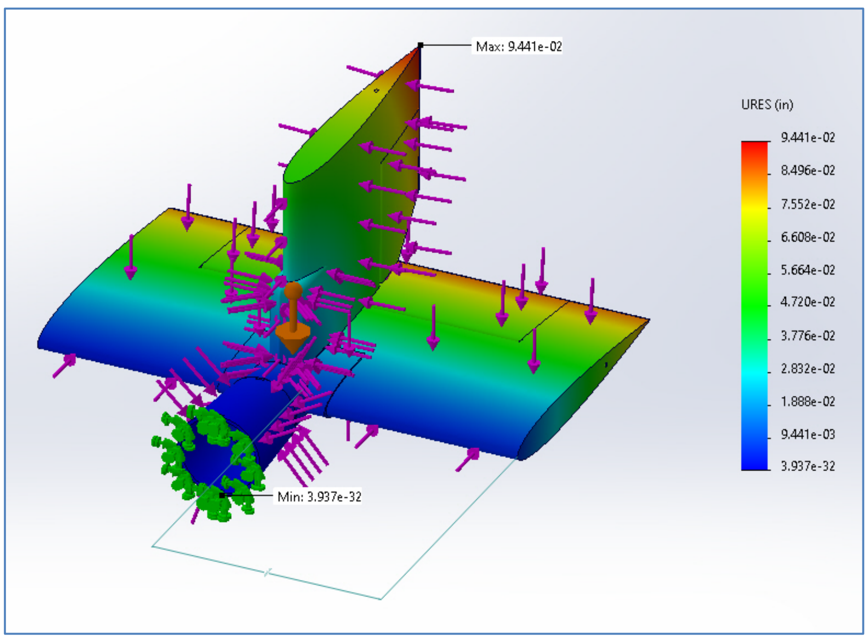

Figure 32: Stress Analysis of Tail With Airfoils

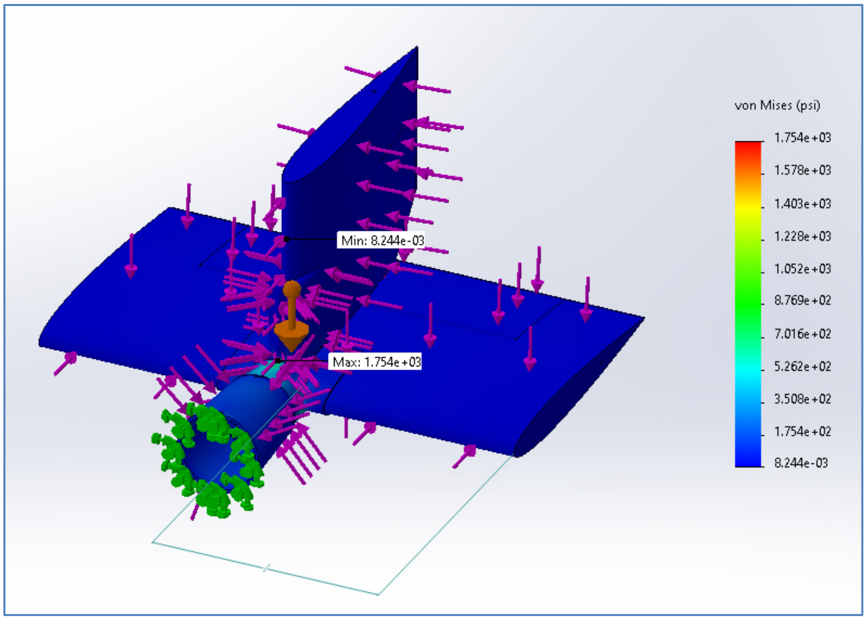

Figure 33: Displacement Analysis of Tail With Airfoils

The final tail design is presented in Figure 34. The tail went through some changes due to not passing the technical inspection at the beginning of the competition. The first revision attempted to comply with hinge gap requirements. The gap had to be smaller than 3/16 inch. Aluminum tape was used as a compliant mechanism. The tail incorporating the compliant idea is shown in Figure 35. This was still not enough to pass inspection. The team decided to use metal piano hinges, shown in Figure 36, and incorporated them into the tail to fully comply with hinge gap requirements. The downside of this decision was the increased tail weight, which changed the mass distribution of the plane, affecting our center of gravity. This change in center of gravity is compensated for with a ballast in the nose of the plane.

Figure 34: Final Tail before Competition

Figure 35: Tail After First Technical Inspection

Figure 36: Tail after Modification and approved by Technical Inspection

3.4 Tradeoffs

The wing must be constructed in parts less than 4 ft long. If the preliminary design foam wings were constructed in lengths of 4 ft, the distance between connections would be too great. The wooden dowel rods would bend too much. Aluminum rods were considered; however, the aluminum was determined to be too heavy for the stiffness properties it provided. Aluminum would decrease the amount of deflection, but the weight would be too much for the lift force generated by the motor. The chord length was going to be longer, but it would increase the volume which increases the weight with almost no lift force benefits. The preliminary design allows additional sections to be added as necessary. For example, adding two more sections will increase the length from 12 ft to 18 ft.

Two primary concepts were considered for the fuselage: a square fuselage biplane design and a tapered fuselage monoplane. The square biplane design had a large cargo bay and would have generated greater lifting forces than the monoplane due to having two wings. It would also have been easier to build as the foam board would not have needed to be rolled. This design was abandoned due to the turbulent zones seen in fluid analysis at the edges of the plane, shown in Figure 37, as well as being much heavier and having far greater drag than a traditional monoplane. A tapered fuselage was selected for the final design as it is more aerodynamic and lighter. It is however more difficult to build out of our selected materials and has significantly less room for potential cargo bay.

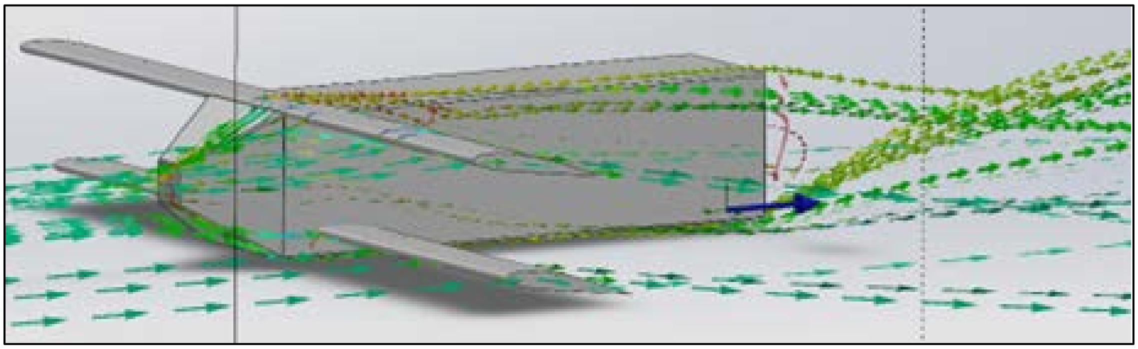

Figure 37: Square Fuselage Fluid Analysis

3.5 Electronics

As our team had limited experience with model aircraft electronics, we utilized a motor and battery bundle option provided by Neumotors, who also make the required electronic speed controller power limiter used in the competition. Appendix H shows how the wiring connections were made within the plane, and Appendix G shows the communication path between components. The motor provided by the package is a 4619/496 kV motor. The bundle suggests a 13 inch diameter by 7 inch pitch to achieve a static thrust force of 7.66 lbs. The dynamic thrust provided by the propeller is determined by the propeller's forward speed. Equation 4 [16] is used to find the dynamic thrust of the system. Eq. 4 is first used to determine the motor revolutions per minute, ω. The propeller pitch, p, is 7 in. The propeller diameter, d, is 13 in. When the propeller forward speed, V_0, is 0 mph, the static thrust force, T, is 7.66 lbs.

$$T = 9.04 \times 10^{-9} \frac{\omega d^{3.5}}{\sqrt{p}} (4.23 \times 10^{-4} \omega p - 2.237 V_0)$$

(1)

The motor has an output of $\omega = 9360$ revolutions per minute. Subbing this value into Eq. 1 and solving for T, we get Equation 5, which is plotted in Figure 38. The dynamic thrust decreases at 0.128 lbs./mph. The maximum velocity the propulsion system can provide thrust at is 62 mph.

$$T = 7.663 - 0.128V_0$$

(2)

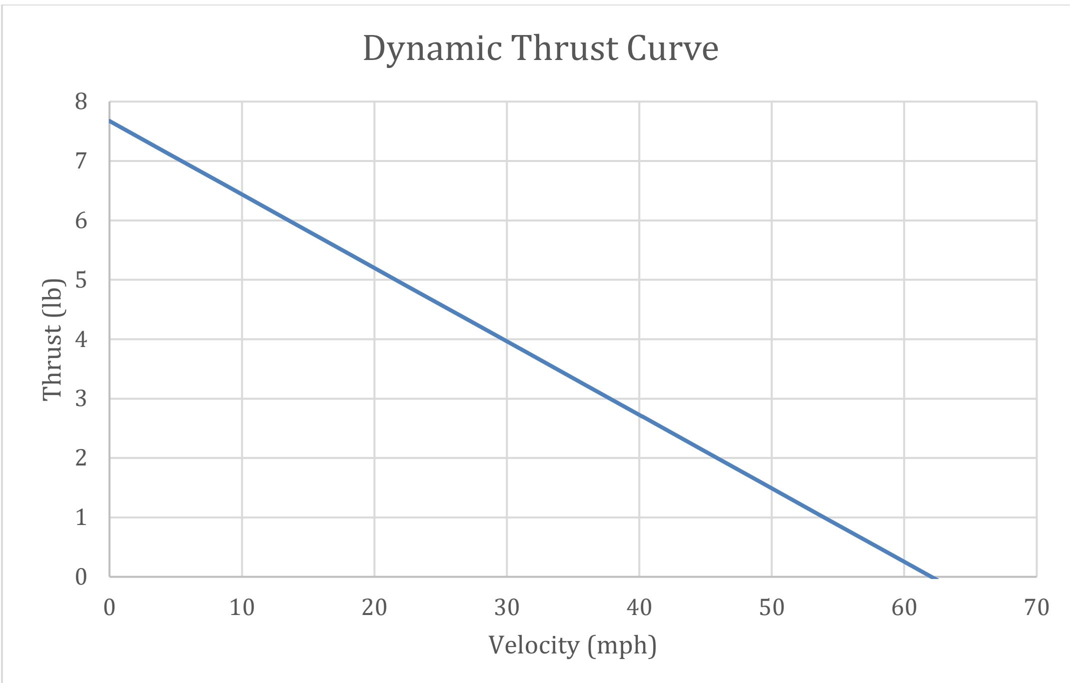

Figure 38: Dynamic Thrust Curve for the Electric Motor and Propeller

Control of all servos and motor input was completed using a FLYSKY 2.4 GHz 10 channel RC Transmitter and Receiver. The receiver was powered separately from the main motor battery using 4 AA batteries in an enclosure. Radio frequencies are regulated by the Federal Communications Commission (FCC). The Radio Control Radio Service (RCRS) bands are designated for one-way short distance communication and are commonly used for model aircraft and boats. [9] The 2.4 GHz frequency receiver we selected uses an unlicensed public use radio frequency that does not require licensure and avoids any interference that could have been experienced with other teams.

For public health and safety, an arming plug is connected between the battery and the rest of the system. Without the arming plug connected, the propeller will not spin, preventing injuries. The controller also has a fail-safe setting. If the receiver is disconnected from the controller, the propeller will stop spinning to prevent any other injuries.

3.6 SolidWorks Velocity Flow Simulation

SolidWorks was used to simulate the air free stream velocity. Figure 39 shows the free stream velocity paths on the final aircraft design. The simulation is run using a free stream velocity from 0 to 67 mph. Those values were chosen to determine the lift and drag forces acting on the aircraft at different speeds. Table 1 shows the results from the velocity flow simulation. The lift and drag forces are from the SolidWorks flow simulation, the thrust force is calculated from Eq 5, and T-D is the thrust force minus the drag force. The highlighted row was an interpolated value used to calculate the maximum velocity and lift force of the airplane, which is 40.24 mph with a lift force of 20.95 lbs.

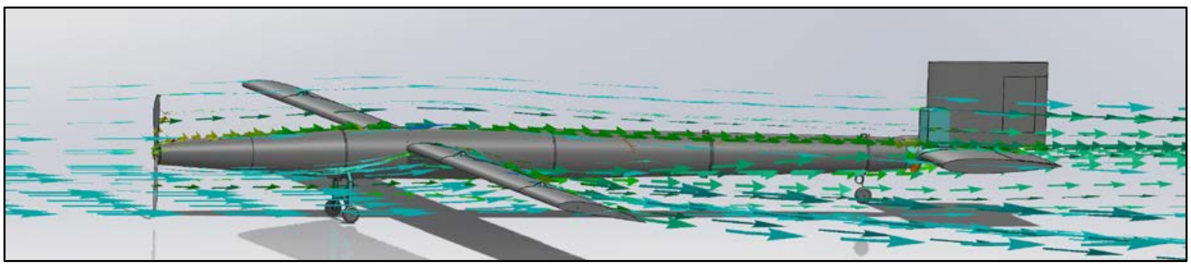

Figure 39: Velocity Flow Simulation

Table 1: SolidWorks Flow Simulation Results

Velocity (mph)	Lift (lb.)	Drag (lb.)	Thrust (lb.)	T-D (lb.)
0.00	0.00	0.00	7.67	7.67
4.47	0.31	0.04	7.12	7.08
8.95	1.04	0.14	6.57	6.42
13.42	2.27	0.31	6.01	5.70
17.90	4.05	0.54	5.46	4.92
22.37	6.40	0.84	4.91	4.07
26.84	9.29	1.19	4.35	3.16
31.32	12.84	1.64	3.80	2.16

35.79	16.86	2.14	3.25	1.11
40.24	20.95	2.70	2.70	0.00
40.27	20.98	2.70	2.69	-0.01
44.74	26.53	3.32	2.14	-1.18
49.21	32.21	4.03	1.59	-2.44
53.69	38.47	4.79	1.03	-3.76
58.16	45.30	5.42	0.48	-4.94
62.64	52.63	6.51	-0.07	-6.59
67.11	60.57	7.48	-0.63	-8.10

Figure 40 is the plot of the air freestream velocity versus the lift force and thrust minus drag force acting on the airplane displayed in Table 1. The airplane will continue to accelerate until it reaches a maximum velocity of 40 mph, providing a lift force of 21 lbs.

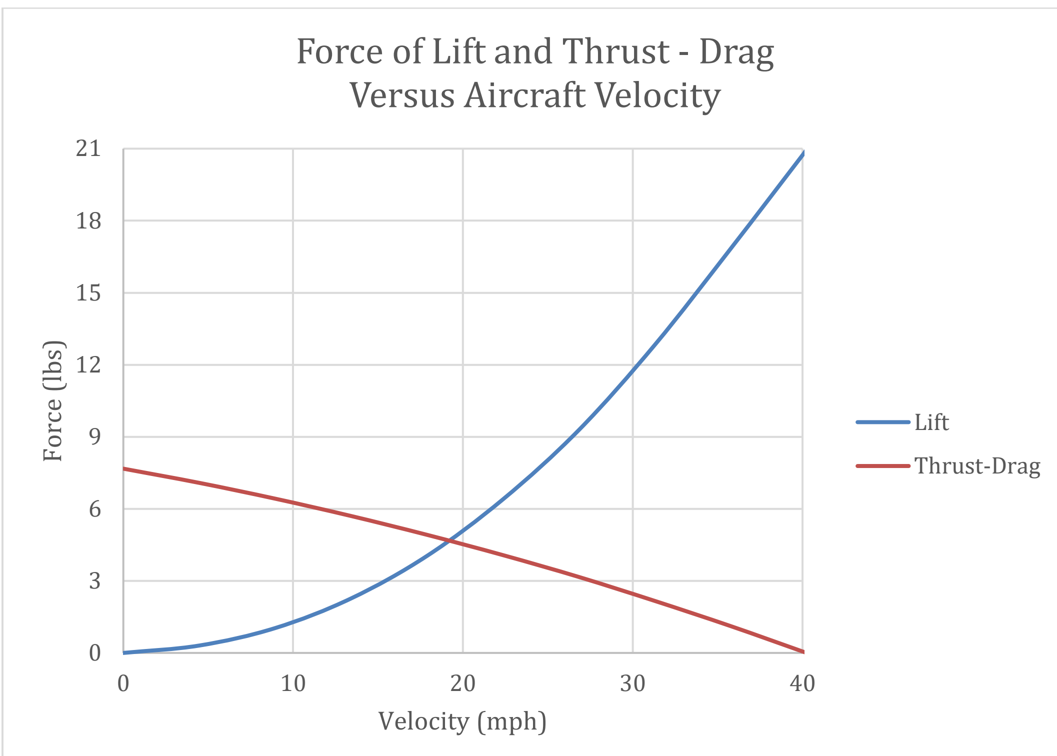

Figure 40: Plot of Freestream Velocity vs Force

4 Economic Considerations

Readi-Board foam board is utilized for the skin of the aircraft due to its low cost at $1.25 a sheet. Our initial budget for the project can be seen in Appendix C, and our final parts list can be seen in Appendix C1. PLA is also used to 3d print connections and rib supports. Other teams at the competition utilized balsa wood supports and aluminum frames which would have been significantly less cost effective. Travel was another economic consideration accounted for in the project. Six people traveled to Fort Worth for the competition. Driving two vehicles was approximately the same price as a single plane ticket from Evansville to Dallas Fort Worth airport. On top of airline tickets, the team would have still needed to transport the plane to Fort Worth which would have required a team member driving or freight shipping.

5 Design Modifications

5.1 Before the Competition

Prior to the competition, the airplane went through several modifications. Wooden dowel rods were originally going to be used instead of wooden yard sticks to support the wings; however, yard sticks provided the wings with more stability and decreased the total deflection. The downward deflection with the rods caused the wing tips to drag on the ground increasing the drag, preventing the aircraft from lifting off the ground.

The connection method between the wings and the fuselage had to change to accommodate the new wooden yard stick design. To locate the center of gravity at the wings, the wings were moved towards the tail, and the electronic speed controller was moved into the nose. Each connector on the fuselage was made taller to better accommodate tool access to bolt heads.

On departure day for the competition, the goal was to test the plane in the Applied Engineering Center (AEC) parking lot. After clearing the shop equipment to access the bay door and beginning to set the plane on the ground, two fuselage connectors tore out of the foam skin leaving the plane in three parts as seen in Figure 41. This failure was due to the foam being coated in paper. The Gorilla Glue saturated the paper but did not extend into the foam. The weight of the aircraft caused it to split into multiple pieces. The motor plate also tore out of the nose after falling in the parking lot. At this point, the team decided that the cargo bay would not be incorporated because the structure, where it was going to be located, needed to be reinforced.

Figure 41: Plane on Departure Day

5.2 At the Competition

The plane did not complete all the technical requirements required to fly at the competition in the first round of inspection. Two fuselage sections were permanently joined together.

The control rods were deflecting too much under compression. To account for the deflection, brass tubes were placed around the rods to stiffen the rods and decrease the amount of slop in the control surfaces. This reinforcement can be seen in Figure 42.

Figure 42: Brass Tubes Over Control Rods

The elevator and rudder were attached with metal piano hinges and ailerons were attached with aluminum tape to comply with the control surfaces hinge gap of no more than 3/16 in as shown in Figure 43 and Figure 44.

Figure 43: Aileron Aluminum Sheet

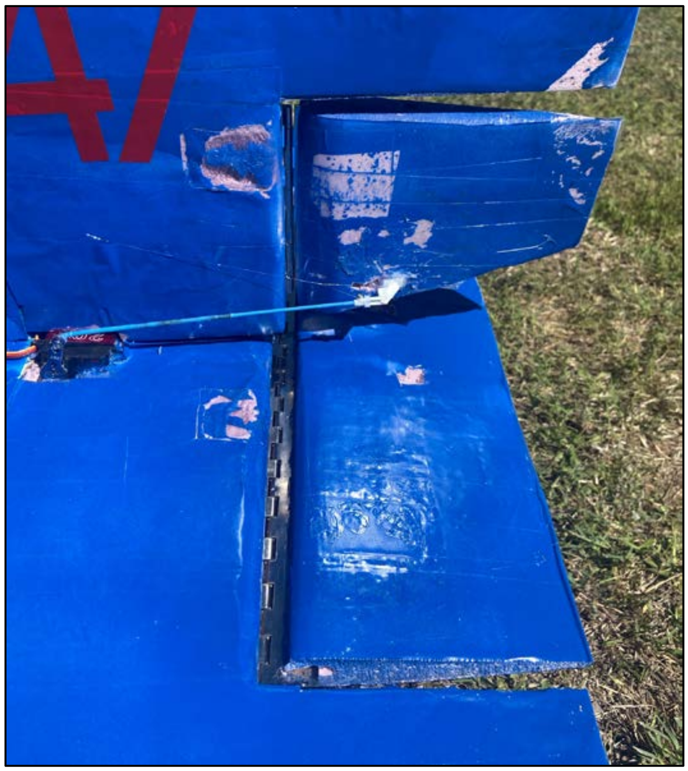

Figure 44: Elevator and Rudder Hinges

As shown in Figure 45, the motor mounting plate was reinforced after failing before leaving for the competition. More bolt mounting locations were added to distribute the load, and aluminum was added around the outside of the skin to strengthen the attachment point and move the center of gravity forward.

Figure 45: Propeller Reinforcement

To ensure the 3D printed connectors would not pull out of the skin, yard sticks are bolted through the fuselage and zip ties were added around the connector ribs for extra support. The zip ties are shown through the skin in Figure 46.

Figure 46: Reinforced Fuselage

During transportation, the front landing gear was damaged. It had been repaired previously, but the repairs also failed. Yard sticks were cut down and added to support the landing gear. These became our “safety measures” for the landing gear in the project and can be seen below in Figure 47. Appendix E includes our failure modes and effects analysis in which we had preemptively considered this failure.

Figure 47: Reinforced Landing Gear

Since weight was added to the tail with the metal hinges, a ballast was added to the nose to balance the center of gravity. The team had to go through technical inspection 5 times and was able to pass inspection on the second day after the flights had been opened and started. The team had to wait until the third day, the final day of competition, to be able to fly.

The team collected their flight log and attempted to fly for the first time. The attempt did not give the desired results of completing the flight loop with the plane since the motor lost power when the plane got off the ground. After this, the plane was carried back to our working station to see why there was no power to the motor. It was determined that the arming plug came loose when it was being set to the runway. This happened since the team had to add red tape around the arm plug to meet arming plug color requirements. The tape added extra thickness that caused the arming plug to not fully seat.

When setting the plane to the floor by our working area, one of the 3D connectors of the wings split. The team determined that there was not enough time for a second flight attempt since the line for making flight attempts was long.

6 Teamwork Experience

The project was split into multiple subsystems, and each team member was responsible for their own systems using designs from ME 471 Mechanical Engineering Design. Communication was completed using Microsoft Teams when working remotely, coordinating dates through instant messaging programs, and over lunch throughout the semester. Disagreements between team members were resolved by trying to incorporate both members' ideas. Designing our subsystem interfaces together would have prevented some conflict.

7 Disposal Plan

The team will coordinate final disposal of plane parts over finals week. The remaining unused foam will be saved and used within the AEC. Plane parts that cannot be reused will be thrown away. Electronic components will be saved for use by future design teams as the servos and motors can be utilized in different projects.

8 Conclusions and Recommendations

8.1 Future Recommendations

For any future teams, it is recommended that the team should have more participants with more assigned roles, because there are a lot of individual sections that make up an entire aircraft. The scope of this project would be easier with more members, as more time could be dedicated to building multiple prototypes further in advance. Our team schedule is included in Appendix B. While we began construction very early, shipping delays limited the progress that could be made and did not leave ample time for testing or part redesigns. The chord length can be significantly increased because it will increase the overall lift force, allowing for the design to accommodate a greater payload. Using an aluminum frame would decrease deflection within the components. Balsa wood is often used in place of 3D printed connectors for airfoils as they are lightweight. Shrink wrap is also often used as skin because it is lightweight and will not deflect under the weight of the aircraft. Using stiff control rods will maximize the distance traveled of the control surfaces with little deflection.

8.2 Conclusion

Overall, the total weight of the airplane was under 55 lbs. with an estimated weight of 13 lbs. Our original expected weight budget is included in Appendix D. Since several modifications were made at the competition, it is hard to give an actual final weight. Even though the flight results of the competition were not the ones desired by the team, the aircraft took off under 100 ft. The wingspan of 12 ft was consistent and was between the requirement of 10 to 18 ft in length. No part measures more than 4 ft in length even with the fixed parts repaired at the competition. We did not achieve the predicted payload weight of 7.5 lbs. since the airplane went through a lot of repairs from predicted and unpredictable failures. The team complied with the technical inspection standards by the SAE Aero Competition which indicates that their design followed and executed the requirements made by the Competition. The most valuable skill the team had was our engineering intuition for coming up with ideas to improve or modify the airplane, when necessary, to comply with the technical inspection at the competition.

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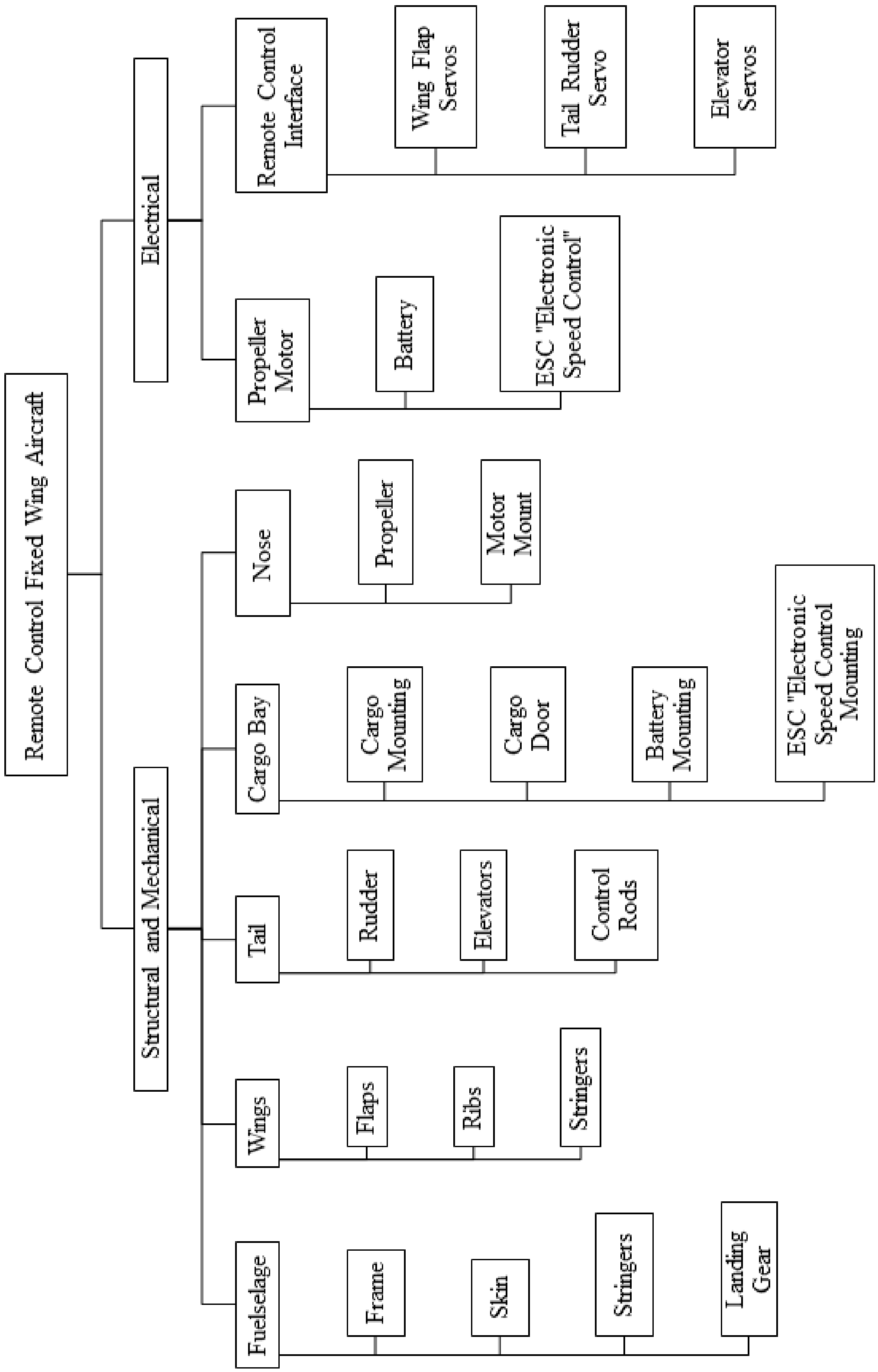
APPENDICIES

Appendix A: *System Hierarchy*



Appendix B: *Schedule*

Goal	Date
Fall 2022	
Working Budget for Parts	9-28-22
First Draft Senior Design Proposal	9-30-22
Quote Parts for Project	9-30-22
Begin Design of Aircraft	10-7-22
Final Draft Senior Design Proposal	10-7-22
Preliminary Design Review Oral Presentation	10-14-22
Senior Design Proposal Oral Presentation	10-17-22
Work on Final Concepts	10-21-22 – 11-28-22
SAE Aero Registration Closes	12-1-22
Agree Upon Concepts for Critical Design	12-5-22
Review Former Budget	12-5-22
Pre-Senior Design Report	12-7-22
Spring 2023	
Arrange Meetings with Senior Design Faculty Advisor	1-9-23
Order Parts for Project	1-20-23
Critical Design Review	2-9-23
Begin Construction on Final Design	2-10-23
Test Flights on Final Design	2-24-23
Begin Design Revisions	3-7-23
Senior Design Presentation	4-7-23
Finish Final Plane	4-7-23
Test Flights Finished Plane	4-10-23
SAE Aero West Competition	4-14-23
Summarize Results from Competition	4-19-23
Senior Design Poster Session	4-27-23
Final Report Due	4-27-23
Final Report Submission	5-5-23

Appendix C: *Budget*

Fee	Quantity	Cost ($)
Registration Fee	1	1400.00
Box Cutter, Utility Knife	1	6.99
SAE Batteries and Charger Bundle: Charger 3300 mAh Battery 5 pairs of XT60 connectors.	2	45.00
Neuromotors SAE Power System Bundle: Thrust/750 W 4425/400 motor APC 15 in x 8 in propeller Caste Creations Edge 75-amp controller 5 pairs of XT60 connectors 8 mm prop adapter 750-Watt SAE limiter	1	219.00
Hatchbox 1.75 mm PLA 3D Printer Filament, 1 kg Spool	1	24.99
6404U ¼" x ¼” x 48” Raw Round Dowel Rods	12	14.16
FOAMULAR 250 2in x 48 in x 8 ft.	2	108.00
Sunxeke 560 pcs. Breadboard and Jumper Wire kit PCB Circuit Board	1	12.99
MMobiel 5 pcs. SG90 9g Micro Servo Motor kit for RC Airplane	1	15.00
Raspberry Pi Pico RP2040 Microcontroller (2 pack)	1	13.59
Readi Board Foam Board 20 in x 30 in	10	10.00
Additional/Unforeseen Materials Budget		406.60
[redacted]		
Total		**3,500.00**

C1 - Full List of Materials

Name	Quantity	Price
FLYSKY FS-i6X 10CH 2.4GHz RC Transmitter Controller/W iA10B Receiver Upgrade Cable for RC Helicopter Plane Quadcopter Glider https://a.co/d/0oYfJL8	1	$52.98
SAE power system bundles including limiter	1	$219.00
SAE batteries and charger bundles	1	$178.00
FOAMULAR 250 2 in. x 48 in. x 8 ft. R-10 Scored Squared Edge Foam Board Insulation Sheathing	2	$112.00
HATCHBOX PLA PRO+ 3D Printer Filament, Dimensional Accuracty +/- 0.03 mm, 1 kg Spool, 1.75 mm, Light Blue	1	$28.00
BTF-LIGHTIN WS2812B WS2811 RGB Electrical Extension Cable 3 Pin 32.8ft/10m 18AWG LED Strip Light Ribbon Wire Connection 3 Core Cord Line for WS2812 Color Changing Flexible LED Tape Rope	1	$12.99
10Pcs Adjustable Pushrod Connector Linkage Stopper 1.3mm & 10Pcs Nylon Control Horns 21x10 mm & 10Pcs 1.2 x 210mm Steel Z Push Rods Parts Compatible for RC Airplane Plane Boat Replacement Ltvystore	1	$11.99
Hobbypark 1 Set Aluminum Main Landing Gear Wheel Kit RC Airplane Cessna 182 Parts Replacement 40 Size ARF PNP	1	$14.98
Readi-Board White Foam Boards, 20x30 in.	40	$50.00
ZOSKAY 1X DS3218 Update servo 20KG Full Metal Gear Digital servo Baja servo Waterproof servo for Baja Cars (Control Angle 180)	5	$78.30
8 oz. Original Glue	2	$25.96
Dowel Rods Wood Sticks Wooden Dowel Rods - 1/4 x 48 Inch Unfinished Hardwood Sticks - for Crafts and DIYers - 50 Pieces by Woodpeckers	1	$46.63
1/4 in.-20 Zinc Plated Hex Nut (100-Pack)	1	7.65
1/4 in.-20 x 3/4 in. Zinc Plated Hex Bolt (100-Pack)	1	$13.60
5 in. Hobby Knife	2	$11.94
Mini Glue Gun	1	$6.87
0.25 oz. All-Purpose Clear Mini Glue Sticks (24-Pack)	1	$5.67
14 in. UV Resist Zip Ties, Black (20-Pack)	1	$4.48

Heat Shrink Tubing - Assorted Colors	1	$12.09
Innov8tive Designs Arming Plug Cable with XT60 Connectors	2	$19.98
ZOSKAY 1X DS3218 Update servo 20KG Full Metal Gear Digital servo Baja servo Waterproof servo for Baja Cars (Control Angle 180)	6	$93.96
SAE LIMITER 2023 750W	1	$85.00
13x7	3	$20.70
Antrader Breadboard Jumper Wires 40 Pin 10CM Male to Female Jumper Cable	1	$5.49
Smseace 160pcs Bullet connector Terminal Insulated Female and Male 22-16/16-14/12 -10AWG Wire connectors Bullet Crimp Terminal SM-03	1	$9.99
SHLA Lowe Yard Stick 100 Year Celebration	20	$39.60
Scotch Heavy Duty Shipping Packaging Tape, 1.88" x 54.6 yd, 3" Core, Clear, Great for Packing, Shipping & Moving, 6 Rolls (3850-6)	2	$49.00
	Total	**$1,216.85**

Appendix D: *Weight Table*

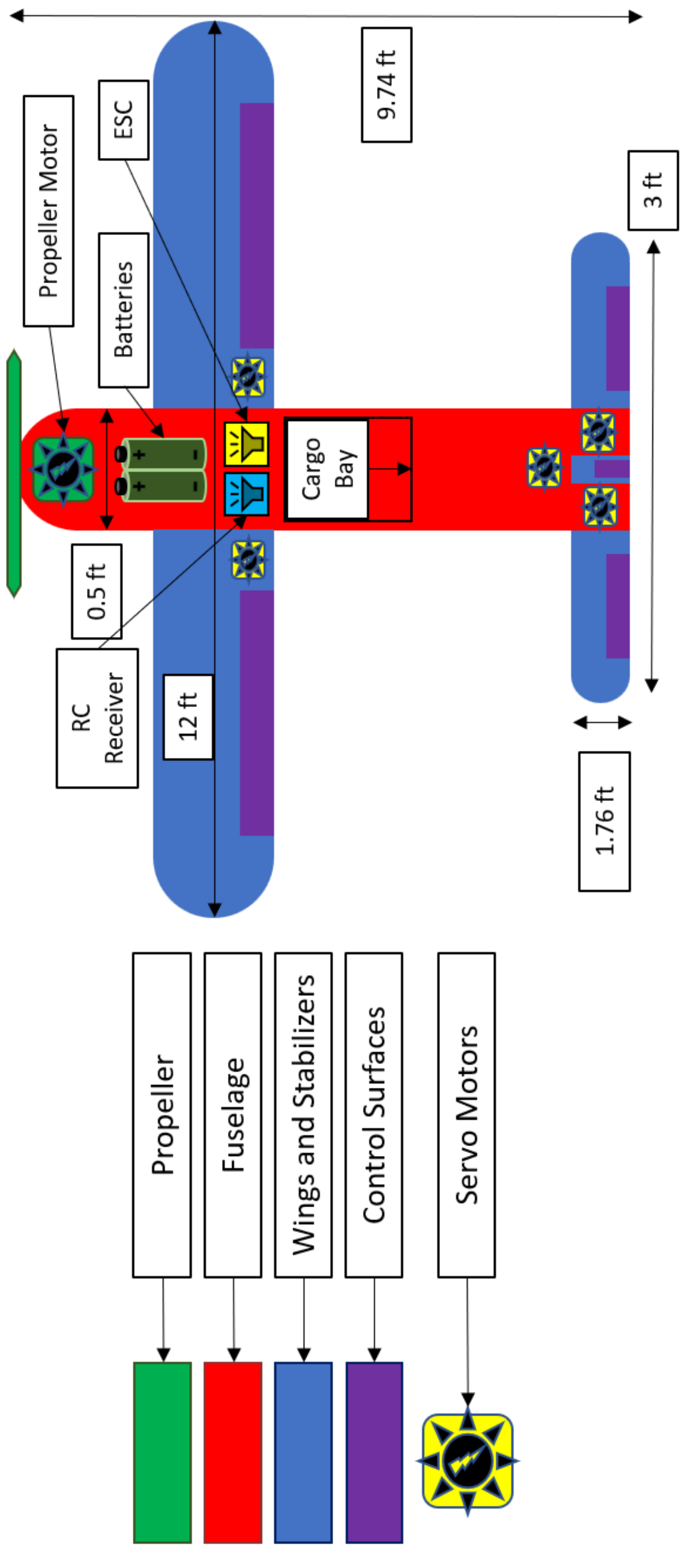
Mass for Project					
Item	Mass (kg)	25% Margin (kg)	Total (kg)	Total (N)	Total (lb)
Motor	0.208	0.052	0.260	2.551	0.573
Batteries	0.507	0.127	0.634	6.217	1.397
ESC	0.100	0.025	0.125	1.226	0.276
Fuselage	0.458	0.115	0.573	5.616	1.262
Wings	0.691	0.173	0.864	8.473	1.904
Rudder	0.125	0.031	0.156	1.533	0.344
Elevator	0.063	0.016	0.078	0.766	0.172
Servo Motors (5)	0.065	0.016	0.081	0.797	0.179
Control Rods	0.231	0.058	0.289	2.833	0.637
Landing Gear	0.038	0.010	0.048	0.466	0.105
Propeller	0.025	0.006	0.031	0.307	0.069
Misc. Wiring	0.060	0.015	0.075	0.736	0.165
Payload	0.333	0.083	0.416	4.078	0.916
Total	**2.903**	**0.726**	**3.629**	**35.598**	**8.000**

Appendix E: *Failure Modes and Effects Analyses*

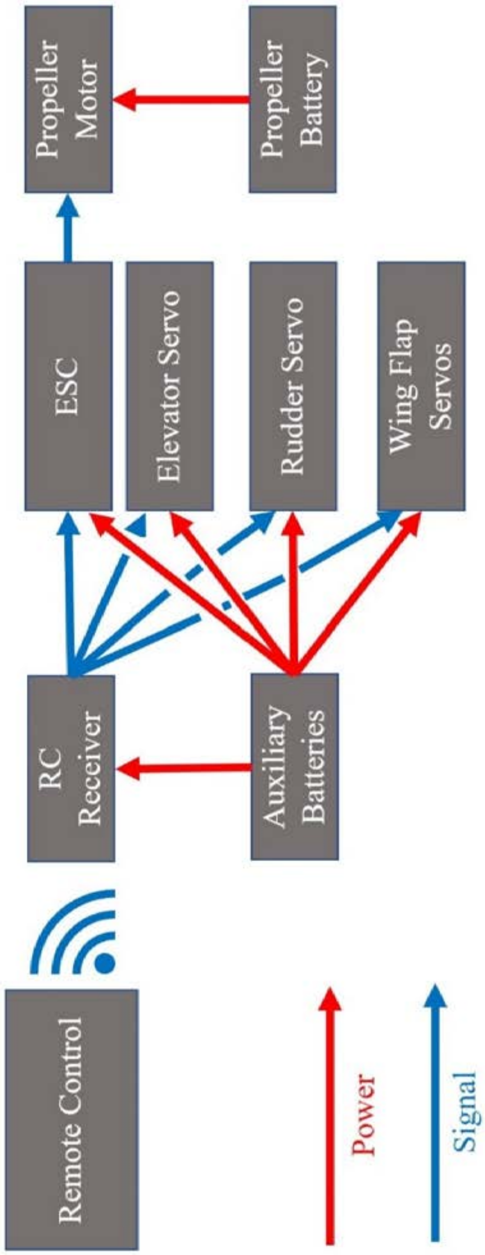
Item	Failure Modes	Causes of Failure	Possible Effects	Probability (1-10)	Level	Possible Action to reduce failure
Servo Motor	Do not provide enough power	Wrong calculations of power needed	No start No lift	4	10	Test the power of the motor before assembling to the struture
	Do not get tested	Late arrival of part		7	10	Set and follow a schedule for ordering parts
Propeller	Rupture	Impact against ground while testing	Turn off during flight Destroyed after impact Does not spins	3	10	Test the stresses that will be acting on the propeller
	Not enough rotational speed	Underpowered Motor		8	8	
Landing Gear	Wrong sizes	Additional weight Overpass the height limit of airplane Late arrival of parts	Aircraft will not take off Disassembly before taking off Crash	2	8	Create models and do simulations the different sizes to determine the right size before ordering
	Rupture	Impact against ground while testing Assembling the part		5	8	Do simulations to determine the impact force that the landing gear can stand
Wings	Weak internal structure	Material selected is not strong enough Weak connections while assembling	Disassembly of the wings while in the air Aircraft will not take off Uncontrollable once in the air	5	10	Test and analyze different internal structure
	Do not get enough lift	Material selected is too heavy Airfoil shape selected provide more drag force than lift		4	10	FEA analysis before testing
Stabilizers	Rupture	Impact against ground while testing Assembling the part	Crash Unable to assembly	5	8	FEA analysis before testing
	Do not provide balance	Uncontrollable on the air		4	8	Flow analysis before testing

Item	Failure Modes	Causes of Failure	Possible Effects	Probability (1-10)	Level	Possible Action to reduce failure
Landing Gear	Rupture	Crash on Impact	Damage to Aircraft	3	8	Test Flights Reinforced Structure
Servo Motors	Don't Actuate	Disconnected Wire Mechanical Failure Broken Output Shaft Power Failure	Crash No Lift No Steering	5	10	Test motor after assembly while loaded
Battery	Dead	Not Replaced after use	No power	2	10	Replace batteries after each flight
Connections	Deformation during travel	Wings won't attach to fuselage	Cannot Compete	4	10	Strong fuselage and wing structure and connections
Structure	Rupture Deformation	Bumpy road during travel	Damaged Connections Deformed Airfoil Damaged Electronics	6	8	Strong fuselage and wing structure and connections. Secure well in trailer.

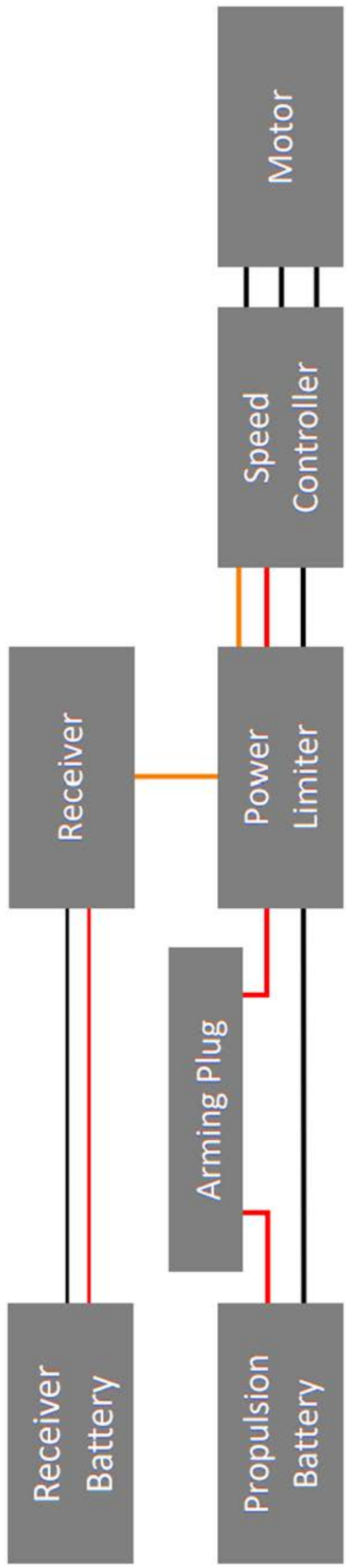
Appendix F: *Mechanical Block Diagram*



Appendix G: *Functional Block Diagram*



Appendix H: *Electronic Block Diagram*



Appendix I: *ABET Outcome 2, Design Factor Considerations*

Table 2: Design Factors Considered

Design Factor	Page number, or reason not applicable
Public health safety, and welfare	PG 8 and PG 33
Global	Not applicable because the airplane construction does not have a global effect.
Cultural	Not applicable because the airplane construction does not have a cultural effect.
Social	Not applicable because the airplane construction does not have a societal effect.
Environmental	Not applicable because the airplane construction does not have an environmental effect.
Economic	PG 35
Ethical & Professional	Not applicable because the airplane construction does not have an ethical or professional effect.
Reference for Standards	PG 32