Design, Simulate, Build, and Test an RC Airplane

A Major Qualifying Project
Submitted to the Faculty of
Worcester Polytechnic Institute
In partial fulfillment of the requirements for the
Degree in Bachelor of Science
in
Mechanical Engineering
By

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Abstract

The objective of this MQP was to design, simulate, and build a radio-controlled airplane in accordance with the annual SAE Aero Design East competition rules (Regular Class). Through internal and external fundraising and careful resource allocation, the project goal was successfully achieved, and the team participated at the competition held in Lakeland, FL.

The project was broken up by each academic term, with A term being dedicated to research, B term to design, and C term to construction. Aspects of project management, design layouts, analyses, manufacturing, and competition results are presented, and a discussion of the lessons learned and the recommendations for future improvements are provided.

Acknowledgements

We would like to acknowledge Daren Hudson and John Yassemides from AMA District I as well as Randy Holtgrefe and Jack Buckley from the Central Massachusetts R/C Modelers club for providing us with knowledge, materials, a pilot, and a place to fly. Special thanks to Aimtek, BAE Systems, Oxford Consulting, and WPI for graciously donating money and supplies, and thanks to all who donated to our Go-Fund-Me and assisted us with administrative duties.

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List of Symbols

A	Aspect Ratio	m	Mass
A_c	Cross-Sectional Area	n	Load Factor
a	Acceleration	P	Cargo Mass
B	Predefined Constant for Tire Sizing	R	Turning Radius
b, b_w	Wing Span	Re	Reynolds Number
C	Predefined Constant for Fuselage Sizing	S, S_w	Reference Wing Area
Cbar, Cbar_w	Mean Aerodynamic Chord	S_1	Maximum Control Surface Deflection
C_{drag}, C_d	Coefficient of Drag	S_2	Maximum Servo Motor Deflection
c_{ht}	Horizontal Tail Volume Coefficient	S_{ht}	Horizontal Tail Area
C_{lift}, C_L	Coefficient of Lift	S_{vt}	Vertical Tail Area
C_{root}	Wing Tip Chord Length	v	Velocity
C_{tip}	Wing Tip Chord Length	v_c	Cruise Velocity
c_{vt}	Vertical Tail Volume Coefficient	v_s	Stall Velocity
d	Distance of Impact	W_{Total}	Total Weight
F_D	Drag Force	W_w	Weight on Wheel
F_N	Net Force	Ybar	Spanwise Location of Cbar
F_T	Thrust Force	α	Angle of Attack
g	Acceleration Due to Gravity	γ	Wing Dihedral Angle
K_p	Predefined Propeller Size Coefficient	Λ	Wing Sweep
L	Fuselage Length	θ	Bank Angle
L_{Force}	Lift Force	λ	Taper Ratio
L_{ht}	Horizontal Tail Moment Arm	ρ	Air Density
L_{vt}	Vertical Tail Moment Arm		

List of Abbreviations

CAD	Computer Aided Design	RPM	Revolutions Per Minute
CG	Center of Gravity	TMA	Tail Moment Arm
NACA	National Advisory Committee for Aeronautics	SAE	Society of Automotive Engineering

List of Figures and Tables

1. Introduction

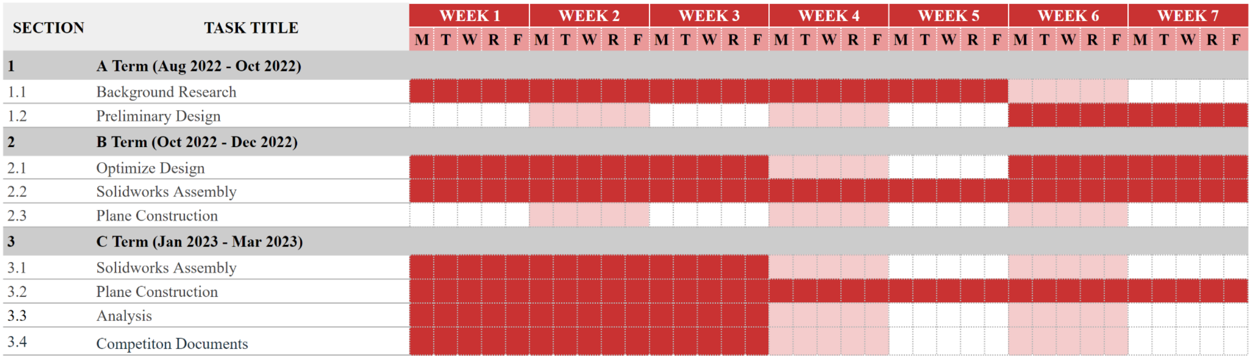
1.1 Goals

The purpose of this project was to design, simulate, build, and test a remote-controlled airplane that could be flown in the 2023 SAE Aero East Design Competition in the Regular Class. To achieve this, the team conducted research, raised adequate funds, produced designs, performed simulations, gathered materials, fabricated components, tested prototypes, and finally competed with the finished plane in March 2023.

1.2 Project Management

1.2.1 Schedule Summary

The team began work in June 2022 by developing fundraising and logistics goals. This project was the first of its kind for Worcester Polytechnic Institute's Mechanical Engineering department, meaning the team had no previous information or prototypes to rely on. Figure 1 displays the project timeline. The team began background research at the start of A term. This included reviewing the designs of successful teams at past SAE Design competitions and of real planes and learning about aircraft design and the math involved. Once this was completed, the team began drafting preliminary designs before choosing one to optimize. Optimization began at the start of B term. After the plane sizing was determined through optimization math, the team began modeling the plane in Solidworks. Materials and electronics selections were determined in early C term as the team concluded the CAD model and began construction. The team completed a mathematical analysis of the model using software such as ANSYS Fluent and XFLR5 as well as general calculations. The technical report and presentation was completed once the CAD and analysis were finalized. Manufacturing of the plane continued until the competition, which prohibited the team from being able to test fly or make modifications before the competition.



SECTION	TASK TITLE	WEEK 1					WEEK 2					WEEK 3					WEEK 4					WEEK 5					WEEK 6					WEEK 7				
		M	T	W	R	F	M	T	W	R	F	M	T	W	R	F	M	T	W	R	F	M	T	W	R	F	M	T	W	R	F	M	T	W	R	F
1	**A Term (Aug 2022 - Oct 2022)**																																			
1.1	Background Research	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	▨	▨	▨	▨	▨					
1.2	Preliminary Design						▨	▨	▨	▨	▨						▨	▨	▨	▨	▨						🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
2	**B Term (Oct 2022 - Dec 2022)**																																			
2.1	Optimize Design	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	▨	▨	▨	▨	▨						🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
2.2	Solidworks Assembly	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
2.3	Plane Construction						▨	▨	▨	▨	▨						▨	▨	▨	▨	▨						▨	▨	▨	▨	▨					
3	**C Term (Jan 2023 - Mar 2023)**																																			
3.1	Solidworks Assembly	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	▨	▨	▨	▨	▨						▨	▨	▨	▨	▨					
3.2	Plane Construction	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
3.3	Analysis	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	▨	▨	▨	▨	▨						▨	▨	▨	▨	▨					
3.4	Competiton Documents	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	▨	▨	▨	▨	▨						▨	▨	▨	▨	▨					

Figure 1: Gantt Chart Timeline of the Project

1.2.2 Personnel Management

The team was composed of four members, one of whom was the designated team captain. The limited number of members prevented the team from splitting into sub-teams that could focus individually on one aspect of the plane’s design. Instead, the team designated roles for certain tasks while keeping larger tasks centralized amongst the whole group. One of the primary roles was that of the lawyer; this individual thoroughly learned the rules for the competition. Another role was dedicated to fundraising and being in charge of the finances. An individual on the team was experienced with simulation software so they became in charge of conducting the simulations for the plane. Lastly, a few members became certified to use certain machines at the school’s maker space, so they became responsible for manufacturing parts requiring those machines.

1.2.3 Cost Report

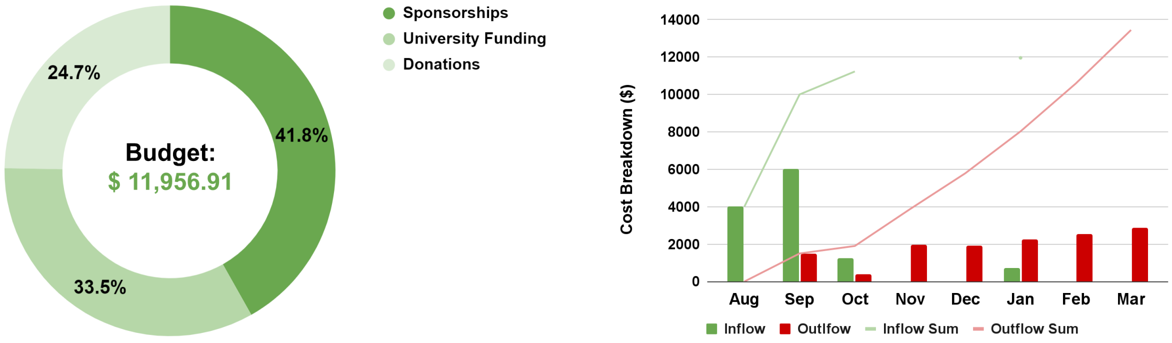


Figure 2a: Inflow Breakdown

Figure 2b: Budget Summary

Figure 2: Cost Summary

The funds for this project were obtained through corporate sponsors, university funding, and online crowdfunding. The team was able to receive the majority of the funding from several sponsorships. The team received $5,000 in monetary donations from BAE systems, roughly $1,000 worth of supplies and materials from Aimtek, and a donation of the apparel the team wore at the competition and during project presentations was gifted by Oxford Consulting. Various WPI departments contributed to this project as well. On top of the MQP budget each student receives, the team gained support from University Advancement, the Mechanical & Materials Engineering Department, and the Dean of Engineering. About $2,000 was donated by friends and family through the GoFundMe page created for the project. Most funding and donations were obtained very early on in project development, necessitating a careful spending approach to ensure adequate funds remained in the months leading up to the competition.

Initially, registration and travel/lodging accounted for slightly over half of the expenses, with the rest going toward construction materials and electronics. An in-depth cost analysis was completed to determine the cheapest method of transporting the team and plane to and from the competition. Immediately before the competition, complications with the travel means occurred resulting in an overdraft of the budget by about $1,500. Had everything gone accordingly, this project would have remained within budget. Figure 2 displays the breakdown of the budget as well as the month in which inflow and outflow occurred.

1.3 Competition Details

The SAE Aero East Design Competition is an international design competition that invites teams of college students to design, build, and fly remote-controlled airplanes. Each year, SAE determines the design objectives of each of the three competition classes—Micro, Regular, and Advanced—and specifies the requirements that each plane must fulfill in order to earn points. This year, the Regular Class objective was to build a plane that was capable of carrying "boxed cargo," which was to be made of metal weight plates that each team fabricated for themselves. The overall competition guidelines were as follows:

- Competition dates: March 10th - 12th in Lakeland, FL
- Weight: maximum gross takeoff weight cannot exceed 55 lbs.
- Wingspan: must be between 120 in. - 216 in.
- Propulsion: a single electric motor limited to 750 W
- Cargo: "boxed cargo" (i.e., weight plates fabricated by each team; must be unloaded by a maximum of 2 team members within 1 minute after landing to be counted towards overall flight score)
- Additional design restrictions:
  - No part can exceed a length of 48 in.
  - Fiber-reinforced materials may only be used in the propeller and landing gear
- Takeoff distance: 100 ft maximum.

- Landing distance: 400 ft maximum.
- Additional deliverables:
    - Technical report detailing the specifications of the airplane and its expected carrying capacity
    - Technical presentation to be given to a panel of judges explaining the design process and features of the airplane

Teams were scored based on the physical performance of the plane, the contents of the technical report, and the results of the technical presentation.

2. Research and Literature Review

2.1 Design Reviews

2.1.1 Real-Life Aircraft

To begin the design process, several real-life airplanes and past SAE Aero competitors' designs were thoroughly reviewed for information regarding which design aspects were beneficial for which applications. The real-life planes chosen were the B24 Liberator, the P38, the M28, the Cessna Skyhawk, the B17, and the P51. The team chose these specific models to review because together they gave a wide range of potential designs to choose from; by reviewing this array, the team was able to determine which aspects would be most beneficial to what was trying to accomplish with the design. For the real aircraft, overall dimensions, fuselage design aspects, landing gear placement, wing design/placement, tail design/placement, motor placement, and stability were considered. After evaluating each design, it was determined that the team wanted the design to include several aspects from the research.

2.1.1.1 Wings

It was found that a wing mounted atop the fuselage was best for stability (Appendix B), as seen in the Cessna Skyhawk; this extra stability could be beneficial to this design in case the team fell short in a different aspect of the design or if the plane were forced to fly in poor atmospheric conditions.

2.1.1.2 Landing Gear

The landing gear seen on several of these models was determined to be a tricycle layout, a configuration including a single nose wheel located at the front of the plane and two located behind the plane's CG. This configuration was more stable than the conventional arrangement since the aircraft's center of gravity sits between the front and rear landing gear. This provides a greater margin for error when landing, which was also decided would be a valuable safety measure in the design.

2.1.1.3 Tail

Finally, the team chose a conventional configuration, including two horizontal stabilizers located on either side of one vertical stabilizer, for the tail of the design. This configuration seemed to be the most common in the real designs and provided stability while also adding the least amount of weight to the plane.

2.1.2 Previous Competition Designs

The design choices made from the real-life models were solidified by looking at the schools from previous competitions' planes. The team chose to review the designs from Texas A&M University, Pennsylvania State University, the University of Michigan, Lawrence

Technological University, the University of Manitoba, and Dwarkadas J. Sanghvi College of Engineering. For these designs, the team primarily looked at the materials used, the dimensions, and the weight of each plane with and without cargo. This information provided reasonable targets to strive for with the team's own design and acted as a guide through the beginning of the process. More detailed information on this background research can be found in Appendix B.

2.2 Aircraft Design Textbook Summary

While reading through the textbook *Aircraft Design: A Conceptual Approach* [3], the team took notes on each relevant chapter in designing a plane. This included chapters 1-6, 8-13, 15-17, and 19. The first half of the book discusses initial requirements, definition, sizing, preliminary geometry, and configuration layout before covering aerodynamics, structures, propulsion, etc.; Chapters 2-3 introduce the reader to the design process, while Chapters 4-11 discuss techniques for the development of an initial configuration layout. The second half of the book explains the processes of concept analysis, optimization, and iteration; Chapters 12-17 describe a detailed analysis of the resulting design layout, and Chapter 19 shows optimization methods. Further detail of these notes can be found in Appendix E.

3. Preliminary Designs & Analyses

3.1 Initial Design Calculations

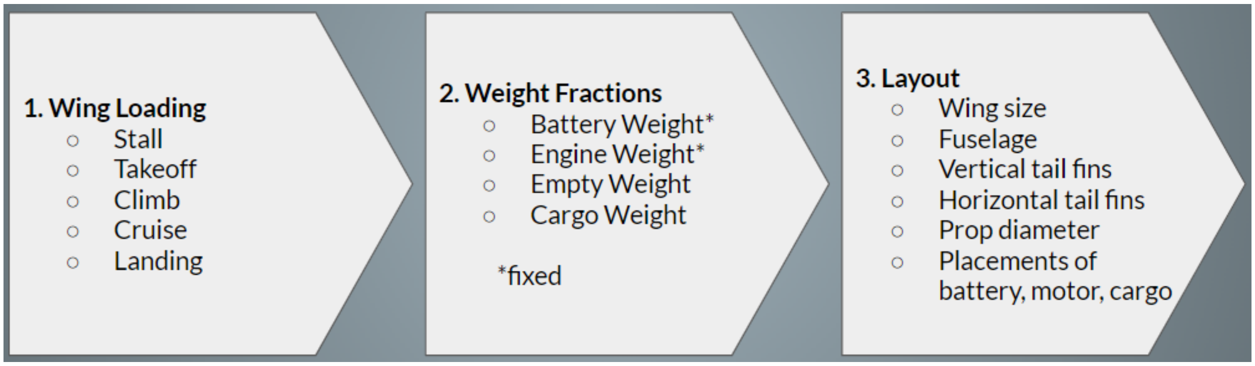
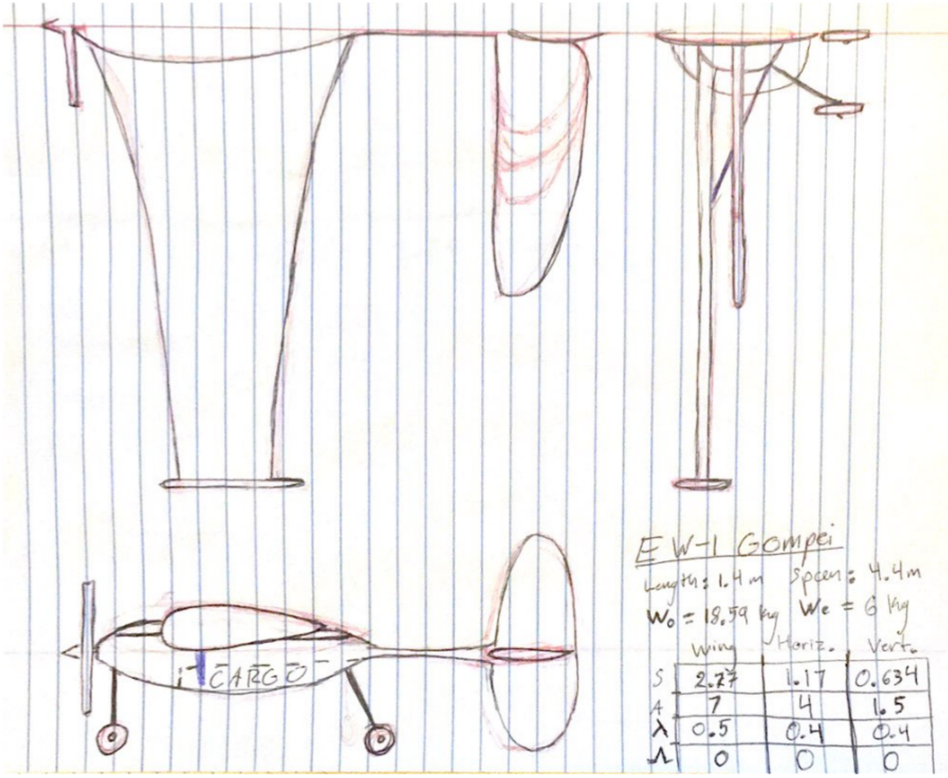


Figure 3: Design Flow Process

After completing preliminary research, the team began the task of creating initial aircraft designs. An Excel spreadsheet was created to house all of the equations and referenced values that were needed for design iteration. When developing figures for the designs, the team followed the design flow process highlighted in Figure 3. Wing loading values for each category of flight were calculated; the lowest possible maximum allowed wing loading value was chosen in order to constrain the design's wing loading and thus prevent wing loading in any aspect of flight to increase above that number. Weight fraction estimates were then decided upon, which influenced the takeoff weight including payload, and thus all dimensions were calculated in the following layout section. The layout section calculated estimated sizing dimensions for the fuselage, wings, and tail fins based on the previous two sections of calculations. From there, preliminary design mockups were drawn, which are highlighted in the following section.

3.2 Summary of Preliminary Designs

3.2.1 Design 1



EW-1 Gompei

Length: 1.4 m Span: 4.4 m

W_0 = 18.59 kg W_e = 6 kg

	Wing	Horiz.	Vert.
S	2.77	1.17	0.634
A	7	4	1.5
λ	0.5	0.4	0.4
Λ	0	0	0

Figure 4: Design 1 Preliminary Drawings and Concept

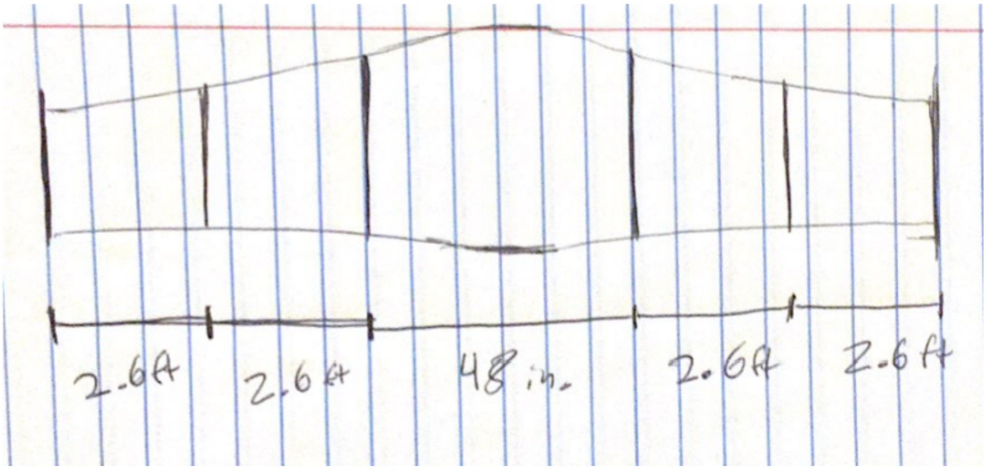


Figure 5: Potential Wing Sections Based on Dimensions of Design 1

Understanding the competition constraints, the team confined values for velocity to a small window, which had the potential to increase the difficulty of flight once built. Considerations were taken to place the wing above the fuselage so that the center of gravity remained below the wing, thus making the aircraft more stable when compared to a wing mounted in the center or at the bottom of the fuselage. Overall plane dimensions were influenced by these initial assumptions, shown in Table 1, which resulted in sizing dimensions as shown in Table 2.

Rear landing gear placement in Design 1, seen in Figure 4, was angled backward to the tail to counter the effects of the shortened fuselage and the potential that, if the rear wheels were placed too far forward on the fuselage, the aircraft would tip backward. The nose wheel placement was carefully considered during optimization to prevent nose-over accidents from happening during takeoff and landing.

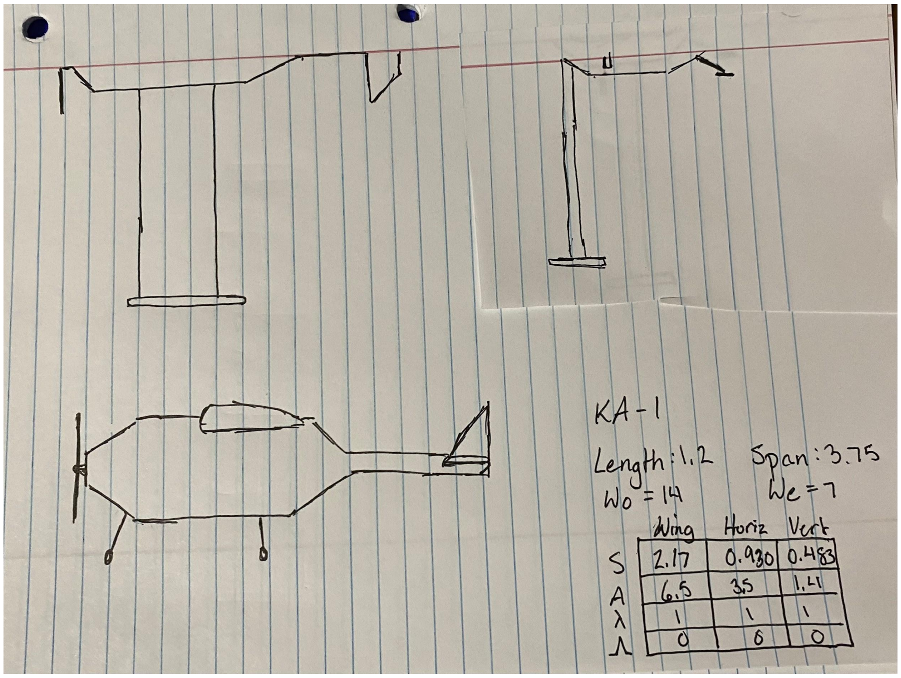
Winglets were also strongly considered for this design because of their capability to reduce wingtip vortices, and thus decrease overall drag. The optimization phase looked at the aerodynamics of the winglets to ensure that their design would not hinder aircraft flight performance.

The wing design itself was also heavily constrained by the competition guidelines. This year, the wing span was constrained to a minimum of 3.05 meters (10 feet) and a maximum of 5.49 meters (18 feet). Additionally, no part on the plane could be over 1.22 meters (4 feet) in length, which posed a serious problem: the wing had to be divided up into sections, as seen in Figure 5. The wing geometry and support structure were carefully considered throughout all design iterations to ensure that the wing would not fail during flight.

Design 1’s empty weight was intended to sit at roughly 6 kilograms (13.23 pounds) with a takeoff weight of just over 18 kilograms (39.68 pounds, including payload). Initial estimates of weight were far greater (almost approaching competition limits), but upon realizing the limited capabilities of just 750 watts (1.01 horsepower) of engine power, these numbers were decreased to their current values. Had empty weight estimates been exceeded in the fabrication process, the total payload carried would have decreased accordingly.

Concerns stemming from these empirically determined values include the fact that the fuselage was relatively short when compared to the wing span. This in turn had an effect on the large size of the horizontal tail fin. During the optimization phase of the project, these values were further examined.

3.2.2 Design 2



KA-1

Length: 1.2 Span: 3.75

$W_0 = 14$ $W_e = 7$

	Wing	Horiz	Vert
S	2.17	0.930	0.483
A	6.5	3.5	1.41
λ	1	1	1
Λ	0	0	0

Figure 6: Design 2 Preliminary Drawings and Concept

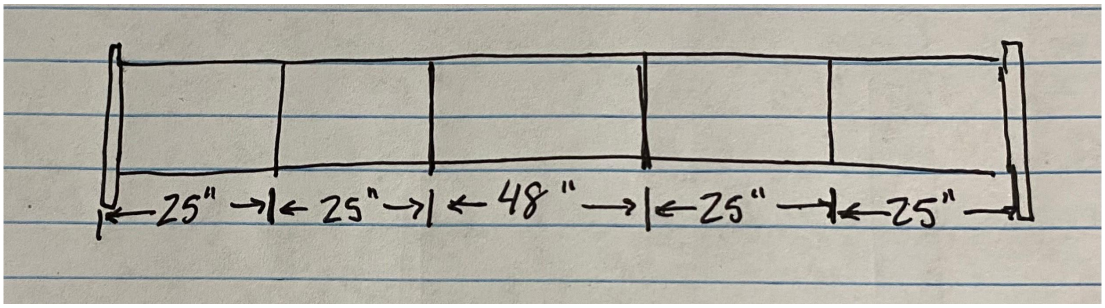


Figure 7: Potential Wing Sections Based on Dimensions of Design 2

This design, seen in Figure 6, had a more angular approach than that of Design 1 and 3, but it held all the same information and design reasoning as expressed in Design 1. The primary assumed aspects remained the same due to the constraints of the competition, but in this design, the maximum velocity, empty weight, and weight of cargo were assumed differently. This design had an empty weight of about 7 kilograms (15.43 pounds) and a total weight of about 14 kilograms (30.86 pounds). Compared to the other two designs, overall, it was smaller in size and overall weight. The complete dimensional values of the design can be seen above in Tables 1 and 2.

The fuselage shape in this design was the only major difference, as this one had a more geometric design. Designs 1 and 3 incorporated more organic structures with softer features. For instance, the fuselage in Design 1 met the tail with a long, swept body, whereas in Design 3, the shape of the tail potentially allowed for cargo to span the entire body of the plane. In Figure 7, the wing breakdown in this design was split into four equal sections of 25 inches (0.635 meters) with a single 48-inch (1.22 meters) central section that would attach to the fuselage. The total wingspan was roughly 12.3 feet (3.75 meters).

3.2.3 Design 3

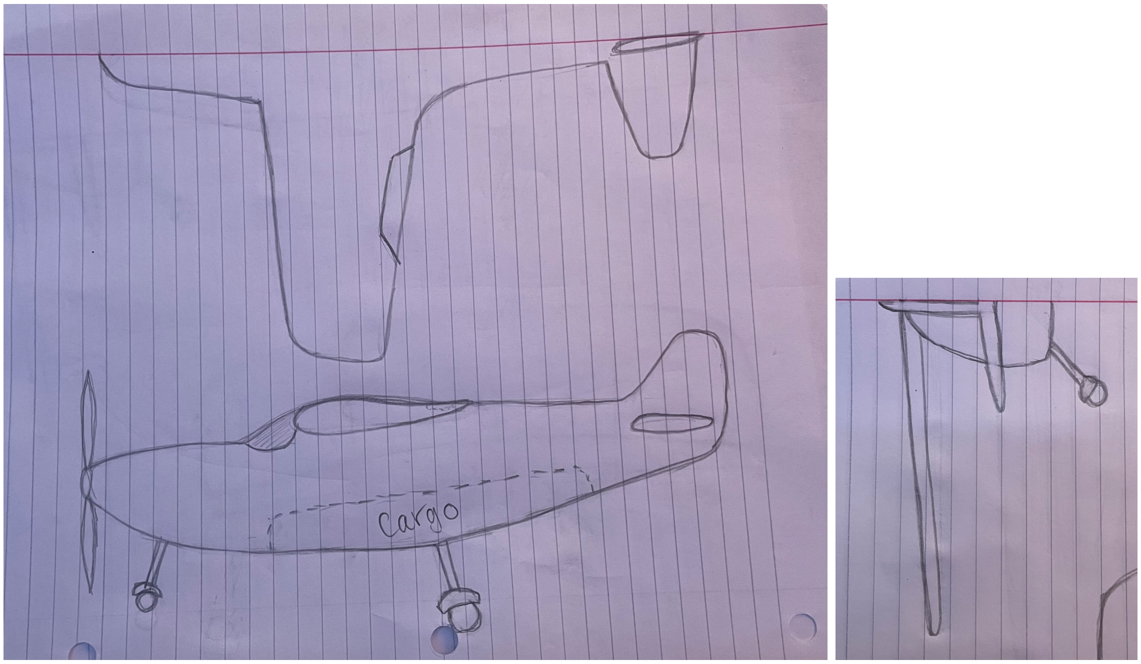


Figure 8: Design 3 Preliminary Drawings and Concept

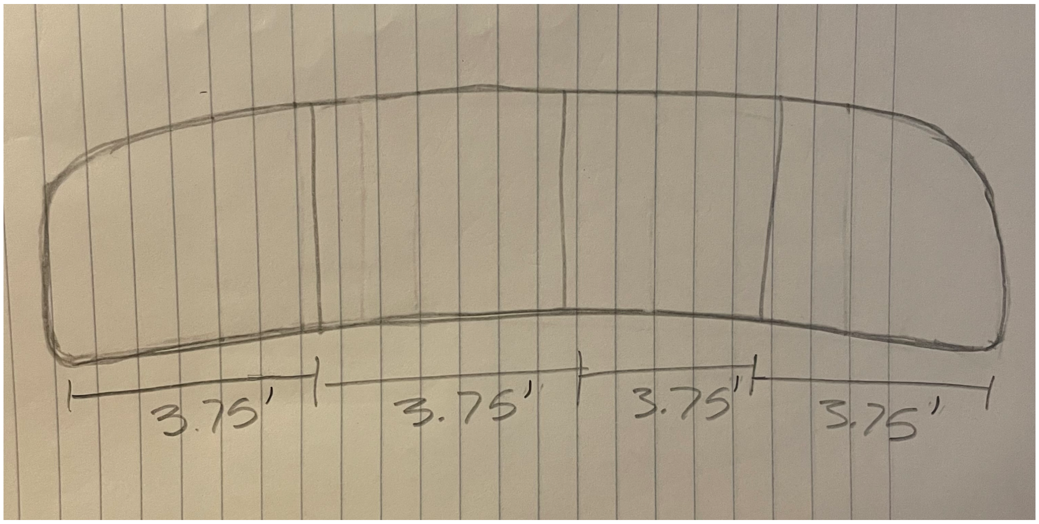


Figure 9: Potential Wing Sections Based on Dimensions of Design 3

This design, shown in Figure 8, differed slightly from Designs 1 and 2, but due to the restraints of the competition, the specified components and design reasoning presented in Design 1 are constant throughout. The primary assumed aspects remain the same, but the variable aspects have changed, including empty weight, the weight of cargo, and maximum velocity. This particular design had an empty weight of about 7 kilograms (15.43 pounds) and a total weight of about 20 kilograms (44.09 pounds). Comparatively, overall, this design was marginally larger in size and weight. The more specific dimensional values can be seen below in Table 2.

Unlike Designs 1 and 2, the fuselage meets the tail in a more conventional way, allowing for cargo to potentially span the length of the plane. This made fuselage geometry the primary difference in this design, as seen in Figure 9. The wing breakdown in this design was split into four equal sections of 3.75 feet (1.14 meters) to total a 15-foot (4.57 meters) wingspan. This choice was a viable option for simplicity of design, but may not have been adequate in terms of structural integrity. Having a wing seam placed in the center of the wingspan was likely to cause problems. Breaking the wing into five sections allowed for a solid wing section to be mounted to the fuselage, which was the decision moving forward.

3.2.4 Preliminary Design Assumed Values and Initial Sizing

Table 1: Initial Assumed Values for Design Calculations

	Design 1	**Design 2**	**Design 3**
Total Weight (kg)*	18.5	14	20.41
Stall Speed (m/s)*	9.14	9	9.14
Cruise Speed (m/s)*	12.19	12	12.19
Max Velocity (m/s)*	15	20	12.19
Take off Dist (m)	30.48	30.48	30.48
Landing Dist (m)	121.91	121.92	121.91
Climb Rate (m/s)*	1.219	1.219	1.219
C_L max	1.35	1.35	1.35
Climb Speed (m/s)*	10	10	10
ρ (kg/m^3)	1.23	1.23	1.23
A*	7	6.5	7

* denotes assumed

Table 2: Design Sizing Dimensions

Wing	**Design 1**	**Design 2**	**Design 3**
λ (taper ratio)*	0.5	1	0.5
γ (wing dihedral angle)	0	0	0
Λ (wing sweep)	0	0	0
b [m] = $\sqrt{(A \times S)}$	4.41	3.75	4.62
C_{root} [m] = $2 \times S/b \times (1+\lambda)$	0.84	0.58	0.88
C_{tip} [m] = $\lambda \times C_{root}$	0.42	0.58	0.44
Cbar [m] = $(2/3) \times C_{root} \times (1+\lambda+\lambda^2)/(1+\lambda)$	0.66	0.58	0.68
Ybar [m] = $(b/6) \times ((1+2 \times \lambda)/(1+\lambda))$	0.98	0.94	1.03
Fuselage			
L [m] = $\alpha \times W_{total}^{C}$	1.29	1.12	1.34
L_{vt} [m] = ~$0.6 \times L$	0.77	0.67	0.81
Vertical Tail			
S_{vt} [m^2] = $(C_{vt} \times (b_w \times S_w))/L_{vt}$	0.63	0.48	0.70
b [m] = $\sqrt{(A \times S)}$	0.98	0.82	1.02
C_{root} [m] = $2 \times S/b \times (1+\lambda)$	1.82	2.35	1.91
C_{tip} [m] = $\lambda \times C_{root}$	0.73	2.35	0.76
Horizontal Tail			
S_{ht} [m^2] = $(C_{ht} \times (Cbar_w \times S_w))/L_{ht}$	1.17	0.93	1.29
b [m] = $\sqrt{(A \times S)}$	3.33	2.75	3.49
C_{root} [m] = $2 \times S/b \times (1+\lambda)$	0.99	1.35	1.04
C_{tip} [m] = $\lambda \times C_{root}$	0.40	1.35	0.41
Tire Size			
TireDia [cm] = $A \times W_w^{B}$	14.14	12.81	14.6
Prop Diameter			
D [m] = $K_p \times (Power)^{0.25}$	0.52	0.52	0.52

4. Final Design Layout and Trades

4.1 Executive Summary

4.1.1 System Overview and Discriminations

From the preliminary designs presented above, the team chose to move forward with Design 1. It was determined that the chosen sizing, modularity, and positioning of certain components such as the tail and wings were best represented in that design. Optimization was performed using that design. Figure 10 displays the full CAD assembly of the final aircraft design. This aircraft was equipped with a removable cargo bay for easy access to payload plates as well as winglets on the tips of the wings for more efficient flight. Table 3 displays the subsystem parts chosen.

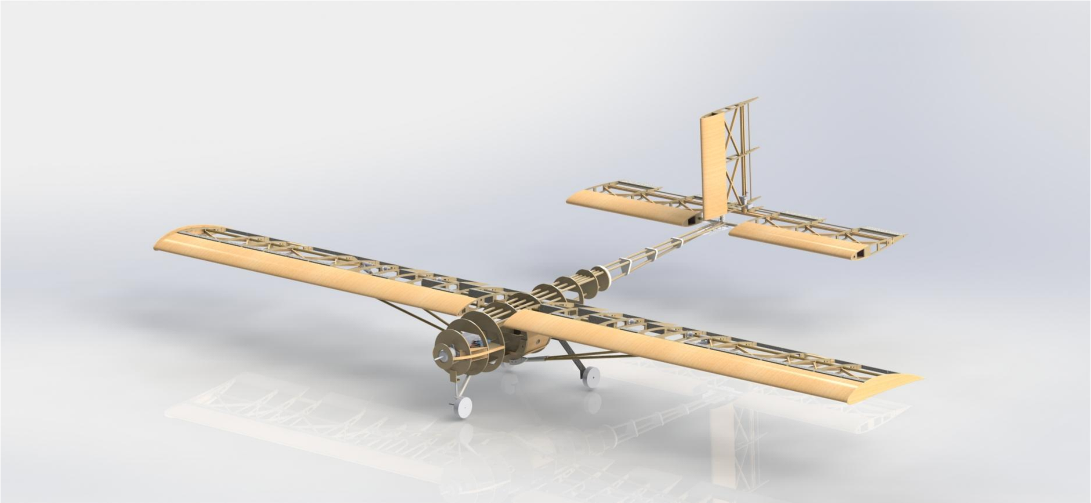


Figure 10: Plane Assembly

Table 3: Subsystem Parts and Details

<table>
<tr><th colspan="3">Electronics</th></tr>
<tr><td>Motor</td><td>Motor Battery</td><td>Receiver Battery</td></tr>
<tr><td>Hacker A60 5S V4</td><td>5000mAh 30C</td><td>Spektrum 2S 6.6V 4000mAh</td></tr>
<tr><th colspan="3">Wing</th></tr>
<tr><td>Airfoil</td><td>Span</td><td>Planform Shape</td></tr>
<tr><td>NACA 6409</td><td>172.5in</td><td>Rectangular</td></tr>
<tr><th colspan="3">Tail</th></tr>
<tr><td>Horizontal Tail Airfoil</td><td>Vertical Tail Airfoil</td><td>Configuration</td></tr>
<tr><td>NACA 0012</td><td>NACA 0012</td><td>Inverted “T”</td></tr>
</table>

4.1.2 Competition Projections

When designing the plane, a maximum gross weight of 40.98 lbs was used. With the weight of 40.98 lbs as the base weight, there was full confidence that the plane would be capable of being flown at its calculated empty weight of 21.95 lbs. The projection of the team's performance at the competition was a top-10 finish. This finish was based on the final competition results over the past few years, along with a buffer in case this year’s challenge had a slightly stronger mission score performance from all teams.

4.2 Overall Design Features and Details

4.2.1 Wings

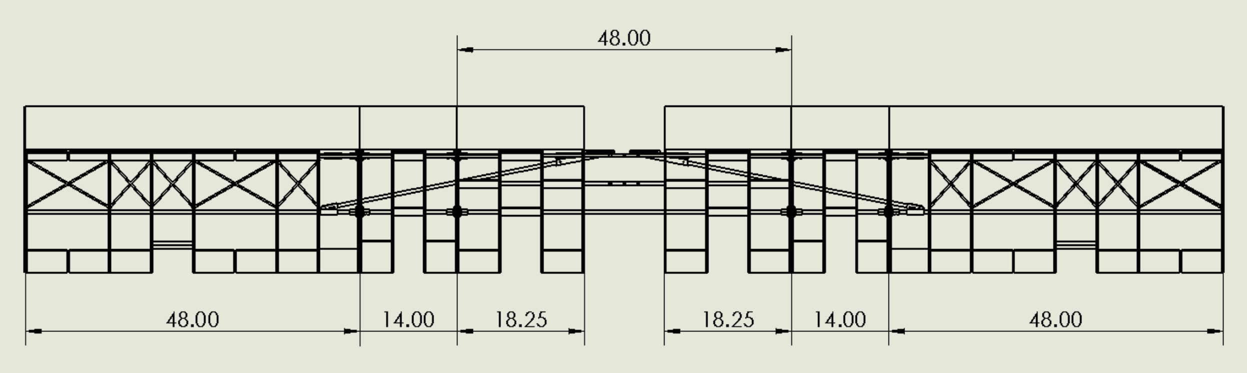


Figure 11: Wing Layout in Inches

The wing utilized a NACA 6409 airfoil with a chord of 23.9 inches and a span of 172.3 inches. For maximum lift potential, a simple wing design was chosen: a rectangular shape with no taper or trapezoidal features. The spars were hardwood dowels (½-inch diameter and varying lengths). The ribs were fabricated from ¼-inch thick Sitka spruce sheets. In between the ribs, R10 insulation foam board was added for structural support. Encompassing the leading edge of the airfoil were formed balsa sheets, creating a 'D' shaped tube structure to increase torsional rigidity. As seen in Figure 11, the wings consist of five sections: one 48-inch centerpiece, two 48-inch outer pieces, and two 14.25-inch connecting pieces. Both 14.25-inch sections contain three spars of varying lengths; when the wing sections are joined, each section is structurally interlocked with the other. The sections were locked into place using custom brackets around the spars that were bolted together through the outermost ribs of each section.

4.2.2 Fuselage

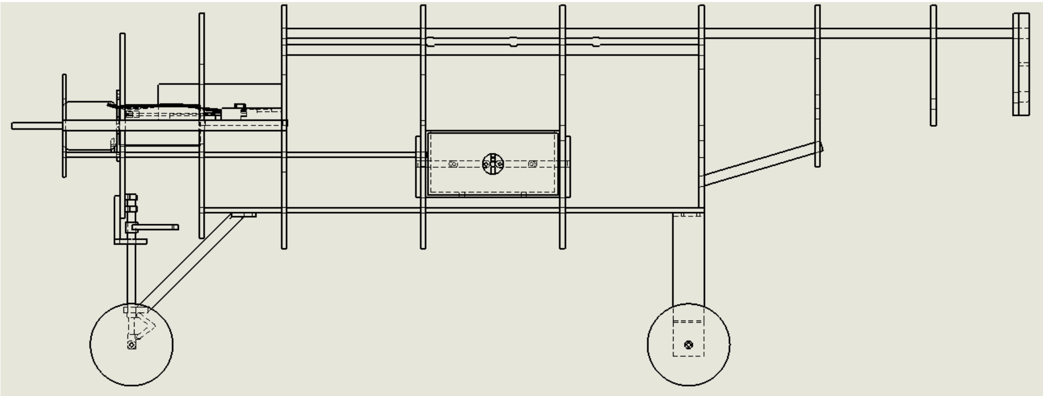


Figure 12: Fuselage Layout

The fuselage was made of pine plywood ribbings and supports. This allowed the airframe to maintain a lighter weight while also maintaining structural integrity. The fuselage consisted of circular-shaped ¼-inch plywood ribs. These ribs were joined via a combination of balsa sticks, plywood sheeting, and hardwood dowels to ensure structural rigidity while minimizing weight. Figure 12 shows the fuselage containing both a tapered nose and a tapered tail to increase aerodynamic efficiency. The central section of the fuselage had an increased quantity of joining pieces to ensure structural soundness in locations where the wing was mounted and where the cargo bay resided.

4.2.3 Landing Gear

A tricycle landing gear was selected for the airframe to meet both the competition requirement of steerable gear and the requirements demanded from takeoff and landing. The nose gear was made from an aluminum strut with a built-in spring-loaded shock absorber. The strut attachment point was reinforced to ensure that the gear would not be ripped from the fuselage during landing. The rear gear was made from a single piece of aluminum bent into a trapezoidal shape, and it also contained a reinforced connection to the fuselage to prevent detaching during landing. All landing gear setups contained 4-in diameter shock-absorbing foam tires designed to help cushion landings.

4.2.4 Tail

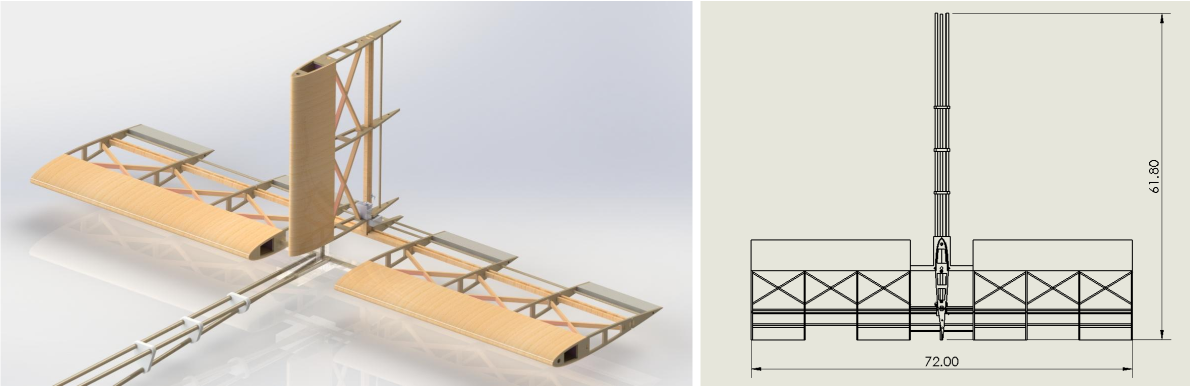


Figure 13a: Tail Layout (isometric) **Figure 13b: Tail Layout in Inches (top)**

Figure 13: Tail Layout

Figure 13 exhibits the tail layout. It was designed in the conventional configuration with both the vertical and horizontal tails using the NACA 0012 airfoil. Cross-members, R10 foam board, and the ‘D’ shaped balsa tubes were added to improve torsional rigidity.

4.2.5 Electronics

Figure 14 below demonstrates the wiring layout of the plane. Most of these elements were located within the fuselage with the exception of two servos located on the wings, two located on the tail, and one located on the landing gear.

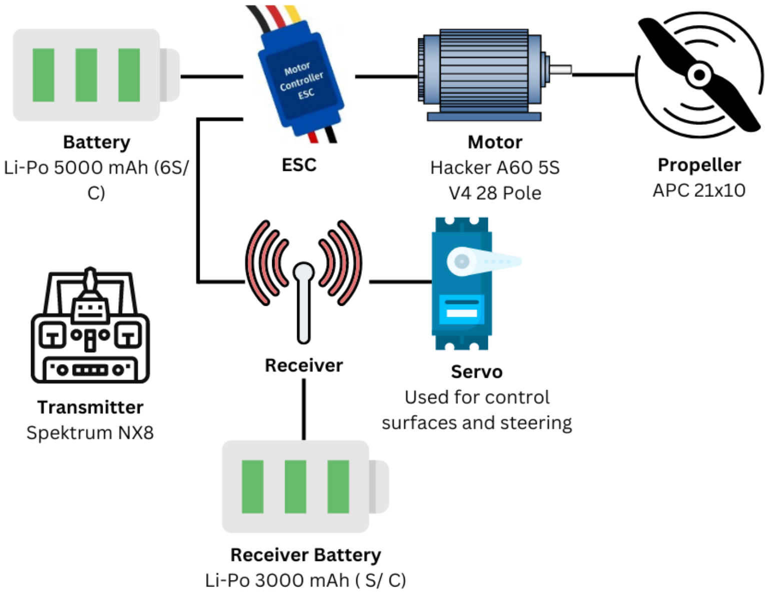


Figure 14: Wiring Layout

4.3 Design Derivations and Optimization

4.3.1 Competitive Scoring and Strategy Analysis

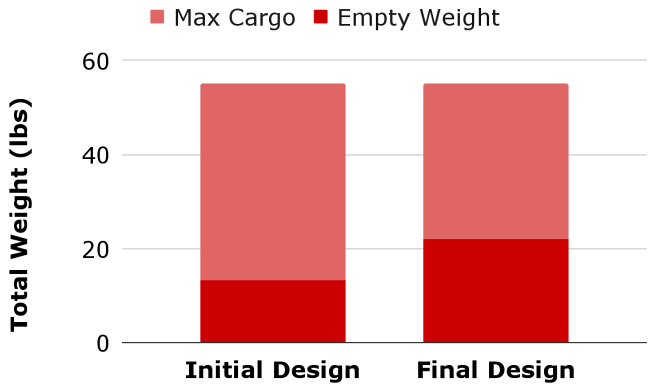


Figure 15: Initial and Final Weight Distribution

The plane's empty weight increased between the initial design and final design, decreasing the total amount of cargo weight the plane could carry as shown in Figure 15. A scoring prediction analysis was then completed, incorporating all competition regulations, that estimated a scoring range between a minimum of 3.25 and a maximum of 13.2 points per flight and a wing span bonus of 14.52 points, resulting in a total flight score range between 24.27 and 54.12 points.

4.3.2 Design Derivations and Sensitivity Analyses

4.3.2.1 Wings

The NACA 6409 airfoil was chosen for the wings due to its ability to supply the plane with the highest lift coefficient and lift-to-drag ratio at a given angle of attack compared to several other airfoil shapes. Eleven total wing airfoils were evaluated; Table 4 and Figure 16 below show the three airfoils determined to be the best options for the wings.

Table 4: Top 3 Airfoil Comparisons

Airfoil	**C_{Lift}**	**Re**	**C_{Drag}**	**C_{Lift}/C_{Drag} Optimal Ratio**	**C_{Lift}/C_{Drag} Ratio at highest lift**
4412	1.55@14°	650,000	0.04	119@6-6.5°	39@14°
	1.17@6.5°		0.01		
6409	1.56@12.5°	650,000	0.045	136@5.5°	36.5@12.5°
	1.28@5.5°		0.009		
23012	1.5@14.5°	650,000	0.03	85@10°	56@14.5°
	1.22@10°		0.015		

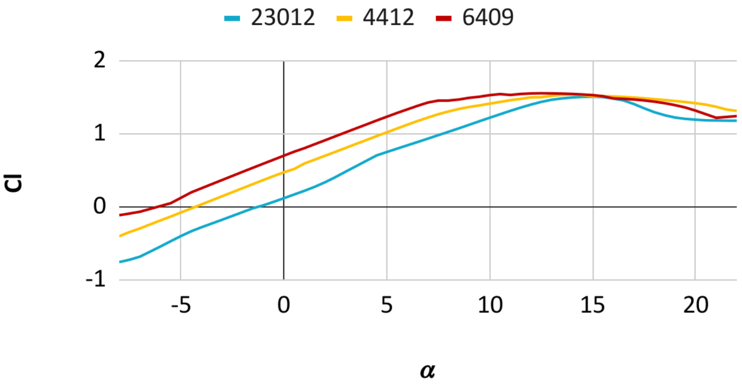


Figure 16: C_L vs. α

4.3.2.2 Fuselage

The fuselage was designed to maintain the same center of gravity (CG) before and after the addition of the cargo weights. Even if the CG were lowered vertically, such a change would not alter the plane's flight behavior. Spruce ribs were used for the frame of the fuselage. The cargo bay area was reinforced with pine plywood to help distribute the load of the cargo weights. This plywood also served to help spread the forces of the landing gear throughout the fuselage, reducing the risk of the landing gear breaking off from the fuselage during landing.

4.3.2.3 Horizontal Tail

A symmetrical airfoil was the best option for a tail with a long tail moment arm (TMA). A longer TMA requires less downforce in order to counterbalance the CG and lift force and provide longitudinal stability; thus, given the plane's long TMA, a symmetrical airfoil was chosen (NACA 0012).

4.3.2.4 Vertical Tail

The NACA 0012 airfoil was selected for the vertical tail as it has a low coefficient of drag and a symmetrical airfoil shape.

4.3.2.5 Electronics

Table 5: Servo Required Torques

Control Surface	Servomotor	Rated Torque (oz-in)	Control Surface Deflection	Required Torque (oz-in)
Aileron	30 kg	416.62	20°	95.59
Elevator	30 kg	416.62	20°	172.98
Rudder	30 kg	416.62	20°	55.85

The required torques of the servos at the control surface hinges were calculated at the cruise speed of the aircraft using the formula indicated in Appendix A. Table 5 indicates the results, which confirms the servos used on this aircraft were more than sufficient.

4.3.3 Optimization

The team used Microsoft Excel to optimize the design by generating rough plane dimensions mathematically; once the initial dimensions were determined, the team refined the design by adjusting variables until the desired dimensions for the airframe were achieved.

4.4 Material Allocation

The airframe was constructed of pine plywood and foam to provide increased structural support and integrity. The plywood was also used as a landing gear plate so the gear would not punch a hole into the fuselage upon landing. Birchwood dowels were used as the primary wing spars and the connection between the fuselage and tail. Table 6 indicates the limits and stresses experienced by each material.

Table 6: Material Allocation and Stresses

Material	Location	Stress Limit (PSI)
Balsa	Leading edge of wings	432
Sitka spruce	Ribs	780
Pine plywood	Cargo bay platform, landing gear plate	232
Birchwood	Primary wing spar, connector to tail	1800
R10 foam	Airfoil internal supports	100

5. Loads and Environments

5.1 Design Load Derivation

5.1.1 Landing Shock

During the landing process, a plane can experience a range of impact loads depending on the angle between the plane and the ground (glide slope); if the load is too high for the landing gear or the overall structure of the plane to handle, the landing gear could fail and be torn away from the body of the plane, likely resulting in additional damage to the propeller, wings, fuselage, and tail. To prevent this, the team calculated the landing impact at several different glide slopes to determine the optimal landing angle using the equation below.

$$Landing\ Impact = -\frac{(\frac{1}{2}m{v_s}^2)}{d}$$

When calculating the impact on the landing gear during touchdown, the velocity of the aircraft was assumed to be equal to the stall speed. Table 7 shows that the smallest glide slope resulted in the smallest load.

Table 7: Landing Impact

Glides Slope (deg.)	Sink Rate (ft/s)	Impact Load (lbf)
3	1.192	56.87
5	1.989	158.49
10	4.009	643.78

5.2 Environmental Considerations

To achieve the best possible flight during the competition, the wind, temperature, and elevation experienced in Lakeland, Florida, in March were factored into the initial design calculations. The calculations were not made in regard to Worcester weather, so had test flights occurred in Worcester, conditions would have likely been different from those that the plane experienced in Lakeland. When comparing the relative humidity, elevation, and temperature of Lakeland in March to that of Worcester in February, it was discovered that the air density in Worcester was slightly higher than that in Lakeland. While Lakeland’s air density and high winds were accounted for in the initial design calculations, the plane would have likely achieved better flights in Worcester than it would have at the competition.

6. Final Analyses

6.1 Analysis Techniques

6.1.1 Analytical Tools

Several different analysis tools were used to design and optimize the plane to the desired performance within the competition design constraints.

1. *SolidWorks*

   SolidWorks, a CAD and analysis software, was used to design all components of the plane and assemble the components in a virtual environment to ensure each subsection of the aircraft design would fit together properly with the other subsections. Additionally, SolidWorks was used to accurately obtain the CG once the full model of the plane was completed. Finally, static analyses were run on the model to test the stresses on the components of the fully assembled plane.

2. *XFLR5*

   XFLR5, the analysis tool used for planes and their components working at low Reynolds numbers, was used to obtain airfoil data. This determined the best shape for the wings and the tail of the plane in order to achieve the best performance.

3. *Ansys Fluent*

   Ansys Fluent, a CFD software, was used to test the airframe and airfoils in fluid simulations to confirm correct areas of low pressure and to examine drag effects. The k-omega equations were used during both 2D and 3D simulations for accurate results.

4. *Microsoft Excel*

Microsoft Excel was used to calculate and keep data as well as to optimize the aircraft design based on the initial parameters used.

6.1.2 Developed Models

To predict the velocity of the aircraft on take-off along with estimated take-off distance, equations with displacement as the other variable were used. The equations utilized are listed below.

$$Lift\ Force\ =\ \frac{1}{2} * \rho * R_{wing} * C_{lift} * v^2$$

$$Drag\ Force\ =\ \frac{1}{2} * \rho * S_{wing} * C_{drag} * v^2$$

$$Net\ Force\ =\ F_T - F_D$$

$$Acceleration\ = \frac{F_N}{m}$$

$$TakeOff\ Distance\ = \frac{v^2}{2a}$$

Lift force and drag force are related to their respective coefficients of lift and drag, the velocity the plane is traveling, the density of the air, and either the 2D wing area or the surface area of the wing. The net force on the aircraft during takeoff is related to the force of thrust and the force of drag. The acceleration of the aircraft then relates to the takeoff distance where velocity represents the speed at which wheels lift off the ground. The takeoff distance is related to both the velocity and acceleration of the plane. For turning flight, the free body diagram of the aircraft in Figure 17 was analyzed while banking. The horizontal and vertical components of lift were equated to centrifugal force and weight respectively. After solving these equations, the maximum angle of bank (θ) and the minimum turning radius (R) were obtained as seen in the following equation.

$$\theta = \cos^{-1}(\frac{W}{L}), \quad R = \frac{m{v_c}^2}{L\sin\theta}$$

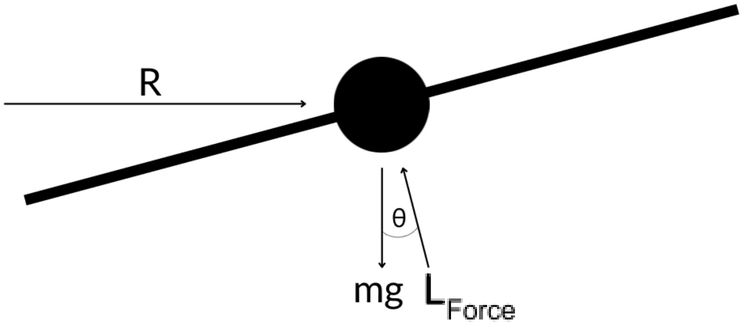


Figure 17: FBD of Plane in Bank

6.2 Performance Analyses

6.2.1 Dynamic Thrust

The dynamic thrust characteristics of the motor and propeller combination that was chosen for the design were analyzed using a dynamic thrust calculator that took into account the propeller size and pitch along with the motor RPMs. The results are presented in Figure 18.

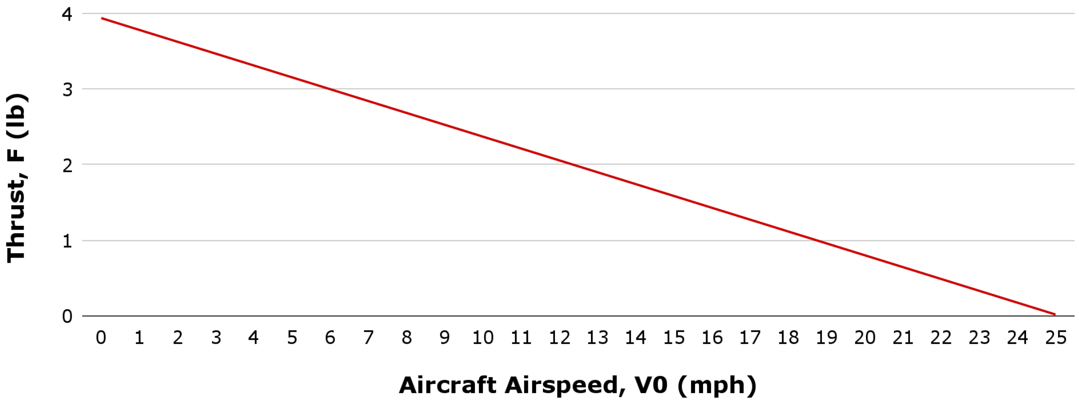


Figure 18: Dynamic Thrust at Varying Speeds

6.2.2 Takeoff and Climb-out Performance

Using the developed model, the takeoff distance was calculated for various plane and cargo weight combinations. The experimental value for static thrust found from the propeller test was used in this calculation. The takeoff distances that would be experienced during flight testing were expected to be somewhat further. Figure 19 demonstrates the result of these calculations.

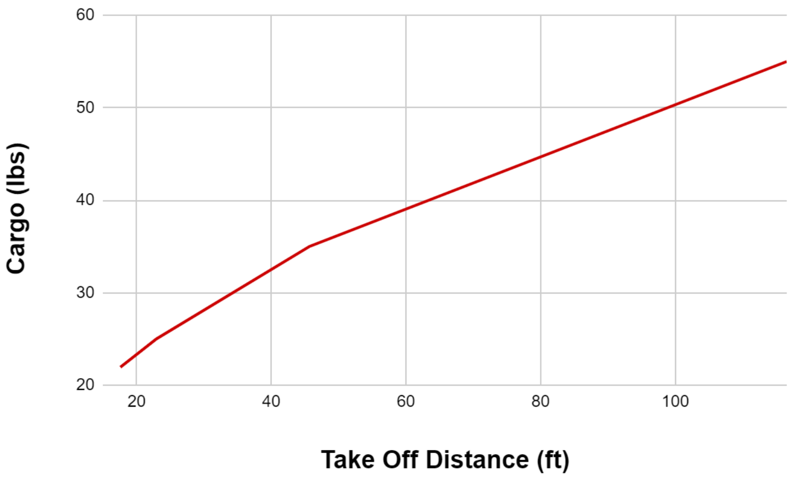


Figure 19: Take-off Distance of Varying Cargo Weights

6.2.3 Flight and Maneuver Performance

The maximum bank angles and minimum turning radii were calculated using the model and varying cargo weights. The results are displayed in Figure 20 below. For the maximum bank angles (Figure 20a), a lighter weight allowed for a larger bank angle while turning; for minimum turning radii (Figure 20b), a lighter weight allowed for a smaller and tighter turning radius. These two calculations were important to determine and understand how maneuverable the plane was in flight. During flight, if the pilot exceeds the maximum bank angle, the plane will stall, losing airflow and lift from the wings, causing a likely unrecoverable roll as the plane crashes to the ground. Knowing the turning radius was important for understanding how long it would take for the plane to make a turn, as being able to execute a turn was needed for the competition.

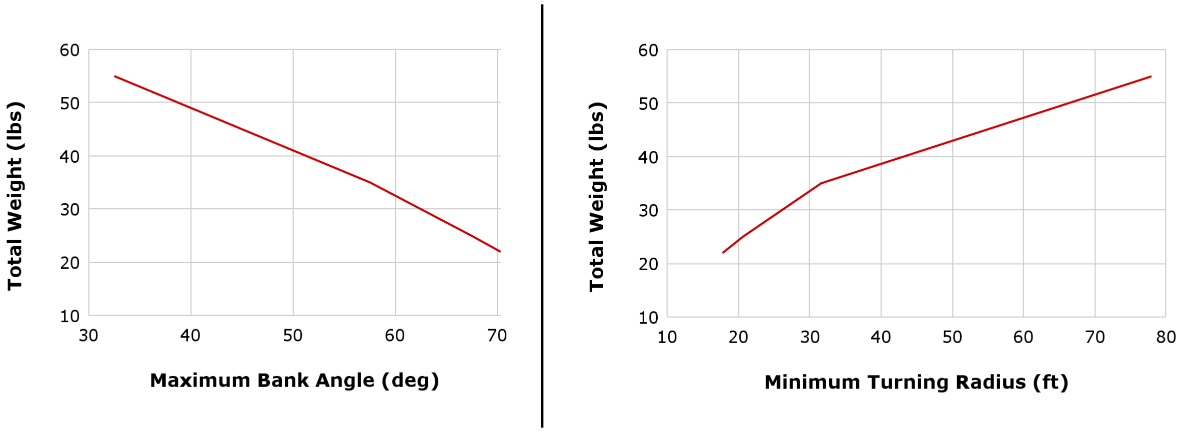


Figure 20a: Maximum Bank Angle **Figure 20b: Minimum Turning Radii**

Figure 20: Maneuver Performance

6.2.4 Static and Dynamic Stability

6.2.4.1 Center of Gravity

The CG of the plane was designed to be in the middle of the wings and fuselage, thus preventing a major CG shift due to the cargo weights being added. Maintaining a constant CG location would have prevented the plane's flight stability from being negatively affected. Figure 21 displays the location of the plane's CG. Furthermore, the plane included top-mounted wings for high stability.

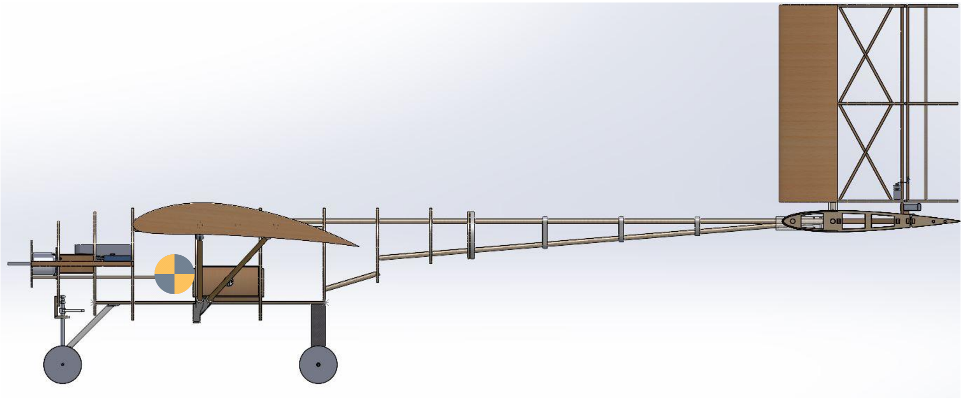


Figure 21: Aircraft Center of Gravity

6.2.5 Airfoil Performance Simulation

Using Ansys Fluent, a 2D simulation of the chosen NACA 6409 airfoil was conducted. The airfoil was placed at a 5.5° angle of attack with an air speed of 35 ft/s (approximately 10.67 m/s), and calculations were performed using the k-omega equations. The 5.5° angle of attack was taken from the calculated ideal angle of attack from earlier design optimization calculations, and the 35 ft/s air speed was taken from the plane's calculated cruise speed. Note that the airfoil is horizontal relative to the screen in the simulation, while the incoming air is angled upwards to cause the 5.5° angle mentioned above. Figure 22 displays the air velocity vectors surrounding the airfoil, while Figure 23 shows the pressure contours around the airfoil. Both simulations were performed with Ansys using the k-omega equations with a 5.5° angle of attack and a velocity of 35 ft/s.

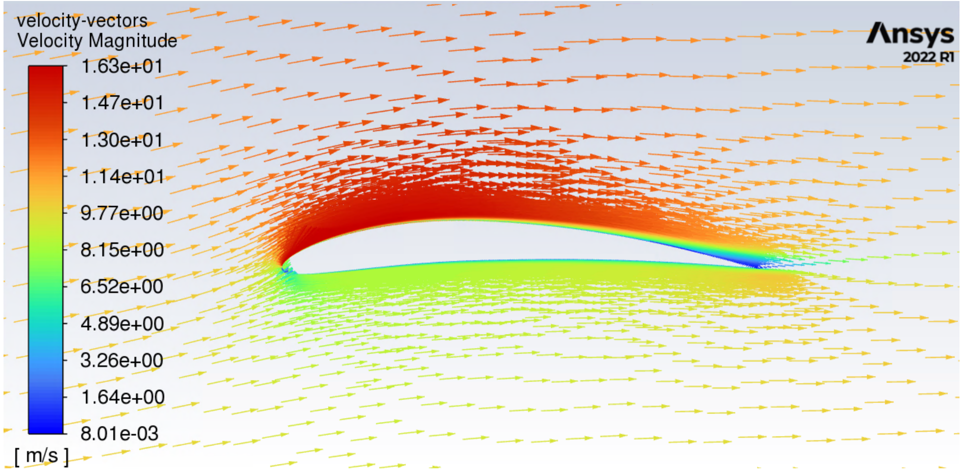


Figure 22: Velocity Vectors NACA 6409

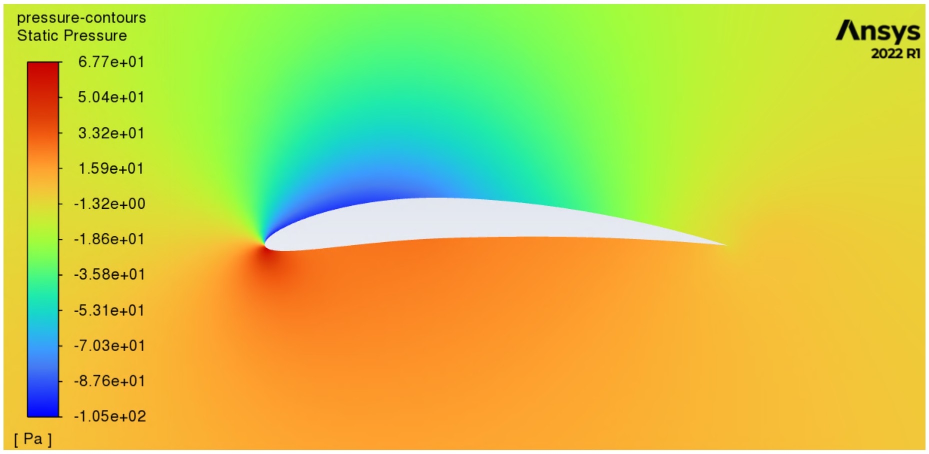


Figure 23: Pressure Contours NACA 6409

To verify results, the simulated coefficients of lift and drag were compared to those documented for the NACA 6409. Shown below in Figure 24 is a graph from the Airfoil Tools website displaying the relationship between the coefficients of lift and drag for the NACA 6409 [2]. The simulated lift coefficient was 0.6979, and the drag coefficient was 0.003112, intersecting at the red dot along the trendline.

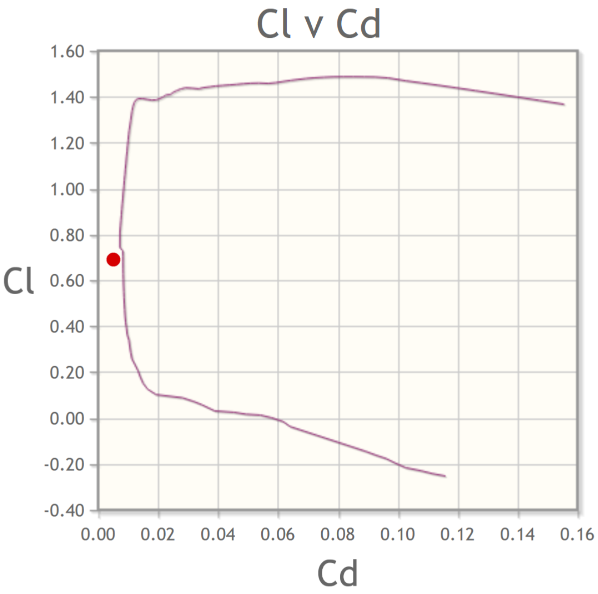


Figure 24: Coefficient of Lift vs. Coefficient of Drag for the NACA 6409 Airfoil

6.2.6 Aircraft Performance Simulation

Additionally, Ansys Fluent was used to simulate the entire aircraft's performance once the full CAD model had been created. Figure 25 displays the pressure contours along one-half of the plane.

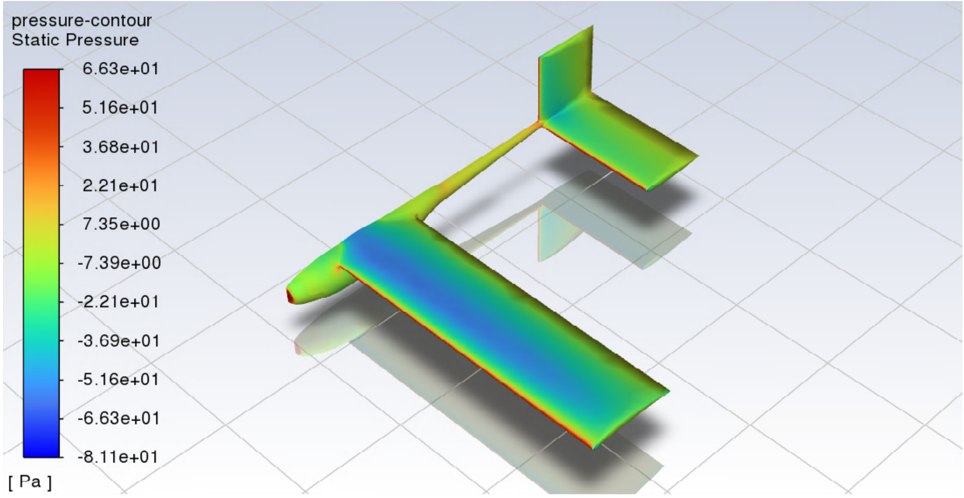


Figure 25: Ansys Fluent Simulation of Pressure Contours Along Aircraft

As this plane design was unique, there were no data to compare results to, and as such, a "common sense" approach to verifying the accuracy of the results was used instead (i.e., areas of lower pressure exist over the wings, meaning lift force would be generated in the proper areas to facilitate flight).

6.2.7 Payload Prediction Analysis

The carrying capacity of the aircraft changes based on the altitude. A max payload of 16.4 lbs was strategically chosen in order to ensure a flight score if the payload prediction bonus was not achieved. In order to determine the variations of payloads with altitude, the team used the DJS Skylark Design Report [1] from the SAE 2019 Design Competition for guidance. The equation below relates an aircraft's total lift force to its total weight.

$$load\ factor = \frac{lift\ force}{total\ weight}$$

The ability of the aircraft to carry load will change with height, which means that the plane's lift force will decrease as altitude increases and the load factor will approach 1. Below is the equation for the load factor reorganized to solve for lift force with total weight divided into the plane's empty weight and cargo weight.

$$lift\ force = load\ factor \times (empty\ weight\ of\ plane + weight\ of\ cargo)$$

Below is the result of inserting variables for lift force, load factor, empty weight of the plane, and weight of cargo from the equation above.

$$\frac{1}{2} \times S_w \times C_{lift} \times v^2 \times \rho = n \times (21.95 \times g + P \times g)$$

The variables that do not change $(S_w, C_{lift}, v^2, g, n)$ can be accounted for with constant K as seen below.

$$K = \frac{\frac{1}{2} \times S_w \times C_{lift} \times v^2}{n \times g}$$

The resulting equation seen below, where ρ changes with altitude, represents the weight of the cargo (*P*) that the plane can carry at varying altitudes.

$$P = K \times \rho - 21.95$$

After inputting the calculated air density ρ = 0.0734lb/f^3 and P = 16.4 lbs, the resultant K = 503.2. Using P = 503.2ρ - 21.95, the graph in Appendix C is obtained. Upon analyzing the data points, the following payload prediction equation in a y=mx+b format was obtained:

$$y = - 0.00101x + 16.4$$

6.2.8 Drag Polar Analysis

The drag distributions of different components of the aircraft were calculated using the equation below and are displayed in Figure 26. In the drag force equation, the variable ρ represents the air density, A_c is the cross-sectional area of the plane component with respect to the front of the aircraft, C_{drag} is the coefficient of drag for that component, and v is the velocity of the plane. To determine the amount of drag each component was contributing, the front cross-sectional area of the component was substituted in for A_c. The coefficient of drag for each component was found using a complex series of drag analysis equations which can be viewed in Appendix D. The drag was then calculated for the wing, horizontal and vertical tails, fuselage, and landing gear to determine how much each component was contributing to the overall drag on the plane. The proportions of total drag are presented below in Figure 26. Due to the large size of the wing, it was the main contributor to drag.

$$Drag\ Force = \frac{1}{2} * \rho * A_c * C_{drag} * v^2$$

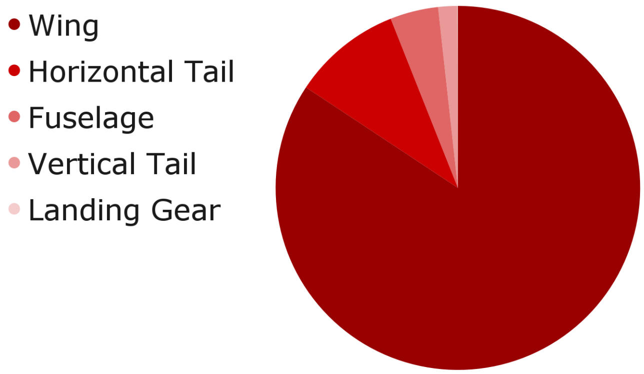


Figure 26: Drag Distribution

6.3 Structural Analyses

6.3.1 Applied Loads and Critical Margins

While performing the load calculations, a specific max weight of 40.98 lbs was used; as the fully-loaded aircraft weight would not exceed that value, the calculations can be assumed to have an adequate margin of safety.

6.3.2 Mass Properties and Balance

6.3.2.1 Weight Distribution

Using Solidworks, the weight of each aircraft component was calculated. Figure 27 shows the comparison between component weights. The heaviest components of the plane were the wings and tail due to their size in comparison to the fuselage.

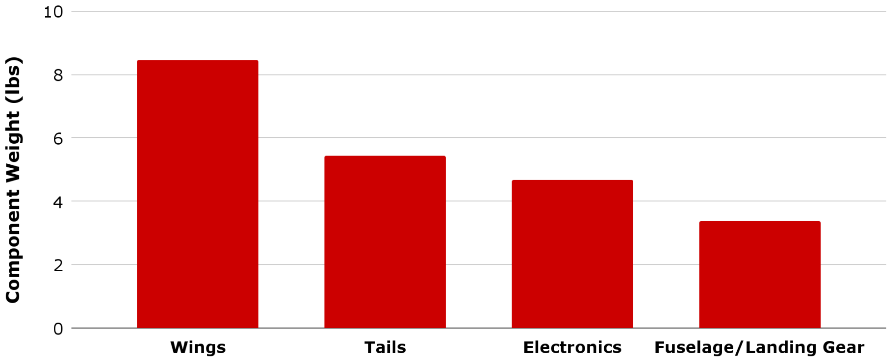


Figure 27: Component Weight Distribution

7. Subassembly Tests and Integration

1. *Propeller Tests*

The team analyzed different propeller sizes with the Hacker A60 5S V4 motor chosen for the aircraft. Two APC propellers (20.5x 10 and 21x 10) were tested. The results show that, for thrust, the 21x 10 propeller was the better choice with a 200 RPM decrease but 0.2 kg of thrust advantage over the 20.5x 10.

2. *Servo Motor Tests*

To confirm the servos would not burn out during the competition, the servos were run continuously for the estimated flight time. Additionally, the servo torque required to move the plane’s control surfaces successfully was calculated in the equation below to verify that the servos were capable of such loads. The force on the servos would be related to the size of the control surface, the distance over which the servo arm extends, and the velocity at which flight takes place.

$$Servo\ Torque\ Required = (8.5 * 10^{-6})\frac{C^{2} * v_{C}^{2} * control\ surface\ span * \sin^{2}(S1)}{\cos(S1)\tan(S2)} * \frac{control\ horn\ height}{servo\ arm\ length}$$

3. Battery Tests

The team verified that the battery charge could last the duration of a single flight by running the motor at full throttle for the estimated flight time in addition to utilizing theoretical online motor calculators.

8. Manufacturing

The ribs for the wing sections, fuselage, and horizontal and vertical tails were laser cut. These parts were then sanded down for a smooth, accurate finish. The cargo plates were fabricated using a bandsaw to cut equal-sized squares. Several custom components such as locking mechanisms for the cargo bay, a connector piece between the two horizontal tail halves and the tail arms, connector pieces between wing sections, and supports for the landing gear were 3D printed. Thin sheets of balsa were wrapped around the leading edges of the wings and tails to create strong tubes along the ribs. Additionally, the wing and tail spars were surrounded with R10 foam board to increase strength and allow for an increased number of attachment points for the ultracote. Thirty-minute epoxy was used to join the wooden components. The thirty-minute cure time allowed the epoxy to soak into the wood, creating a stronger bond. While the epoxy cured, magnets were used to hold the ribs in place to prevent any potential bonding errors or deformation. Once each section was constructed, its weight was compared to that of the corresponding CAD model to ensure the CG was located in the correct place. The manufacturing process started at the beginning of February and lasted until the first week of March resulting in a 5-week build period. Throughout the manufacturing process, there were troubles with parts breaking or the framework structures not being strong enough, resulting in additional material needing to be used to add weight to the plane. The original design of the plane had an approximate weight of 18 lbs, but the final weight ended up being roughly 22 lbs and tail heavy leading to ballast weights being added to the nose of roughly 6 lbs 9 ounces. The final empty weight of the plane at the competition was roughly 29 lbs.

9. Results

The team placed 20th out of 25 teams in the final standings of the competition. The team's technical report originally placed 14th of the 25 submissions, but after a 5-point penalty for having changed the plane after submitting the technical drawing, the team placed 18th. The technical presentation the team performed on March 3rd, placed 14th. The team did not record a successful flight during the competition as the plane did not take off before the 100-foot mark for the takeoff distance.

10. Conclusions and Recommendations

10.1 Conclusions

Now that the project has concluded, the team has considered this a successful journey and project. This project has taught every member of the team many lessons on designing a system, manufacturing, and problem-solving skills from all the struggles throughout the process.

10.2 Recommendations

10.2.1 Research

The team's research involved analyzing historical aircraft, reading aircraft design textbooks, and looking at pictures online of aircraft from previous years' SAE Aero Design competitions. Less emphasis should be placed on historical research as it is difficult to learn much of value from old designs unless one knows what information is important to look for. More of an emphasis should be placed on looking at previous competition years' designs, especially the designs of teams who placed within the top 10. Additional value can be gained from analyzing the build of modern gliders and other lighter-than-air aircraft.

It is crucial that the competition resources that SAE provides be analyzed in great detail. The papers and articles they provide are a great introduction to the knowledge that is necessary to begin aircraft design. Further knowledge is required, however, and this knowledge can be obtained by reading the textbook noted in Appendix E (separate document). Many sections in the provided text are useful but are not the end-all-be-all when considering overall aircraft design. The dimensions of the aircraft should mainly be dictated by the competition rules, and any remaining design choices open to interpretation can then utilize the textbook and other resources.

10.2.2 Solidworks

The complexity of the model to be developed with Solidworks cannot be taken lightly. The team ran into several issues while developing the aircraft model, whose solutions will be discussed in this section. It is imperative that material properties, part dimensions, part organization, file organization, and how the overall model is broken down into smaller assemblies are carefully considered during development.

The SolidWorks model will become complex and it is important that the parts are properly organized. Different aspects of the plane should be grouped into subassemblies, and depending on the complexity of these structures, further subassemblies may be needed. Competition requirements must also be taken into consideration when deciding on the breakup of the model. In general, smaller assemblies are easier to modify and change and are also easier to reincorporate into the whole model after modifications are made when compared to larger assemblies. In our model, we divided up assemblies into 3 main components: fuselage, tail, and wings. The wings and tail were further broken down into smaller subassemblies because of the modularity requirement of the competition. Should the competition rules remain relatively similar in 2024, it is strongly recommended that a similar assembly and subassembly structure be developed.

Material properties should be carefully considered in the model development as well. This was perhaps one thing that led our group astray when it came time to manufacture. Many of the material properties may not have accurate density data which may cause issues with center-of-mass displays as well as model mass properties when compared to the overall weight of parts when manufactured. If possible, it is recommended that custom material properties be put in either from matweb.com or from the material manufacturer's/supplier's website.

Part tolerancing is another key detail that must be considered when designing the aircraft in SolidWorks. The 3D printers in the Makerspace and Prototyping lab do not have the highest tolerances and thus parts that are printed must be designed accordingly to achieve desired fits. Another thing to consider when printing parts is that depending on the material, the part may cool and shrink after printing. Tolerance testing is highly recommended prior to printing any desired parts.

10.2.3 Aircraft Design

Designing an aircraft is a complex task that requires numerous iterations. A list of important things to consider is given below:

- Weight
- Wingspan, chord, sections
- Cargo storage
- Material selection
- Access points (hatches)
- Center of gravity (CG) location
- Tail sizing

Of the items in the aforementioned list, only a few of which will be touched upon in this section. The total weight of the aircraft is by far the largest determining factor in whether or not the plane will fly and meet the required competition takeoff distance. Thus it is imperative that the plane be made as light as possible but still remain structurally sound. Keeping the plane’s total weight down but maintaining structural integrity plays heavily into material selection and part design of the plane. Material selection will also play heavily into the layout of the aircraft as it will have an effect on the CG location. The CG location is the most important part of the aircraft's design, as it will impact all aspects of flight performance.

10.2.4 Manufacturing

The manufacturing process is a long and oftentimes quite tedious process. The project timeline should dedicate 5-7 weeks solely to part production and total aircraft assembly. Special care should be taken during the manufacturing process to ensure that all parts are correctly dimensioned and fit appropriately. Any imperfections that exist will be very difficult to conceal and may potentially negatively impact performance. Drawings of subassemblies in SolidWorks should be used for manufacturing, as a technical inspection will take place at the competition. During the fabrication process, CA glue with a hardening catalyst may be used to set parts in place (similar to spot welding), after which a 30-min resin can be applied to lock parts into place. Any hardware that is planned to hold parts together should be modeled in Solidworks so that when manufacturing begins, correct amounts can be purchased.

10.2.5 Project Timeline

Based on the variance between this project's timeline in practice versus in theory, the team has created a revised timeline that better suits the scope of the project in the limited time provided to complete it. With the new timeline being proposed and a larger team of at least eight members, future teams should be able to balance their academics, personal life, and this project proportionately. Firstly, the team recommends that a decent portion of the background research and work be completed over the summer. Having familiarized themselves with the design of this year's plane, of planes that succeeded at the competition in the past, of real airplanes, and of the math and knowledge behind aircraft design, they will be on track to start developing a preliminary design at the start of A term. During this term, a final design should be created and the CAD for it should be made as well. Once the CAD is finalized, the team can then begin the simulation process in early B term. This will also allow for manufacturing to begin in this term as well. With the larger team, it is believed that the manufacturing process that took the current four-member team five weeks to complete can be shortened and completed within B term. If things do not go according to plan, an additional week of manufacturing in C term is still permissible with this timeline. The primary focus of C term would then be writing the technical report and creating the technical presentation as well as conducting test flights and making necessary modifications to the plane to assure it is competition ready. Once the competition is completed during the C-D break, D term can be dedicated to writing the MQP report and preparing for Project Presentation Day.

11. Broader Impacts

11.1 Engineering Ethics

This project required a great deal of research to bring the team engineers up to speed with the appropriate standards of aircraft production. In order to produce the best plane possible, the team consulted with competition resources but sought outside help to ensure that the plane was acceptable. As progression through the aircraft's design and construction was made, the team was sure to include the sponsors, advisors, and other supporters throughout the process so that they felt their donations and help were valued and used wisely.

11.2 Societal and Global Impact

The goal of this particular MQP project did not involve aspects of societal or global health, welfare, or culture. It could be concluded that there were, however, impacts on certain groups of people or communities within WPI in terms of education. This project was the first of its kind for the Mechanical and Material Engineering department. Due to it being the inaugural year for this MQP, the members and advisor had to start from the ground up. This year's team has gained valuable knowledge and experience not only about the project but the entire MQP process as well. Passing this information along to future teams will allow them to be well-equipped for success.

Project Presentation Day granted the team the ability to showcase their project to other Mechanical and Material Engineering students, students from other disciplines, faculty, sponsors, and WPI friends and family. Presenting interdisciplinarily gave the team the opportunity to inform the WPI community about their new found expertise on the project material and share the lessons they learned throughout the process.

The competition aspect of this project allowed the team to compete against groups from various countries across the world. Teams were able to converse with each other about their plane designs and discuss what aspects lead them to success or failure. This was a great opportunity to share the project with groups outside of WPI and outside of the country.

11.3 Environmental Impact

Due to the nature of this project, environmental impacts were not in the foreground during the planning stages of this MQP. There was no sustainability aspect in the SAE competition guidelines nor in the MQP specifications for this project. There were, however, unintended sustainable and unsustainable practices used throughout this project.

During the manufacturing process, there were several instances of inadvertent environmental consciousness. When ordering the supplies to construct the plane, the team made an effort to purchase all the electronics, hardware, and materials from the same vendor at the same time. This allowed parts to be delivered at the same time, facilitating the team's manufacturing efforts. Additionally, this meant that parts were not sourced from a wide variety of locations and at different times, meaning less shipping distance and frequency required to deliver the materials. The team also made an effort to use materials wisely and sparingly in order to reduce waste. Materials that were no longer of use to the team were either recycled or left in the scrap pile in the WPI makerspace for other students use. At the conclusion of this project, the team left the unused materials for the use of future teams as well as the plane, which could be stripped for parts if desired. This provides future teams with a starting foundation and hopefully will allow them to use and reuse the leftover materials and electronics from this project instead of having to purchase them new.

With the SAE Competition being held in Florida, transportation of both the team members and the plane was unavoidable. Traveling to the airport, from airport to airport, and to and from the competition all contributed to the teams' carbon footprints. There may have been more sustainable approaches to the travel methods used to complete this project. However, the team possessed a limited budget and had no control over the location of the competition, so the situation was managed accordingly.

11.4 Codes and Standards

As discussed in section 1.3 Competition Details, the team was constrained by the design requirements given in the SAE Aero Design rulebook, including everything from part size to material properties. Of important note is the guideline limiting the maximum gross weight of planes to no more than 55 pounds; this rule ensures that all aircraft competing at the event are considered "small unmanned aircraft" according to Part 107 of FAA Regulations. If a plane were to exceed this 55-pound limit, it would have to be registered with the FAA using paper registration [4], which would add an additional layer of complexity to the competition that would likely bar many teams from participating, especially international teams who would not have the same access to the FAA as other teams would (if the international teams had access at all).

11.5 Economic Factors

The SAE Aero Design series presents an opportunity for engineering students to design, build, and fly aircraft at a competition. After the success that this MQP had as the ME department’s first year running the project, the department would like to continue running it in future years. Moving forward, this project has the potential to generate a club and grow into a larger legacy MQP. This would present unique opportunities for students and WPI to garner new relationships and sponsors for the project. The ultimate long-term impact this project would like to have is similar to that of the FSAE club and MQP: an opportunity for students to grow their knowledge surrounding engineering design through hands-on experience in a competitive environment.

12. References

1. DJS Skylark Team 027. (2019). (rep.). *DJS Skylark Regular Class Design Report* (Ser. SAE Aero Design East).

2. *NACA6409 9% (n6409-il)*. Airfoil Tools. (n.d.). Retrieved April 24, 2023, from http://airfoiltools.com/airfoil/details?airfoil=n6409-il

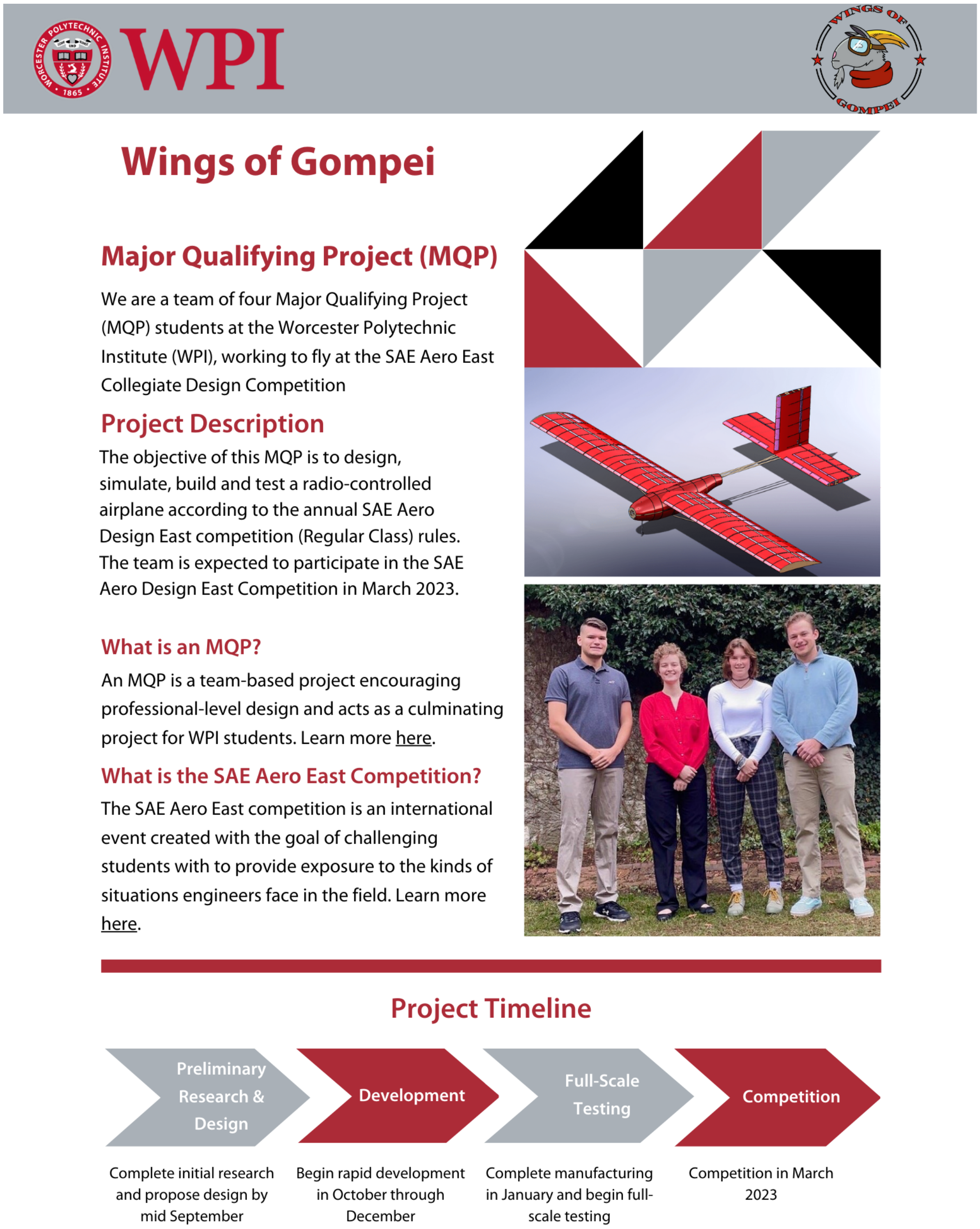
3. Raymer, D. P. (2021). *Aircraft design: A conceptual approach*. American Institute of Aeronautics and Astronautics.

4. *Risk management services*. UAS Frequently Asked Questions | Risk Management Services. (n.d.). Retrieved April 27, 2023, from https://riskmanagement.unt.edu/Unmanned-Aircraft-Systems/UAS-FAQ#:~:text=Federal%20law%20requires%20that%20small,legacy%20paper%2Dbased%20registration%20process.

13. Appendices

13.1 Appendix A: Sponsorship Packet

13.1.1 Page 1



WPI

WINGS OF GOMPEI

Wings of Gompei

Major Qualifying Project (MQP)

We are a team of four Major Qualifying Project (MQP) students at the Worcester Polytechnic Institute (WPI), working to fly at the SAE Aero East Collegiate Design Competition

Project Description

The objective of this MQP is to design, simulate, build and test a radio-controlled airplane according to the annual SAE Aero Design East competition (Regular Class) rules. The team is expected to participate in the SAE Aero Design East Competition in March 2023.

What is an MQP?

An MQP is a team-based project encouraging professional-level design and acts as a culminating project for WPI students. Learn more here.

What is the SAE Aero East Competition?

The SAE Aero East competition is an international event created with the goal of challenging students with to provide exposure to the kinds of situations engineers face in the field. Learn more here.

Project Timeline

Preliminary Research & Design	Development	Full-Scale Testing	Competition
Complete initial research and propose design by mid September	Begin rapid development in October through December	Complete manufacturing in January and begin full-scale testing	Competition in March 2023

13.1.2 Page 2

WPI

Plane Requirements

Motors are limited to 750 W

100 ft. to take-off

Hold as much weight as possible, up to 55 lbs.

Minimum wingspan: 10 ft.
Maximum wingspan: 18 ft.

Limited to one motor per aircraft

Batteries that offer at least 4000 mAh

Preliminary Budget

CATEGORY	COST
Registration	$1500
Raw Materials	$3000
Motor	$300
Controller/Radio	$600
Hardware	$1000
Travel Expenses	~$7000
TOTAL	$13,400

+ 0.5x Raw Material Cost + Apparel

COST
$13,400
$1500
$600
$15,500

Sponsorship

We're seeking sponsorships to help complete this project. Sponsors will be advertised via logos on our plane and on team apparel at competition events!

$2500+ or Material Equivalent
- Sponsor Logo on Team Apparel
- Large Logo on Plane
- Team & Plane visit to Sponsor

$1000- $2500 or Material Equivalent
- Sponsor Logo on Team Apparel
- Small Logo on Plane

< $1000 or Material Equivalent
- Sponsor Logo on T-Shirt

Contact

This project is being developed by four mechanical engineering students and one advisor.
Email: aebadi@wpi.edu

13.2 Appendix B: Design Review Notes

- B24 Liberator
    - Wing span: 110’
    - Length: 67’2”
    - Height: 18’
    - Used high aspect ratio Davis wing
        - Aspect ratio = length of the wing/width of the wing (for constant chord and symmetric designs)
        - Aspect ratio = wing span^2/wing area (for wing chord variances)
        - Aerodynamic aspect ratio has a strong inverse effect on lift induced drag
            - Optimizing attack angle along with speed for specified attack angle will minimize drag
                - Induced drag causes wingtip vortices (vice versa is not true) because high pressure air below wing meets with lower pressure air above wing at wingtip
                    - Skin friction causes the most drag, induced drag causes second most drag
                    - Winglets can reduce induced drag
                    - Elliptical spanload (spanwise distribution of lift) will produce minimum drag for a planar wing but at the expense of potentially stalling the entire wing at once with little warning

            - Measured between cores of wingtip vortices that occur at about 80% of the geometric wingspan
            - All fixed wing aircraft experience ground effect
        - Wing was longer than b17 but wing area was 25% less than b17
            - This resulted in wing loading increasing by 35% compared to b17 which also resulted in decreased wing durability
    - Wing wheels spaced 25’7.5” apart
    - Fuselage built around wing
    - Spars and bulkheads used for wing support structure
    - Left and right chord plane is set an angle of 3 deg 26 min to the horizontal
    - Construction tip and root sections are set normal to chord plane
    - Greater airspeed compared to B17 configuration
    - Flaps capable of moving 0-40 deg down
    - Ailerons capable of moving 0-20 deg up and down
    -
- P38
    - First to utilize a twin boom design with cockpit centered between engines on the wing
    - 52’ wing span
        - Wings are 327.5 sq ft
        - Full cantilever construction
        - Aspect ratio of 8.256
        - Root chord 117.0 in

        - Tip chord 36.0 in
        - Mean aerodynamic chord 84.25 in
        - Wing incidence 2 deg at root, 0 at Sta. 289
    - Flaps can extend to -40 deg
    - Low roll rate compared to single engine fighters
    - Ailerons have freedom of movement ranging -25 deg to 20 deg
    - Elevator has an area of 24.5 sq ft
        - Movement range from 23 deg to -8 deg
    - Utilizes tri-wheel configuration for landing gear
    -
    -
- Texas A&M
    - Little to no info on design of aircraft
    - Wingspan is 7 ft
    - Stored cargo in wings to maximize load taken per flight
    - Aircraft 14 ft in length
    - Utilized wing fences
- Twin engine turboprop (M-28)
    - Wing span: 72’ 4”
    - Length: 43’
    - Height: 16’ 1”
    - Used for STOL mission
    - High-wing strutted monoplane

        - Because of the high-wing structure the engines and propellers are protected from getting damaged on an unprepared runway
    - Tricycle style landing gear pattern
        - Front of nose and middle of body
    - Double winged tail
    - Flaps capable of moving 0-40 deg down
- Penn State (Placed 4th)
    - Double wing (bottom of body and then raised off top of body)
    - Double winged tail
    - Tricycle style landing gear
    - Rectangular body
- UMichigan
    - Double wing (bottom of body and then raised off top of body)
    - Tail is a standard tail that is then attached to the body by a very thin support
    - Tricycle style landing gear
    - Longer body than Penn State

Cessna Skyhawk:

https://cessna.txtav.com/en/piston/cessna-skyhawk#_model-avionics

https://calaero.edu/cessna-quintessential-training-aircraft/

https://www.boldmethod.com/learn-to-fly/aerodynamics/straight-tail-vs-swept/

- Dimensions
    - Length 27 ft 2in
    - Height 8ft 11in

    - Wingspan 36ft 1in
    - Wing area 174ft^2
- Cabin interior
    - Height 48in
    - Width 40in
    - Length 11ft 10in
    - Small cabin, not meant for cargo or storage
- Landing gear
    - Doesn't have a conventional set up, has tricycle landing gear (nosewheel and two wheels behind it)
    - This structure of landing gear is much easier to land, similarly to bombers from WWII
    - The CG sits in front of the main wheels allowing for landing leeway
- Wing placement/design
    - High wing design, placed on top of the fuselage
    - High wing planes are more stable because the center of mass is beneath the center of lift
- Stability
    - Cessna's are very stable aircrafts, which is why they are so popular as training aircrafts
    - Wing placement and weight distribution aid in Cessna's having positive static stability which means if the aircraft is disturbed mid flight, the aircraft can level itself without touching the controls

- Tail placement/design
    - Has a swept tail vs a straight tail which some other cessna models have
    - Swept tail doesn't contribute to lift as much as straight tail and has to be bigger, increasing drag
    - The drag isn't substantial, but a straight tail is more aerodynamic
    - Vertical component is located at the end of the fuselage and horizontal component is body mounted
- Motor placement
    - The engine is located in the nose of the plane, making its center of mass towards the cabin/front of the fuselage at the propeller

Lawrence technological university: (2020, 23th overall) (2019, 13th overall) (2011, 8th overall)

https://ltu.scalefunder.com/cfund/project/17139?utm_source=scalefunder&utm_campaign=site_share&utm_medium=plain

https://www.ltu.edu/aero/gallery.asp

- Dimensions
    - 26in propeller
- Fuselage
    - New design involves a trapezoidal cross section within the body of the plane in order to have ample room for payload while also minimizing the external surface area
    - Sort fuselage with small rod attaching to the tail at an upward angle

    - Old design involved a more cylindrical body
- Landing gear
    - Have always had a tricycle configuration
- Wing placement/design
    - Swept wings
    - Built on top of the fuselage
    - Increased wing size in their newer designs
- Tail placement/design
    - In the newer design the tail is higher up than the rest of the body
    - In the old design the tail was inline with the body
    - Both had the conventional set up
- Motor placement
    - Front of fuselage at the propeller
- Material
    - Seems to be made of primarily wood with some kind of wrap around the body and the wings

University of Manitoba (Canada): (2018, 1st overall)

https://news.umanitoba.ca/sae-aero-team-soars-to-1st-place-at-international-aerospace-competition/

https://harlequinz_eg0.artstation.com/projects/EVNJOe

- Dimensions
    - 12lbs
    - Carried 38lbs of cargo

- Fuselage
  - Hollow/primarily rectangular designs with lots of room for cargo
- Landing gear
  - Tricycle configuration
- Wing placement/design
  - Wings built on/near top of the fuselage
- Tail placement/design
-
  - Placed inline with the fuselage
  - Unconventional design; twin tail
- Motor placement
  - Front of body
- Material
  - Wood? With an external wrap around wings fuselage and tail
- B17

  https://www.boeing.com/history/products/b-17-flying-fortress.page

  https://www.airplanes-online.com/b17-flying-fortress-design-models-specifications.htm

  https://www.486th.org/Aircraft/B17/B17Gspecs.htm
  - low-wing monoplane
  - combined aerodynamic features from the XB-15 giant bomber & the Model 247 transport
  - Specs:
    - span: 103 feet 9 inches

        - length: 74 feet 9 inches
        - height: 19 feet 1 inch
        - wingspan: 1420 sq. ft.
        - power: four 1,200-horsepower Wright R-1820-97 engines
        - typical bomb payload: 4000 lbs (long missions), up to 8000 lbs (short missions)
            - additional external storage racks under the wings
    - Very large tail for extra stability & better control
    - high-altitude bombing
    - better high-altitude performance & could resist more battle damage than the B-24
    - had trouble running deep raid missions w/o long-range escort fighters like the P-51 Mustang to provide support
    - generally considered to have "excellent flight characteristics"

- P51

  https://www.britannica.com/technology/P-51

  https://www.nationalww2museum.org/visit/museum-campus/us-freedom-pavilion/warbirds/north-american-p-51-mustang

    - single-seat, single-engine fighter
    - piston engine
    - low-wing monoplane
    - low-drag laminar-flow wing & efficient low-drag engine cooling system
        - allowed for excellent speed & range

    - served as low-altitude fighters & long-range photo-recon aircraft
    - specs:
        - wingspan: 37 feet
        - length: 32 feet
        - max speed: 437 mph
        - max range: 1000 miles w/Allison engine; 1600 miles w/Merlin engine & additional fuel tanks
        - max load: 2000 lbs of bombs OR ten 5-inch rockets
    - switched from Allison engine to Merlin engine
        - Merlin engine had a mechanical supercharger that allowed for excellent high-altitude performance
    - external wing tanks for fuel allowed for longer flight but caused stabilization issues, especially during dives

- Dwarkadas J Sanghvi College of Engineering (India) (DJS) (Placed 4th overall)
    - Webpage (2019): https://vishalsmehta.com/djs-skylark-20182019
    - Technical Report (2019): https://static1.squarespace.com/static/60ab9204d5abe22cec6d8528/t/60bdd0e527cb4f57a332e81f/1623052530714/Team+027+DJS+Skylark+-+Regular+Class+Design+Report.pdf
        - Wings
            - vortex generators to help prevent boundary layer separation

        - Hoerner Tip: 40° to the horizontal to reduce drag by 5%; 16" tip chord length
        - Ailerons: cover 12% of wing area
        - Wing root: 24" chord length in 55% rectangular span section
        - S1223RTL airfoil
        - used wing internal space for cargo storage (tennis balls)
    - Landing gear
        - tricycle; "immunity to ground looping and nose-overs"
    - Tail
        - Vertical: EH0009 airfoil; root chord 17", tip chord 13"
        - Horizontal: modified(?) NACA0012 & E211; 13" chord, span 54"
        - Rudder: covers 34% of vertical tail area
        - tail moment arm = 49.5"
    - Materials used
        - Fuselage (wing locking bolts): Mild Steel
        - Trusses, ribs, spars: Balsa
        - Longerons, landing gear block: Yellow Birchwood
        - Primary wing spar: aluminum
- Instagram: https://www.instagram.com/djsskylark/

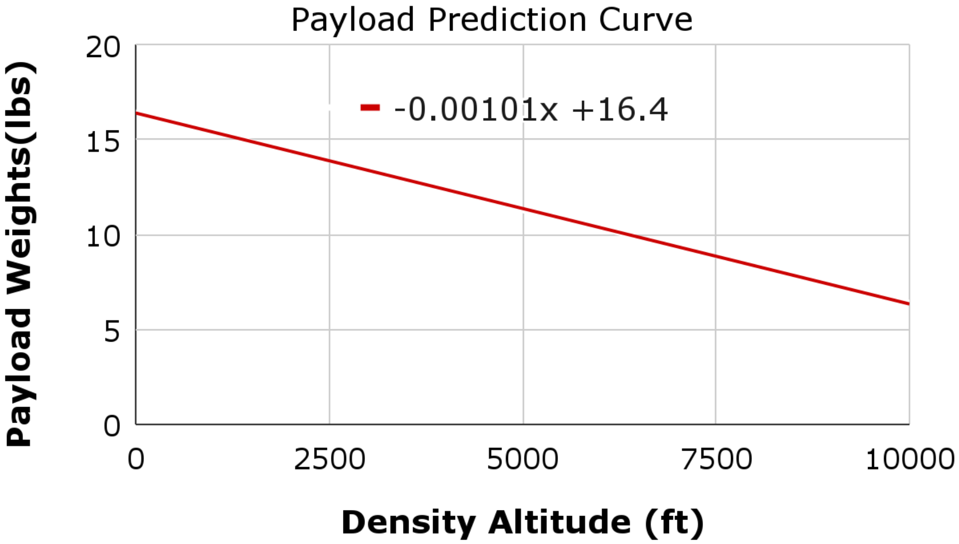
13.3 Appendix C: Technical Data Sheet

Payload Prediction Curve (Regular Class)

Team Name: Wings of Gompei - Regular Class

Team Number: 023

School Name: Worcester Polytechnic Institute



13.4 Appendix D: Mathematical Aircraft Optimization

https://drive.google.com/file/d/1JuCjGNW9sKM8s6QhQt1YjnKvWI2obVUT/view?usp=sharing