

University At Buffalo

Goose



Works

Design • Build • Fly

2022-2023 DESIGN REPORT

UNIVERSITY AT BUFFALO

HAMMERHEAD X-2



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ABBREVIATION AND NOMENCLATURE

μ	Air dynamic viscosity	M_T	Mission Total Score
A_a	Tail airfoil area	MTOW	Maximum Take-off Weight
AOA	Angle of Attack	N	Individual Team Score Ratio
AR	Aspect Ratio	PETG	Polyethylene Terephthalate Glycol
CAD	Computer Aided Design	PLA	Polylactic Acid
CAM	Computer Aided Manufacturing	Re	Reynolds Number
$C_{D,min}$	Minimum Drag Coefficient	S	Wing surface area
CFRP	Carbon Fiber Reinforced Polymer	s	Maximum Wingspan
CG	Center of Gravity	S_H	Horizontal Tail Area
$C_{L,0}$	Zero Lift Drag	t	Mission Time
$C_{L,max}$	Maximum Coefficient of Lift	TPU	Thermoplastic Polyurethane
C_M	Moment Coefficient	UAV	Unmanned Aerial Vehicle
CNC	Computer Numeric Control	V	Velocity of Aircraft
E	Elastic Modulus	V_∞	Freestream Velocity
EQN	Equation	V_{Cruise}	Aircraft Cruise Speed
ESC	Electronic Stability Control	V_H	Horizontal Tail Volume Coefficient
F_L	Lift Force	V_{Stall}	Stall Speed
FRP	Fiberglass-Reinforced Polymer	VTOL	Vertical Take-off and Landing
GFRP	Glass Fiber Reinforced Polymer	W_{EP}	Electronic Package Weight
GM	Ground Mission	XPS	Extruded Polystyrene
$L_{antenna}$	Antenna length	α	Angle of attack
L_H	Length Between CG and Tails Aerodynamic Center	Θ_{dh}	Dihedral Angle of Tail
m.a.c	Mean Aero Chord	ρ	Air Density
M1	Mission 1		
M2	Mission 2		
M3	Mission 3		
Max	Highest Score Reached by a Team		

1.0 EXECUTIVE SUMMARY

This report describes the engineering process behind University at Buffalo's Design Build Fly team (UB DBF), for the purpose of participating in the 2023 AIAA Design/Build/Fly competition. The team consists of twenty active members, all of which are undergraduates. The overall objective was to create an aircraft capable of performing electronic warfare by carrying a mock-up antenna and electronic package payload. The aircraft and all other required components must be able to fit within a box of dimensions that add to less than 62 inches, and be assembled within five minutes. Furthermore, the aircraft must take off in under 60 feet.

1.1 Design Summary

UB DBF's design process began by conducting a score sensitivity analysis to determine which design parameters are most impactful to the mission score. The analysis concluded that the most critical parameters are the test weight, cruise velocity, and payload weight, and most importantly, reliable and consistent performance. Next, Microsoft Excel was used to calculate aircraft performance metrics based on algebraic formulas. This informed the sizing analysis, which identified an optimum cruise velocity of 58 mph and a maximum takeoff weight of 15 lbs. Constraints on the sizing analysis included a maximum battery capacity of 100Wh and a maximum allowable stall speed defined as 25 mph, for safe and repeatable landings. The antenna length would be increased experimentally until the aircraft began to exhibit undesirable flight characteristics. To determine the aircraft configuration, the team used decision matrices for each design choice. A blended body v-tail was chosen based on the need for a high cruise velocity. Fixed tail-dragger landing gear was chosen for its low weight and simplicity, and a conventional tapered wing was chosen as a balance of manufacturability and aerodynamic performance. The motors are located at the wingtips, which has the effect of reducing induced drag, thus increasing cruise velocity. In order to meet the structural demands of the ground mission while remaining lightweight, UB DBF made extensive use of carbon fiber reinforced plastic (CFRP) for the wing skins and spar, due to its unmatched specific strength. Composite construction also lends itself well to a blended body design, due to its ability to be manufactured with a high degree of geometric freedom.

1.2 Performance/Capabilities Summary

The fully loaded aircraft weight is 15 lbs. The aircraft has a 70" wingspan with a wing area of 900 in². The aircraft's propulsion system outputs an impressive 9 lbs of thrust, which should allow the aircraft to cruise at 58 mph while carrying a 6 lbs electronics package. The wing sections and spar are designed to carry a 100lb test weight during the ground mission. Flight testing was performed on an initial prototype, which demonstrated acceptable stability and control. Unfortunately, the prototype was destroyed on its maiden flight, after a stall-spin occurred on final approach due to low airspeed. This loss prevented further performance testing of the prototype, but thorough performance testing will be done with the Version 2 competition aircraft during the final stages of its design and production.

2.0 MANAGEMENT SUMMARY

The University at Buffalo (UB) team is composed of 25 undergraduate students in various points of their bachelor's degrees. All students were given various responsibilities and contributed to the various sub-teams throughout the fall and spring semesters to design and build the plane. A Gantt chart was created early in the fall semester and was edited throughout both semesters as tasks were completed, and as changes were made.

2.1 Organization Description

The University at Buffalo Design/Build/Fly (UB DBF) team consists of one faculty advisor, five executive board members, two captains, four project leaders, and many sub-team members. The academic advisor assists the team in departmental administrative work. The executive board members handle logistics such as raising funds, purchasing materials and flight tickets, and lodging for the dates of the competition. The captain's main responsibilities are to lead the team through the engineering design process as well as allocate tasks to the four sub-team leaders, who distributed the workload among the participating students. The four sub-team leaders were each in charge of specific design aspects of the aircraft: Flight Dynamics, Missions, Propulsions, and Structures. The structure of the team is depicted below:

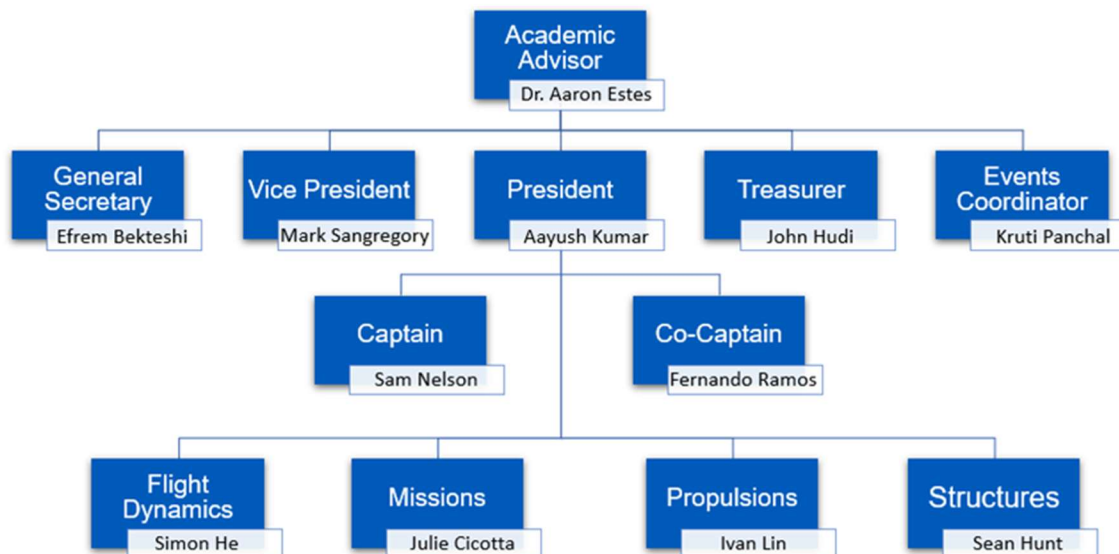


Figure 1. UB DBF Team Organization Chart

All groups and sub-teams met weekly to give updates on the progress of their various tasks and discuss plans or issues that arose during that week. This ensured synchronization between the various systems and components developed among different sub-teams. The responsibilities of each specialized group are described below:

Table 1. Responsibilities and required skills of each DBF group

Sub-Team	Responsibilities
e-board	- Organize events for different team members - Keep entire club involved with the UB association - Plan volunteering events
Captains	- Develop a timeline for the important phases of the project - Delegate tasks to all sub-teams
Propulsions	- Use eCalc to identify the motors and propeller size that provide sufficient power to meet cruise speed and weight requirements - Perform thrust test of motors to determine maximum power, current, and voltage
Flight Dynamics	- Choose airfoil and determine the wing and tail geometry - Conduct flight stability analysis and tests - Perform Computational Fluid Dynamics
Structures	- Perform tensile stress tests to identify material properties - Test prototype wings to determine max load before failure - Perform Finite Element Analysis to identify structural limits and possible failure mode - Composite manufacturing
Mission	- Design a quick-connect attachment module - Develop an airspeed and IMU data collection system in conjunction with the flight dynamics team - Design and build the test fixtures and box

All groups meet weekly to update their progress and discuss plans. This ensures synchronization between the various systems and components developed among different sub-teams.

2.2 Project Schedule

A Gantt chart was developed to organize the team's workload and make a plan that ensures all deadlines are met.

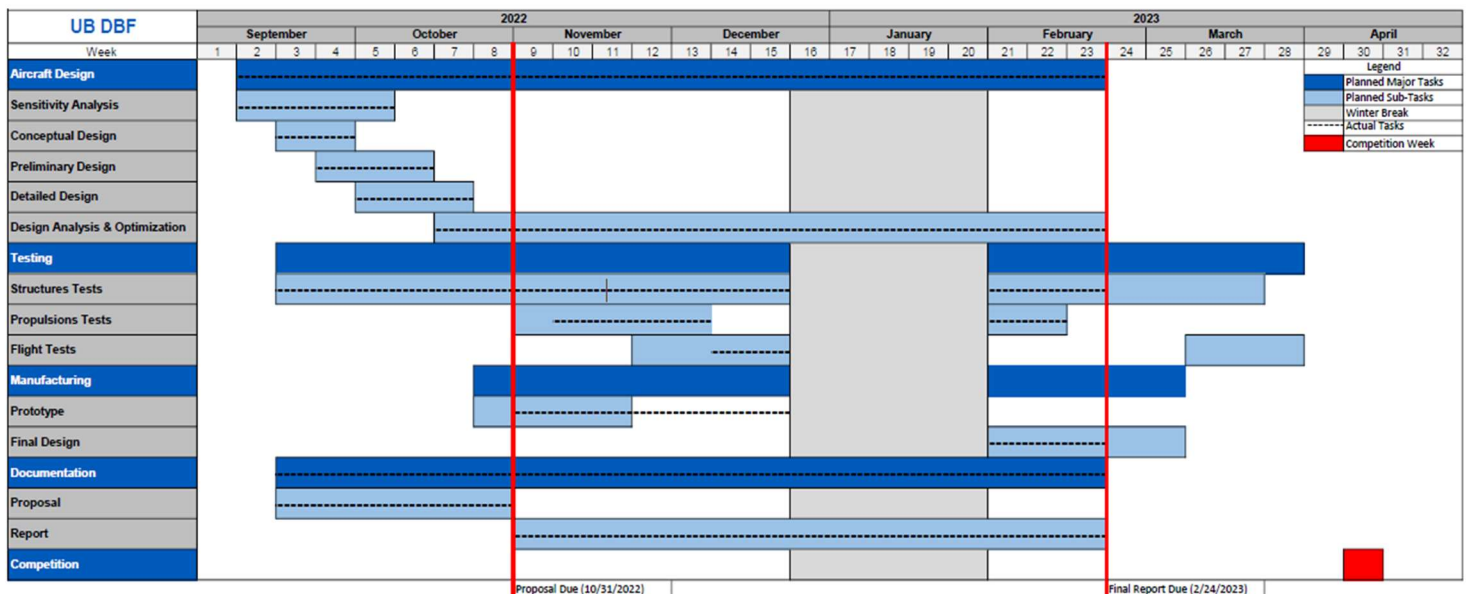


Figure 2. UB DBF Team 2022-2023 Gantt Chart

3.0 CONCEPTUAL DESIGN

The objective of the 2023 DBF competition is to design, build and test an aircraft capable of executing electronic warfare missions. This section outlines the design process used by the UB DBF team to create a conceptual design of the aircraft. The competition rules, mission requirements and scoring functions were analyzed in detail to develop a list of critical design requirements. A score sensitivity analysis was conducted to determine which mission parameters have the largest impact on the total team's score. The results of the study were used to select the major airframe component configurations to develop an initial conceptual design of the aircraft.

3.1 MISSION REQUIREMENTS AND SCORING

A study of all missions was performed to determine the main critical system parameters.

3.1.1 General Mission Requirements

The team will start all flight missions by bringing the aircraft and payloads inside a shipping box to the staging area. A coin will be flipped twice to determine which wing set components will be used. The aircraft is then assembled, and the payload is installed within a 5-minute window. After loading and checkout is completed, the aircraft is ready to be called to the flight line and start the mission. The flight course is shown below:

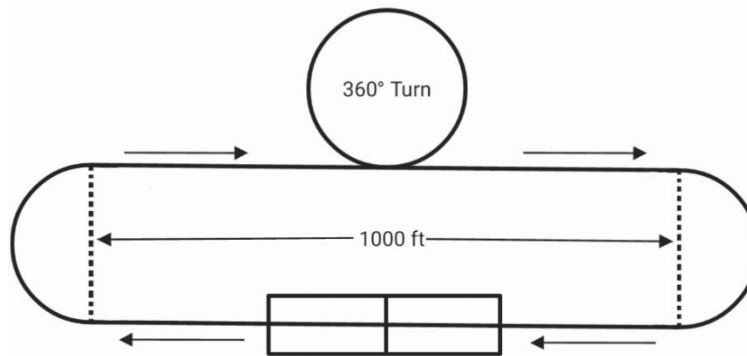


Figure 3. Flight course for all missions

All missions require that the aircraft must takeoff within 60 ft. Additionally, the time window for each mission starts at the initial throttle-up, and it ends when the time limit has been reached. A successful landing is required to complete all missions but landing time is not included in the time window.

3.1.2 Mission 1 – Staging Flight

The staging flight consists of flying three laps within a five-minute window without a payload. A lap is completed when the aircraft crosses the start/finish line in the air. The time count begins when the throttle is advanced. The aircraft must land successfully to complete the mission. Upon successful completion, the score of mission 1 (M1) is the following:

$$M_1 = 1 \quad (3.1)$$

3.1.3 Mission 2 – Surveillance Flight

The payload for this mission is an electronic package mock-up. The payload must meet the minimum dimensions and weight requirements shown in table 2. The surveillance flight consists of flying as many laps as possible within a ten-minute window with the electronic package onboard. The score is a function of the electronics package weight (W_{EP}) and the number of laps flown (n_{laps}). The score is computed by taking the ratio between the individual team score and the highest score reached out of all teams plus 1. The score of mission 2 (M2) is expressed as follows:

$$M_2 = 1 + \frac{[W_{EP}(n_{laps})]_N}{[W_{EP}(n_{laps})]_{MAX}} \quad (3.2)$$

Table 2. Electronic package minimum requirements for the DBF2023 Competition

Minimum Requirement	Design Constraint
Weight must be equal to or greater than 30% of the gross vehicle weight flown	$W_{EC} \geq 0.3W_{aircraft}$
Size must be equal to or greater than 3x3x6 in	$h_{payload} \geq 3 \text{ in}$ $w_{payload} \geq 3 \text{ in}$ $l_{payload} \geq 6 \text{ in}$

3.1.4 Mission 3 – Jamming Flight

The payload for this mission is an electronic antenna mockup. It must be attached to the wingtip of the aircraft with two fasteners and an adapter of the team's designs. A counter-weight can be attached in the opposite wing tip to balance the weight distribution. The antenna mockup is a PVC pipe with the properties outlines in table 3. The jamming mission consists of flying three laps in a five-minute window with the antenna attached to the aircraft. The length of the antenna is recorded prior to the start of the mission, and it is measured from the point the antenna exits the adapter. The score is a function of the antenna's length ($L_{antenna}$) and the mission time ($t_{mission}$). The final mission score is computed by taking the ratio between the individual team score (N) and the highest score reached out of all teams (Max) plus 2. The score of mission 3 (M3) is the following:

$$M_3 = 2 + \frac{(L_{antenna}/t_{M3})_N}{(L_{antenna}/t_{M3})_{MAX}} \quad (3.3)$$

Table 3. Jamming antenna material characteristics for the DBF2023 Competition

Material Characteristics
- Unmodified ½ inch Schedule 40 PVC pipe in accordance with ASTM-D1785 or equivalent - Section of pipe that identifies it as schedule 40 must be visible - No internal stiffeners may be added to the antenna

3.1.5 Ground Mission – Structural Margin Demonstration

The purpose of the ground mission is to demonstrate the structural margin by performing a weight loading test on the aircraft. Only the assembly crew member and the pilot can participate. The mission is divided in the following four main phases that must all be completed within a ten-minute window:

- Staging: The team enters the staging area with all aircraft components and payloads inside the shipping box. A coin is then flipped twice to determine which wing set components will be used in the mission.
- Aircraft Assembly: The crew member proceeds to assemble the aircraft with the heaviest payload configuration declared in the technical inspection. Once the aircraft is put together, the pilot verifies that all the controls are working properly.
- Test fixture installation: The structural test fixtures are installed onto the aircraft wing tips by the crew member.
- Weight load test: Test weights are applied to the center of the aircraft fuselage until max weight is called or time expires. Once the final weight is applied, the aircraft must be able to hold the weight for 30 seconds. While under load, the pilot verifies that all the controls are working properly.



Figure 4. Loading test setup

All four stages must be completed without losing functionality of the flight controls, and without structural failure or deformation in the aircraft. Once the mission is completed successfully, the amount of weight applied to the aircraft is recorded. The score is a function of the total test weight (W_{test}) divided by the max aircraft weight (W_{aircraft}). The final mission score is computed by taking the ratio between the individual team score (N) and the highest score reached out of all teams (Max). The score of the ground mission (GM) is:

$$\text{GM} = \frac{(W_{\text{test}}/W_{\text{aircraft}})N}{(W_{\text{test}}/W_{\text{aircraft}})\text{MAX}} \quad (3.3)$$

3.1.6 Total Mission Score

The team mission score (TS) is given by adding all missions scores and multiplying the result by the report score as illustrated below.

$$\text{TM} = \text{Report Score} * (\text{GM} + M_1 + M_2 + M_3) \quad (3.4)$$

3.2 GENERAL CONSTRAINTS AND REQUIREMENTS

The final aircraft developed must meet the general requirements and constraints set forth by the DBF committee in the official rules [Table 4]. The requirements have been allocated under general, performance, ... A summary of the list is shown in the table below:

Table 4. General requirements & Constraints for the DBF 2023 Competition

Type	Requirements and Constraints
General	• Must be unmanned and remote-controlled with radio signal by a pilot in line of sight. • Components must remain attached or within the aircraft for duration of the flight. • Propulsion must be propeller and electric driven. • Must fly with same configuration in all missions except mission 3. • Aircraft must enter the staging box inside the closed shipping box. • The TOGW (take-off gross weight with payload) must be less than 55-lb.
Structures	• Rotary wing or lighter-than-air aircraft configurations may not be made. • Blades of the propeller may be painted for balancing purposes. • The propeller can have folding blades. • The propeller can have a modified diameter by clipping the tip. • All components of the aircraft and payloads must fit inside a shipping box with dimensions that add to less than 62 inches. • The shipping box in combination with all internal items must be less than 50 lb. • Two pairs of left and right wings must be provided. • Left and right-wing sections must make up at least 80% of the total wingspan. • Aircraft will be lifted with one lift point at each wing tip to verify adequate wing strength. • Must have the loaded and unloaded CG locations on exterior of aircraft. • The propeller diameter/pitch can be changed for each flight attempt.
Propulsion	Batteries • A maximum of one battery can be connected to a propulsion system. • The choice of a NiCad/NiMH or Lithium Polymer batteries may be used. • Only one battery type may be used. • The total stored energy must not exceed 100 Watt-hours. • Arming fuse for LiPo batteries cannot exceed a discharge current rating of 100 Amps. • Must be commercially obtained with a manufacturer's label and specifications. • Each pack and system must be independently connected and have its own arming fuse. Motors and Propellers • Must be an over-the-counter unmodified model electric motor that is commercial brush or brushless. • Multiple motors or propellers are allowed. • Commercial ducted fan units are allowed.
Avionics	• Motor arming fuse must be "blade" style fuse that is accessible without reaching across the propellers. • The mechanical motor arming fuse must be separate from the onboard radio Rx switch. • The mechanical motor arming system must be externally accessible.
Payload	Electronic Package • Total package weight must be greater or equal to 30% of the gross aircraft weight. • The size of the package must be greater than 6x3x3. • No part of the package can extrude outside the aircraft. Jamming Antenna • Must be an unmodified 0.5" schedule 40 PVC pipe in accordance with ASTM-D1785. • PVC pipe identified at schedule 40 must be visible. • No internal stiffeners may be used with the antenna.
Takeoff	• Must takeoff within field length of 60 feet. • No externally assisted take off is permitted.

3.3 TRANSLATION OF MISSION REQUIREMENTS INTO SUBSYSTEM DESIGN REQUIREMENTS

The subsystem design requirements necessary to complete all missions successfully are shown below:

Table 5. Mission Requirements and Sub-System Qualitative Requirements

Mission	Score	Mission Requirements	Sub-system Requirements
GM	$GM = \frac{(W_{test}/W_{aircraft})_N}{(W_{test}/W_{aircraft})_{MAX}}$	- Assembly time must be less than 5 minutes - Maximize test weight - Minimize aircraft weight	- Quick connection modules - Easy mating of aircraft parts - Strong wing spar - Rigid
M1	$M_1 = 1$	- Fly 3 laps - Stable flight	- Low stall velocity - High static margin - Dynamically stable
M2	$M_2 = 1 + \frac{[W_{EC}(n_{laps})]_N}{[W_{EC}(n_{laps})]_{MAX}}$	- Fly with the electronics package for 10 minutes - Maximize number of laps - Maximize weight of payload	- High cruise speed - Ability to lift heavy payload - Power efficient - Payload volume capacity
M3	$M_3 = 2 + \frac{(L_{antenna}/t_{M3})_N}{(L_{antenna}/t_{M3})_{MAX}}$	- Fly with antenna attached for 3 laps - Maximize antenna length - Minimize mission time	- High cruise speed - Dynamically stable - Strong antenna adapter

3.4 SCORE SENSITIVITY ANALYSIS

The total points earned depend on the report grade and all the mission scores. To maximize the overall outcome, both the report and mission scores must be maximized. A score sensitivity analysis was performed to understand which parameters have the largest impact on the total team's score.

3.4.1 Total mission score breakdown

The total mission score (M_T) is given by all the individual mission formulas combined as shown below:

$$M_T = 4 + \frac{(W_{test}/W_{aircraft})_N}{(W_{test}/W_{aircraft})_{MAX}} + \frac{[W_{EP}(n_{laps})]_N}{[W_{EP}(n_{laps})]_{MAX}} + \frac{(L_{antenna}/t_{mission})_N}{(L_{antenna}/t_{mission})_{MAX}} \quad (3.5)$$

Variables such as the number of laps of mission 2 and the completion time of mission 3 are directly dependent in the aircraft cruise speed (V_{cruise}) through the following relationships:

$$n_{laps} = \frac{d_{total}}{d_{lap}} \rightarrow n_{laps} = \frac{V_{cruise} t_{M2}}{d_{lap}} \quad (3.6a)$$

$$V_{cruise} = \frac{d_{total}}{t_{M3}} = \frac{3d_{lap}}{t_{M3}} \rightarrow t_{M3} = \frac{3d_o}{V_{cruise}} \quad (3.6b)$$

Combining equations 3.6 into 3.5, and separating grouping constants for maximum values the total mission score equation becomes the following:

$$M_T = 4 + \frac{1}{A} \left(\frac{W_{test}}{W_{aircraft}} \right)_N + \frac{1}{B} (W_{EP} V_{cruise})_N + \frac{1}{C} (L_{antenna} V_{cruise})_N \quad (3.8)$$

- where the constants A, B, and C are the following:

$$A = \left(\frac{W_{test}}{W_{aircraft}} \right)_{MAX} \quad B = \left(\frac{t_{M2}}{d_{lap}} \right) (W_{EP} V_{cruise})_{MAX} \quad C = \left(\frac{1}{3d_{lap}} \right) (L_{antenna} V_{cruise})_{MAX}$$

3.4.2 Sensitivity Analysis

It is expected that each of the variable parameters in the total mission score (Eq. 3.9) have a linear relationship with the total score. The magnitude of the relation depends on the maximum scores reached by a team within each mission. Historical data and experience were used to best estimate the highest scores that could be achieved in each challenge. The estimated values are shown in the table below:

Table 6. Maximum estimated values used in Sensitivity Analysis

Estimate	$W_{test}/W_{aircraft}$	n_{laps}	W_{EP}	$L_{antenna}$	$t_{mission3}$
Maximum	5	15	12 lbs	1 m	120 s

A MATLAB script was developed. It uses the Taylor Series Expansion method to determine the change of the total mission score given a change in value of the mission parameters. The slope of each variable's line directly corresponds to their impact on the total score. The results are displayed in the following figures:

Table 7. Sensitivity Analysis Results

Parameter	Impact in total score
Test weight	$\frac{\delta M_t}{\delta W_{test}} = 0.20840$
Aircraft Weight	$\frac{\delta M_t}{\delta W_{aircraft}} = -0.20840$
Payload Weight	$\frac{\delta M_T}{\delta W_{EC}} = 0.0739$
Velocity	$\frac{\delta M_T}{\delta V_{cruise}} = 0.16630$
Antenna Length	$\frac{\delta M_T}{\delta L_{antenna}} = 0.09599$

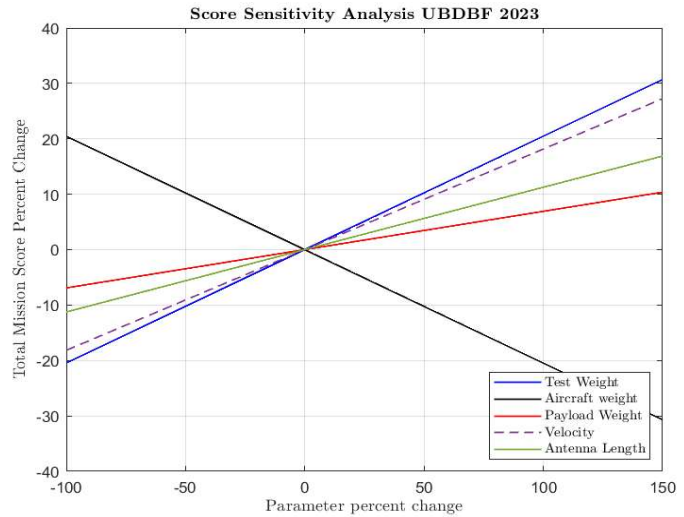


Figure 5. Flight course for all missions

The results show that the parameters of highest priority are the test and aircraft weight. Results also show that increasing the cruise velocity has the second largest positive impact in total mission score. Additionally, increasing the antenna length and the payload weight also favorably impacts the total mission score but in significantly lower magnitude.

Overall, the sensitivity analysis study conveyed that the team should focus on maximizing the strength of the wing spar and wing structure while minimizing the aircraft weight. Additionally, the aircraft cruise speed should be maximized within safe flight limits. A high cruise velocity will enable the airplane to achieve a higher number of laps mission 2 and a faster completion time in mission 3. The payload weight and antenna length are the parameters that can be trimmed down if necessary to increase the aircraft strength and speed.

3.5 CONFIGURATIONS AND CONCEPTS CONSIDERED

Decision matrices were used to determine the configuration of the landing gear, engine placement, fuselage design, wing placement, wing design, and tail configuration.

3.5.1 Landing gear configuration

A tail dragger configuration was chosen, narrowly defeating the tricycle gear. The tricycle configuration had the advantage of superior ground handling, but that was outweighed by the improved durability and reduced drag of a tail dragger. Additional considerations included the ability to pack down into a small size. A nosewheel adds a long protrusion to the fuselage and would need to be removable in order to fit inside the box, while a tailwheel likely would not need to be removed due to its small size.

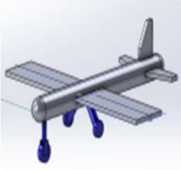
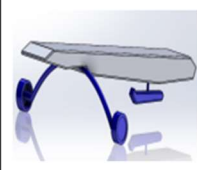
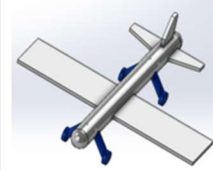
		Score		
				
Criteria	Weight	Tricycle	Tail dragger	Four on the floor
Ground Handling	5	3	2	1
Manufacturability	3	2	2	1
Durability	5	2	3	3
Drag	3	2	3	1
Total		37	40	26
Rank		2	1	2

Figure 6. Landing Gear Configuration Designs

3.5.2 Engine configuration

A double wingtip engine configuration was chosen, for its improved aerodynamic efficiency and contributions to the ground mission. By moving mass towards the wingtips, the bending moment on the wing spar is reduced, as the lever arm the motors acts on goes to zero. However, the main advantage of wingtip motors is the impact on induced drag. There is extensive research to suggest that the propwash from wingtip-mounted propellers can effectively negate the wingtip vortices caused by high- and low-pressure areas mixing at the wingtip, which are a primary source of energy loss in most aircraft [5]. This has been demonstrated on NASA projects such as the VTOL UAV 'Greased Lightning' and is further being investigated by the X-57 'Maxwell'.

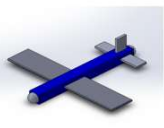
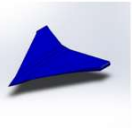
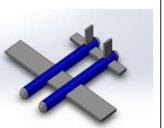
		Score			
					
Criteria	Weight	Rectangular	Blended Body	Circular Body	Double Fuselage
Drag	4	1	3	2	1
Manufacturability	3	2	2	2	2
Breakdown	5	3	2	2	0
Weight	4	2	3	2	0
Total		33	40	32	10
Rank		2	1	3	4

Figure 7. Engine Configuration Design

3.5.3 Fuselage Configuration

A blended body fuselage was selected, due to its reduced weight and drag. The traditional downside here is the difficulty to manufacture. However, foam and composite construction allows for much more geometric freedom than typical built-up wood structures, so the added manufacturing challenge was neglected in the decision matrix.

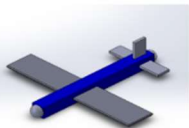
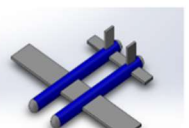
		Score			
					
Criteria	Weight	Rectangular	Blended Body	Circular Body	Double Fuselage
Drag	4	1	3	2	1
Manufacturability	3	2	2	2	2
Breakdown	5	3	2	2	0
Weight	4	2	3	2	0
Total		33	40	32	10
Rank		2	1	3	

Figure 8. Fuselage Configuration Design

3.5.4 Wing Location

A low, middle, and high wing design were considered. A high wing was selected, primarily as a result of its superior stability characteristics and propeller clearance. By mounting the propellers on the wingtip, any roll angle upon landing, for example during a crosswind, would put the plane at risk of a ground strike. By using a high wing, the chance of this occurring is mitigated. This moves the wing further out of ground effect, which impedes takeoff and landing performance, but this was considered a low priority due to the relatively long takeoff distance allowed.

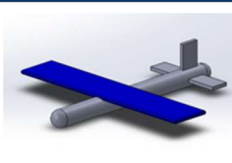
		Score		
				
Criteria	Weight	Low	Middle	High
Stability and control	2	1	2	3
Manufacturability	3	2	2	2
Takeoff Capability	3	3	2	1
Structures	3	2	3	2
Prop clearance	4	1	2	3
Payload Access	3	3	1	2
Total		36	36	39
Rank		2	2	1

Figure 9. Wing Location Design

3.5.5 Aerodynamic Surface Configuration

The team considered a variety of aerodynamic configurations, including the flying wing, biplane, conventional, and 3-surface designs. Ultimately, the flying wing won by a significant margin, due to its lower drag and weight. Removing the tail also makes it easier to assemble and pack down. However, flying wings have a smaller static margin, which requires greater accuracy when determining the CG. Furthermore, they require airfoils that are optimized for having low moment coefficients rather than high lift coefficients, and have a planform that is typically incompatible with flaps. This means they would be likely to have a high stall speed, given the same size wing. Higher stall speeds and reduced stability directly goes against the philosophy of safety and reliability over performance, so the team disregarded the results of the decision matrix and selected a conventional configuration.

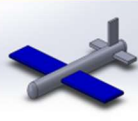
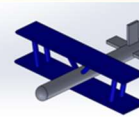
		Score			
					
Criteria	Weight	Flying Wing	Conventional	Biplane	3 Surface
Safe Flight Characteristics	5	1	2.5	3	3
Manufacturability	3	3	2	2	2
Assembly Time	5	3	2	1	1
Weight	4	3	2	1	2
Drag	4	3	2	1	2
Packing in box	4	3	2	1	2
Total		65	52.5	38	50
Rank		1	2	4	3

Figure 10. Aerodynamic Surface Configuration Design

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3.5.5 Tail Configuration

After deciding the plane would have a tail, the configuration of the tail had to be chosen. The team compared V-tails, conventional tails, T-tails and H-tails, and found that V-tails were the best choice by a significant margin. Because a V-tail consists of two symmetrical parts, both manufacturing and design are simplified, as only one unique part is produced. A V-tail also achieves the same aerodynamic stability with less wetted area, which means it will weigh less and take up less space in the box.

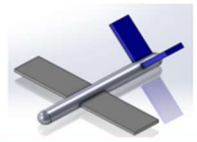
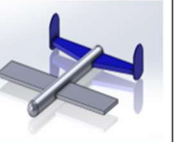
		Score			
					
Criteria	Weight	V Tail	Conventional	T Tail	H Tail
Drag	2	2	2	3	2
Manufacturability	5	3	2	1	1
Stall Recovery	4	2	3	1	3
Fit in box	5	3	2	1	2
Assembly time	5	3	2	2	3
Weight	4	3	2	2	1
Total		69	54	38	50
Rank		1	2	4	3

Figure 11. Tail Configuration Design

3.6 FINAL CONCEPTUAL DESIGN

The final conceptual design is depicted in figure 12:

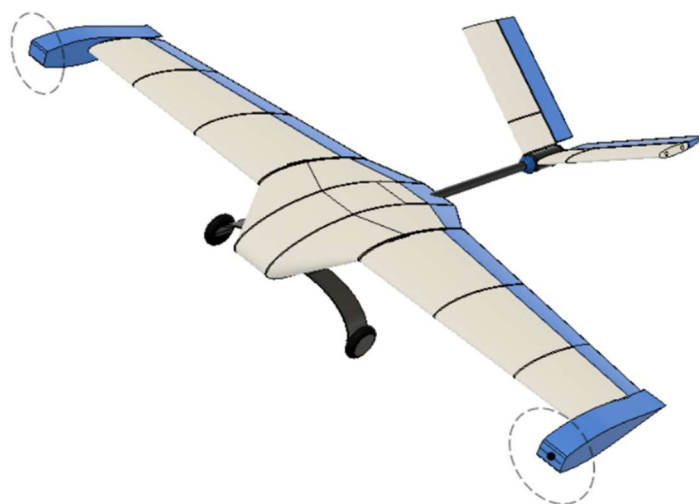


Figure 12. Final conceptual design of aircraft

4.0 PRELIMINARY DESIGN

4.1 DESIGN METHODOLOGY

UB DBF uses a two-step iterative design process. It began with a sensitivity analysis, which identified the performance metrics that would most heavily impact mission score. This informs which factors should be maximized, minimized, or optimized, and the decision matrices (shown in previous section) are completed. To determine the weight and dimensions of the initial prototype, a mathematical model was created on Excel which uses algebraic equations to calculate basic aircraft performance metrics. The Excel model is used to optimize airframe size and weight and velocity, such that score is maximized within the constraints of battery capacity. At this point, a propulsion system was chosen based on calculated power requirements. Then, the initial prototype was modeled using CAD software, manufactured, and tested. The test flight was followed by a design review, which informed the design changes to be made to second prototype. The second prototype was then modeled in CAD and will be constructed and tested after the report submission.

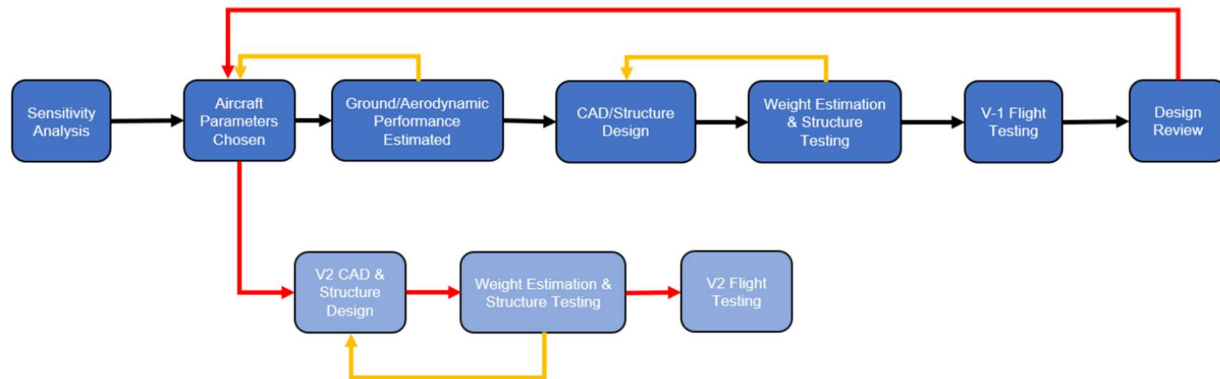


Figure 13. Design and analysis methodology

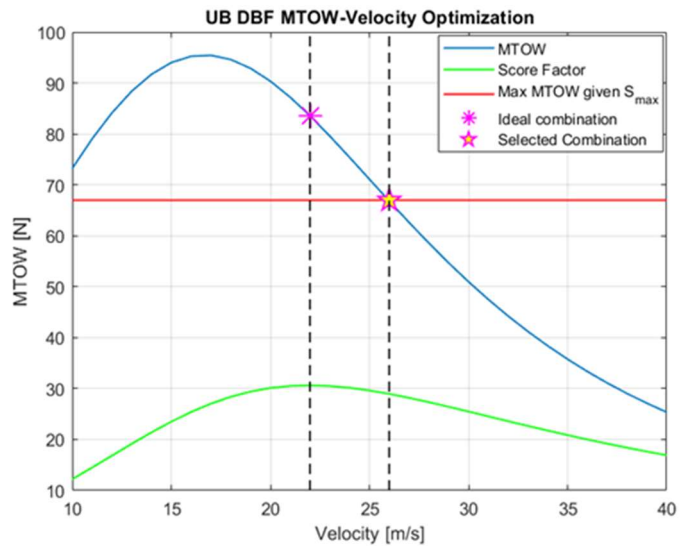
4.2 DESIGN AND SIZING TRADES

4.2.1 Overall Aircraft Size

The team determined the aircraft size and weight using a series of airplane performance equations incorporated into an Excel spreadsheet. Mission 2 was selected as the focus of the aerodynamic optimization, because it is the most demanding, due to the extended duration of the mission. For a large plane, the entirety of the 100Wh battery should be used to maximize score. The power consumption was calculated the power-required equation was used, in conjunction with formulas for stall speed, drag, and lift. A stall speed of 25mph was set, to ensure reliable and safe landings. The aspect ratio was set at 5.00, to strike a balance between aerodynamic performance during missions 2 and 3 and structural performance during the ground mission. Other values were estimated, shown in the table below, along with the outputs from the calculator.

Table 8. Parameters and estimated values

Inputs to Model	
Parameter:	Est. Value:
Zero-lift drag coefficient	0.03
Energy available in battery	360000 J
Ratio of battery used	0.7
Oswald Efficiency Factor	0.7
Distance travel (level flight)	610 m
Distance traveled (banking)	572 m
Motor efficiency	0.8
Propeller efficiency	0.7
Total propulsive efficiency	0.56
Stall speed	11.2 m/s
Max. lift coefficient (with flaps)	1.8

**Figure 14.** MTOW vs Velocity optimization

The above graph was generated based on the approximations presented in the above table. There exists a limited average power consumption that allows the aircraft to fly for 10 minutes during Mission 2. The power consumption of the aircraft is dictated by both its weight and velocity, which both impact the score for Mission 2. Estimates were provided for all other aircraft parameters, leaving weight and velocity the only two unknown variables. Using equations for stall speed:

$$V_{stall} = \sqrt{\frac{2W}{\rho S C_{L, Max}}} \quad (4.1)$$

and power required:

$$P_{req} = \frac{1}{2} \rho V^3 S C_{Do} + \frac{W^2}{\frac{1}{2} \rho V S} \left(\frac{1}{\pi e A R} \right) \quad (4.2)$$

the velocity and MTOW could be plotted against each other. Since the score is dependent on the product of the two, the product of the variables was also plotted as a function of velocity (with the actual value of this 2nd plot having a meaningless output). The location of the max value of the product function indicates the velocity at which maximum score occurs. However, the MTOW associated with this ideal velocity would require a wing too big to fit in the box. As such, a smaller MTOW and higher velocity were selected. The box fit was demonstrated using CAD, and the design was iterated until maximum box space was used.

4.2.2 Aerodynamic Surface Design and Sizing

4.2.2.1 Wing Design and Sizing

The main goal of the wing design is to generate sufficient lift during flight. The most lift is needed during the takeoff phase. Therefore, the wing is designed to generate sufficient lift of MTOW 15.8lbs. Payload in Mission 2 is included in MTOW. The wingspan has been optimized for fitting in the shipping box. Result

from the optimization analysis shows the max wingspan (s) is 1.68 meters. As shown in Equation 4.3, coefficient of lift (C_L) and wing area (S) needs to be maximized to produce maximum lift force (F_L).

$$F_L = \frac{1}{2} \rho C_L v^2 S \quad (4.3)$$

$$S = \frac{s^2}{AR} \quad (4.4)$$

Wing area can be calculated by using aspect ratio (AR), shown in Eqn. 4.4. To optimize fitting the wing into the shipping box while maximizing the aspect ratio, AR has been selected to be 5. The resultant wing area is 0.562 m^2 .

4.2.2.2 Airfoil Selection

The airfoil candidates are selected from historic usage by the “Design Build Fly” team at University of Buffalo. Our team has also reviewed and selected airfoils used on top 3 winning teams from previous competitions. The candidates are Clark Y, NACA 0024, NACA 2412, NACA 2414, and SD7062. To determine the best suited airfoil during flight, our team performed analysis on maximum lift coefficient, minimum drag coefficient, critical angle of attack, maximum lift and drag ratio, angle of attack at maximum lift and drag ratio, and zero lift angle.

Each mission desires different flight characteristics. Mission 2 with payload desires a high lift coefficient airfoil whereas Mission 3 with antenna attached desires a low moment coefficient at low angle of attacks. It is difficult to distinguish one airfoil that is the best fit for all missions. Rather, our team strives to find an airfoil that has a balanced performance between all. The ideal airfoil will produce sufficient lift at takeoff and cruise. Other than aerodynamic characteristics, the airfoil also needs to have enough thickness to house all internal structures, be easy to manufacture, and optimized for fitting into the shipping box.

The airfoil analysis was performed using XFLR5. Average velocity, V_∞ , of our competition plane is 25 m/s and average chord of the plane is 0.3125 m used as the characteristic dimension, L . At an altitude of 700 m , air density (ρ) is 1.1673 kg/m^3 and air dynamic viscosity (μ) is $1.77\text{e-}5 \text{ kg/ms}$. Therefore, we calculated the Reynolds number (Re) using Eqn. 4.5. Analysis was performed with Reynolds number of around 550,000.

$$Re = \frac{\rho V_\infty L}{\mu} \quad (4.5)$$

Table 9 indicates the design and airfoil parameters of each candidate. Results were then plotted in MATLAB as shown in Figure 14-17

Table 9. Design and parameters of each airfoil

Parameter	Clark Y	NACA 0024	NACA 2412	NACA 2414	SD7062
Max. lift coefficient	1.4018	1.1442	1.2424	1.2748	1.6037
Crit. AoA (deg)	13	16.5	12	15	15
Max. lift/drag ratio	84.8012	47.4201	73.8153	76.3507	84.0724
AoA at max. lift/drag ratio (deg)	4	10	5	6	6
Zero lift angle (deg)	-3.5	1	-4	-3	-4.5
Max. thickness (%)	11.71	13.06	24.01	12	13.98

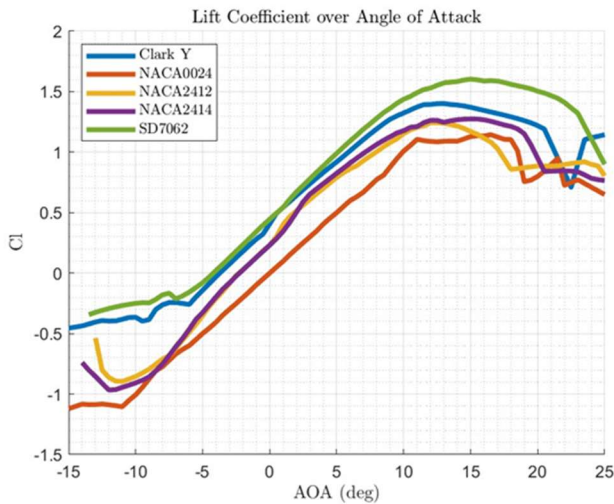


Figure 15. Airfoil Moment vs Angle of Attack

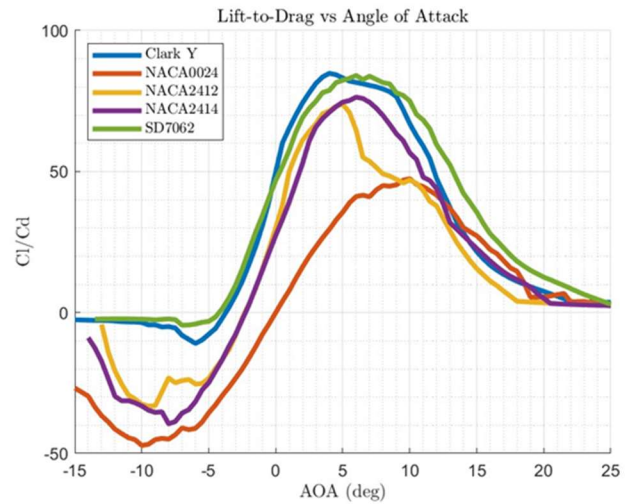


Figure 16. Airfoil Lift vs Drag Coefficients

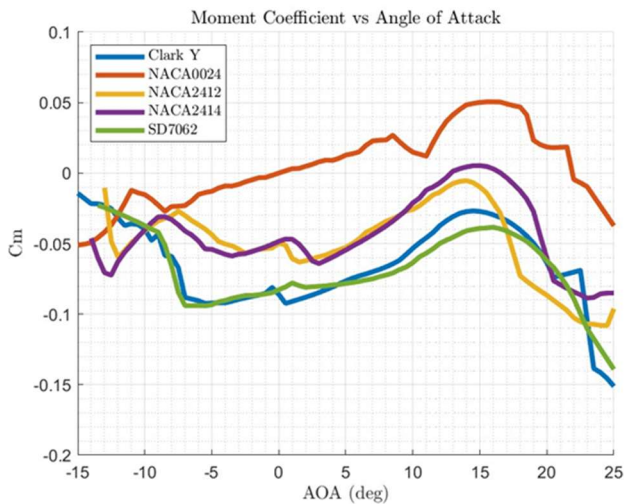


Figure 17. Airfoil Lift Coefficient vs Angle of Attack

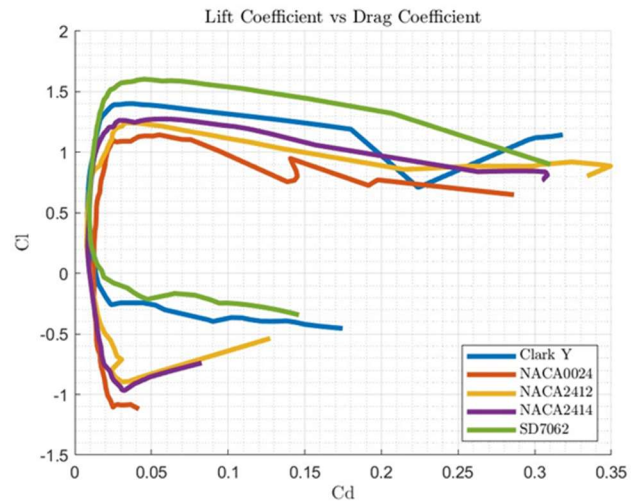


Figure 18. Airfoil Lift-to-Drag vs Angle of Attack

Investigating the analysis results, SD7062 and Clark Y seem to be the best candidates out of all. From Figures 15 and 16, SD7062 produces the highest lift coefficient out of all candidates. But from Figure 17, Clark Y produces a slightly higher max lift and drag ratio against SD7062. For our mission needs, SD7062

and Clark Y are both strong candidates. Investigating further at the lift coefficient (C_L) vs drag coefficient (C_D) plot, SD7062 has a high drag at the upper limit of C_L . Upon further investigation at Figure 17, the high and wide range of C_L provides a high efficiency in operation range. Another advantage of the SD7062 is shown in Figure 14. Its low moment coefficient (C_M) produces a nose down moment. This is advantageous for Mission 3 where the antenna will produce a nose up moment. The ground mission requires the wing to be loaded therefore structural components will be embedded inside the airfoil. The higher maximum thickness the SD7062 allows more loading members to be embedded. From multiple advantageous characteristics, SD7062 airfoil was selected. This foil is designed by Selig and Donovan. Its primary intended usage is for small wind turbines where high lift and soft stall characteristics are desired. It is designed to perform close to the Reynolds range our team's plane will be flying. [12]

4.2.2.3 Control Surface Design and Sizing

The final design of the aircraft forgoes flaps while implementing ailerons and elevators as the control surfaces. Flaps were removed from the design as the final aircraft has a take-off distance within the allowed 60 ft and their removal allows for substantially increased rigid lift surface which improves stability. The ailerons were designed using historical data and information from "Aircraft Design: A Conceptual Approach" by Raymer. According to figure 6.3 on page 161 in "Aircraft Design", common ranges of aileron chord to wing chord are from .1 to .35 percent for a range of aileron spans. Considering that the control surface sizing chart was intended for full-size aircraft which are less maneuverable and responsive than is required at the R-C aircraft scale, aileron span was slightly increased over the presented guidelines. Ailerons were sized at 22% of wing chord at a span of 50%, which is slightly higher than the guideline values of 45% span at 22% chord. This slight increase of aileron span maintains wing rigidity while increasing total maneuverability. In terms of tail control surfaces, the v-tail design makes it such that the airfoils act as both elevators and rudders simultaneously. Table 6.5 [7] lists guidelines for control surface sizing of elevators and rudder in some common plane types. Elevators in the final v-tail design were designed at 36% of tail airfoil area, which lies between the values listed for business jets (32%) and sailplanes (43%) and is hypothesized to be adequate for sufficient in-flight control.

4.2.2.4 Tail Design and Sizing

As chosen by the comparison metrics in the decision matrix, a V style tail needed to be designed. The design process of the tail started with the decision of an adequate tail volume coefficient. Referencing "Aircraft Design: A Systems Engineering Approach" by Sadraey, a horizontal tail volume coefficient .6 was chosen. Dimensions for the tail were derived primarily using the following equations for horizontal tail volume coefficient:

$$V_H = \frac{S_H L_H}{(S_W * m.a.c)} \quad (4.6)$$

and a projection of area to the x plane:

$$S_H = 2(A_a \cos \theta_{dh}) \quad (4.7)$$

Variables defined as following: V_H is the horizontal tail volume coefficient, S_H is the horizontal tail area, L_H is the length between the tails aerodynamic center and the aircrafts C.G. S_W is the wing area, m.a.c is mean aero. chord of the wing, A_a is the tail surface area and θ_{dh} is the dihedral angle of the tail w.r.t the x axis. From here, using equation 4.6 we can set to .6 and plug in known values of S_W , m.a.c and L_H , (900 in², 13 in, and 31.5 in respectively). Solving for target S_H yields approx. 220 in². With a chosen dihedral angle of 35 deg. to compromise between pitch and yaw authority, we can calculate for A_a using equation 4.7. This yields $A_a = 134.29$ in² as the target area for each of the v-tails airfoils. To calculate for actual dimensions of chord, thickness and length additional restraints are required. For purposes of prototyping, a .75 in thickness was set such that two airfoils could be cut out of one 2 in foam block. With a thickness of .75 in a NACA 0010 airfoil has a 9-inch chord. From here, length is calculated by dividing A_a by 9 to yield a length of 14.92 inches. [8]

4.2.3 Landing Gear Design and Sizing

As per the decision matrix, a tail dragger style landing gear had to be designed. The team decided to use custom landing gear manufactured in-house to allow for greater geometric freedom. The main considerations for the landing gear dimensions were prop clearance and box size. If a critical bank angle is reached while on the ground, the propellers are likely to contact the ground and break. The landing gear was made to be 19" wide, which is as much as the box would allow. The height was determined to be 7", which gives a critical ground bank angle of 15 degrees.

4.2.4 Propulsion System

A single tractor, double tractor, double wingtip tractor, and a single pusher configuration were being considered. A twin-tractor wingtip with a single battery propulsion system was selected for the plane configuration as the wing tip mounted propellers reduces the wingtip vortices and helps counteract the drag produced by the antenna. Based on the chosen configuration, a RC plane configuration analysis tool eCalc [9] was used to determine the ideal combination of motor, battery, and propeller for the plane. The plane dimensions, weight, desired performances, propeller size, and other inputs were put into eCalc which in return gave us different motor and battery combinations with the performance associated with each pair. After testing different combinations, a final combination producing the most desirable results was reached. The best combination ended up being the T-Motor CINE 66-925 for the motors, a LiPo 4500mAh —45/60 C for the battery, and APC 8x8 for the propellers.

4.2.4.1 Batteries

The LiPo 4500mAh battery was chosen as it has a nominal battery voltage of 22.2 volts with a high C rating which delivers better performance, has a maximum continuous output of 203 Amps and falls under 100 watt-hours FAA regulation for a commercial flight carry on [1]. At 50% throttle the battery yields 17-minutes of flying time which is enough to complete the laps required for each mission.

4.2.4.2 Motor and Propeller

From eCalc, when the motors are at 100% throttle, the max current draw is 34.77 A, the voltage is 20.61 V, and the power required is 1303 watts which all falls within the capabilities of the selected battery. The propeller selected was the APC 8x8 as it produced the best results out of potential propellers. The 8x8 propeller produces enough thrust for the plane to take off and cruise with a thrust to weight ratio of 0.94 and a pitch speed of 195 km/h. The larger pitch from the propeller allows the plane to achieve higher top speeds in flight compared to the other candidate propellers with a lower pitch.

4.2.4.3 Avionics

The other electronic elements are five 7.5 Kg*cm servos, a 2.4GHz 8-channel Spektrum receiver, and a 1300mAh 2s1p LiPo battery to power those elements. The battery was chosen due to it being lightweight and compact while still having a high energy density. The battery's life yields about 15 minutes of flying time which is enough for each mission and is also compatible with the servos. The servos were selected because they generate enough actuator torque to withstand aerodynamic forces experienced by the four control surfaces and are lightweight enough for static stability purposes. The extra servo is used to operate the tail dragger. The servos are connected to the battery in the fuselage by wiring within wing stringers and the tail boom and spar. The chosen receiver has built-in stabilization which helps stabilize the plane in the high wind conditions the plane faces in Buffalo and the excess drag encountered on the side with the antenna in M3.

4.3 PERFORMANCE PREDICTION METHODOLOGY

4.3.1 AIRCRAFT CAPABILITIES

Aerodynamic performance was estimated by creating a model on Microsoft Excel. The model used equations for stall speed, wing loading, power required, and takeoff distance to calculate the speed and endurance of the aircraft.

The model's inputs consisted of the design parameters the team had direct control over, such as aspect ratio, battery capacity, payload weight, payload mass fraction, power available, and cruise velocity. Stall speed was set as an input, which allows the team to define a maximum safe stall speed and determine the aircraft parameters around that. Other inputs included natural constants such as air density, rolling resistance coefficient, and estimates for the distance travelled during each lap.

Outputs included wing area required, wingspan, lap time, and the number of laps that can be flown on a single battery. That last output is especially useful for optimizing Mission 2 performance. If the number of laps flown as limited by battery matches the number of laps flown as limited by the 10-minute window, then it can be concluded that maximum score is reached.

4.3.1.2 UNCERTAINTIES AND ASSUMPTIONS

These inputs contain several important assumptions. Firstly, the induced drag was assumed to be doubled while the airplane is in a bank, to account for the increase during turns. This correlates to a 60° bank angle, which is a fair assumption for DBF flights. Additional assumptions include a zero-lift drag coefficient of 0.03, which is roughly that of a Cessna 172. Our aircraft appears to be more streamlined than the Cessna 172, which should result in conservative outputs – a desirable trait in any model. Since this is the first time the model has been used, it is hard to determine how accurate the assumptions are. During the flite testing phase, speed and power consumption will be closely monitored to determine the accuracy of the model's predictions. However, the fact that conservative estimates have been used should lead to acceptable results, despite the inherent assumptions built into the model.

4.4 AERODYNAMIC CHARACTERISTICS

A preliminary lift and drag prediction were performed using MATLAB [4] XFLR5 [2], and SolidWorks Flow Simulation [11].

4.4.1 LIFT PREDICTION

XFLR5 [2] was used to generate a C_L over alpha plot of the SD7062 airfoil for the expected cruise velocities in each mission. A linear fit was applied to the linear portion of the C_L vs alpha plot to determine the zero coefficient of lift ($C_{L,0}$) and the lift coefficient slope ($C_{L,\alpha}$). That allows to estimate the total coefficient of lift of the wing in the following way:

$$C_L = C_{L,0} + C_{L,\alpha} \quad (4.8)$$

Once the coefficient of lift is determined, the lift is predicted using the equation below:

$$L = \frac{1}{2} \rho C_L V_\infty^2 S_{wing} \quad (4.9)$$

The table below summarizes all the relevant lift parameters that are expected for each mission. Additionally, the lift at angles of 0 and 2 degrees are presented to convey that the wings generate more than enough lift to keep the aircraft in the air.

Table 10. Estimated lift parameters for each mission

Parameter	Mission 1	Mission 2	Mission 3
V_∞	20 m/s	25 m/s	27 m/s
C_L	0.6032	0.6511	0.4094
Angle of attack, α	1.4°	1.9°	-0.39°
Lift at selected cruise speed and $\alpha = 0^\circ$	65.85N	102.08N	119.65N
Lift at selected cruise speed and $\alpha = 0^\circ$	97.38N	151.07N	176.74N

4.4.2 DRAG PREDICTION

Drag in an aircraft can be typically divided into two main components, induced drag ($C_{D,i}$) and parasitic drag ($C_{D,0}$). The addition of both components results in the total drag coefficient ($C_{D,T}$) as shown below:

$$C_{D,T} = C_{D,0} + C_{D,i} \quad (4.10)$$

Equation 4.10 allowed the team to estimate the drag performance of the aircraft for the different missions. A XFLR5 [2] study of the aircraft at the desired operating angle of attack (α) and flight velocity (V_∞) of each mission was performed to determine the respective minimum drag coefficient and lift coefficient. Then, the resulting coefficient of lift was used to calculate the induced drag through the following relation:

$$C_{D,i} = \frac{C_L^2}{\pi A R e} \quad (4.11)$$

Additionally, the coefficient of drag of the landing gear and jamming antenna were determined using SolidWorks Flow Simulation [11]. Both components of induced and parasitic drag were used to determine the overall aircraft C_D . The total drag of each of the discussed components was calculated using the drag equation:

$$D = \frac{1}{2} \rho C_{D,T} V_\infty^2 A_{cross} \quad (4.12)$$

To cover for the rest of the unaccounted drag that could have been missed or could not be measured, an 8% margin of the total drag value was added as a miscellaneous drag. The percentage increase is expected to make the data more accurate. The total expected drag coefficient and drag force for each mission are shown in the following table:

Table 11. Estimated Drag parameters for each mission

	Mission 1		Mission 2		Mission 3	
Cruise Speed	20 m/s		25 m/s		27 m/s	
Component	Pressure and Parasitic Drag					
Wing, fuselage, and tail	0.01335	2.287N	0.01335	3.574N	0.01335	4.169N
Landing gear	0.03	27.875	0.03	43.555	0.03	50.802
Antenna	-	-	-	-	1.1114	2.032N
	Miscellaneous Drag					
8% margin	0.001068	0.18296	0.001068	0.28592	0.001068	0.33352
	Induced Drag					
Wing	0.0257	0.014N	0.03	0.017N	0.0119	0.007N
	Predicted total Drag					
Total Estimate	0.070118		0.074418		1.167718	

4.5 STABILITY PREDICTION

Dynamic and static stability analysis of the aircraft was performed using XFLR5 [10]. The weight and approximate locations of all payloads, electronics and components were input into each mission model aircraft. The neutral point was calculated to be 6 inches behind the leading edge of the wing. The study identified the center of gravity and the static margin of each mission aircraft configuration with respect to the neutral point in percentage of MAC chord. The expected overall weight, center of gravity and static margin of the aircraft in the different mission configurations is the following:

Table 12. Stability and inertia properties of aircraft in XFLR5

Mission	Weight [lbs]	CG _x [in from LE]	Static Margin [%]
M1	9	4.201	13.13
M2	15	4.368	12.19
M3	9.32	4.220	13.48

The higher static margin of the M3 aircraft configuration is achieved by placing the jamming antenna ahead of the aircraft's CG. The higher static margin is expected to counteract the negative pitching moment that is generated by the antenna's drag.

4.5.1 STATIC STABILITY

An aircraft is statically stable if the coefficient of moment at zero angle of attack is larger than 0, and if the gradient of the coefficient of moment with respect to alpha is negative [RE 4]. Figures 18 and 19 show that the static stability requirements are met by the aircraft Hammerhead X-1. Additionally, plot in Fig. 18 shows that the operating points of the missions (where $C_M = 0$) ranges between 0.9° to 1.56° AOA. Furthermore, plot in Fig. 19 shows that a coefficient of lift of about 0.5 can be expected at the operating points.

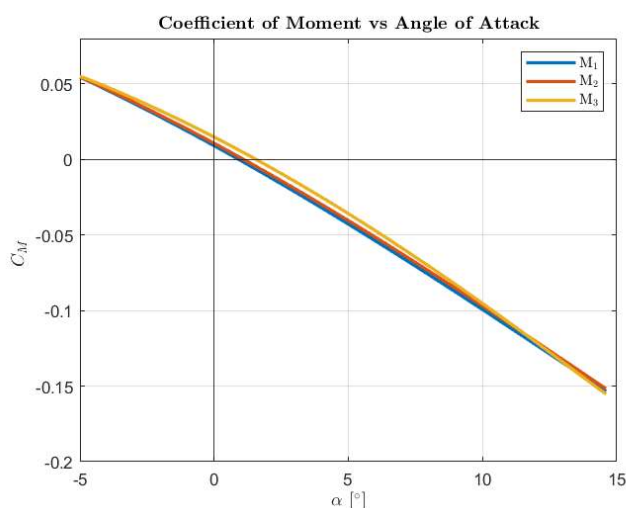


Figure 19. Coefficient of moment over angle of attack

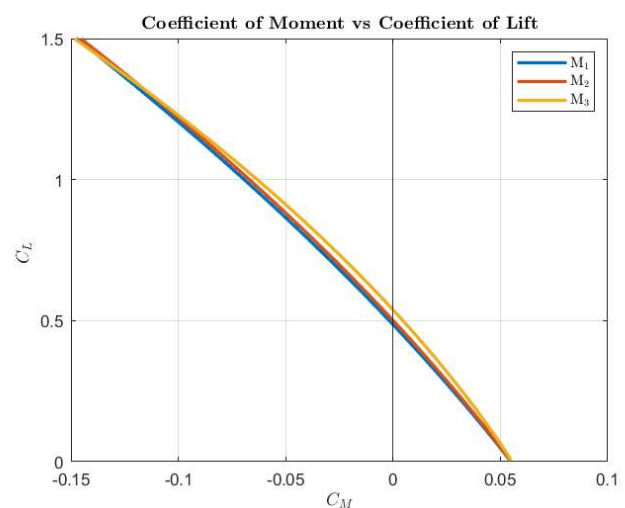


Figure 20. Coefficient of lift over coefficient of moment

4.5.2 DYNAMIC STABILITY

A dynamic stability analysis of the multiple mission aircraft configurations was conducted in XFRL5. The eigenvalues of all the longitudinal and lateral modes were calculated and recorded in Table 11. The negative eigenvalues indicate that the aircraft is dynamically stable in the short period, phugoid, roll and dutch roll modes. The settling time response of all the modes are shown in Figures 21-24. Only the spiral mode is expected to be unstable; however, the pilot will have a window of about 20 seconds to correct.

Table 13. Longitudinal and lateral stability eigenvalues

Mission	Longitudinal Stability		Lateral Stability		
	Short Period	Phugoid	Roll	Dutch Roll	Spiral
M1	$-6.5859 \pm 6.7291i$	$-0.0131 \pm 0.6715i$	-7.1349	$-0.5386 \pm 4.0233i$	0.1767
M2	$-6.6787 \pm 8.4726i$	$-0.0134 \pm 0.5788i$	-9.0448	$-0.6180 \pm 5.1222i$	0.1489
M3	$-6.6756 \pm 6.9815i$	$-0.0134 \pm 0.6580i$	-5.8439	$-0.4627 \pm 3.8339i$	0.1664

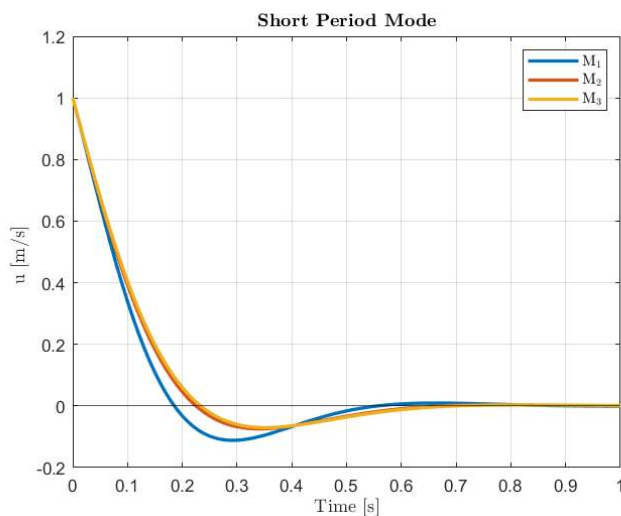


Figure 21. Time response of the short period mode

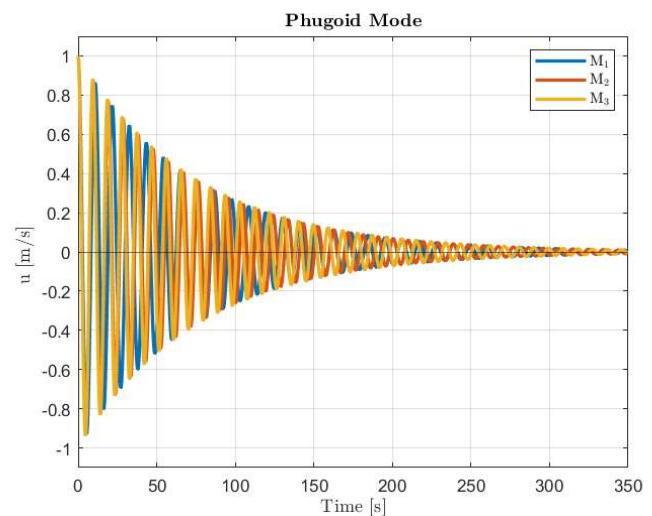


Figure 22. Time response of the phugoid mode

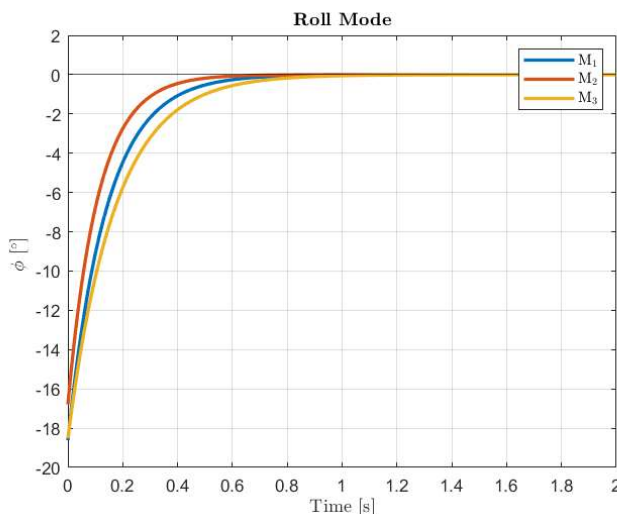


Figure 23. Time response of the roll mode

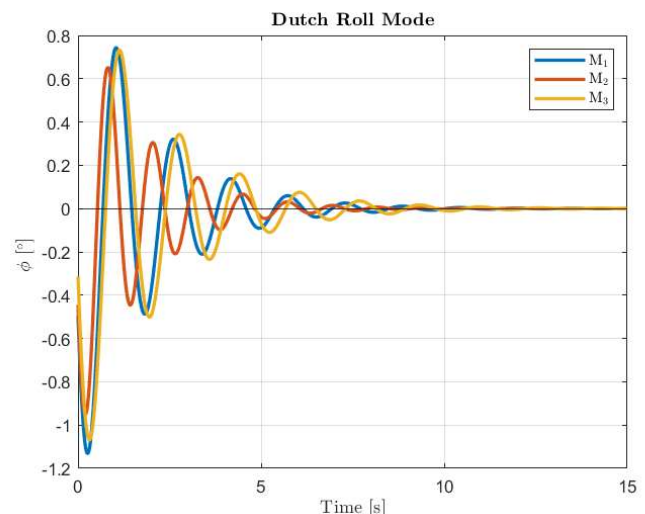


Figure 24. Time response of the dutch roll mode

4.6 AIRCRAFT MISSION PERFORMANCE

4.6.1 FLIGHT MISSION PERFORMANCE

Mission performance was estimated using the team's tried and true Excel calculator. Using the drag predictions from ANSYS, the speed achieved, and power required could be calculated for a given weight and aircraft geometry. The below table shows various parameters.

Table 14. Aircraft flight mission performance

	Mission 1	Mission 2	Mission 3
Payload weight	0	6.8 lb	0.1824 lb
Takeoff gross weight	9.00 lb	15.8 lb	9.1824 lb
Takeoff distance	19 ft	53 ft	20
Stall speed	18.9 mph	25 mph	19 mph
Average cruise speed	40 mph	56 mph	65 mph
Lap time	66 s	47 s	40 s
Mission duration	3.3 mins	10 mins	2 mins
Number of laps	3	12	3
Personal mission performance	1	12 laps x 6 lbs	30" x 120s
Maximum estimated mission performance	1	15 laps x 12 lbs	39" x 120s
Normalized personal mission score	1	1.4	2.77
Total personal flight mission score	5.17		

4.6.2 GROUND MISSION PERFORMANCE

Finite Element Analysis was performed to understand how our plane would act under a 100-pound test weight and to ensure that the plane would still function with a large force. Due to this analysis, we are comfortable aiming for 100 pounds for the ground mission. Since the analysis demonstrated the feasibility of a high ground mission scores, it became evident that the sensitivity analysis underestimated the maximum ground mission scores. As such, the ground mission maximum estimate has been updated.

Table 15. Ground mission aircraft performance

Ground mission	
Total test weight	100lb
Total aircraft weight	15lb
Performance factor	6.67
Estimated maximum performance factor	10
Ground Mission score:	0.667

5.0 DETAILED DESIGN

This was the last design phase before manufacturing the final competition aircraft. The design developed in this phase lead to major structural, functional, and stability improvements over the previous prototype. Additionally, sub-systems such as connection modules, antenna adapter and test fixture designs were finalized.

5.1 AIRCRAFT DIMENSIONS

The dimensional parameters of the final aircraft are the following:

Table 16. Final aircraft dimensional characteristics

Tail		Fuselage	
Total span	25"	Total length	28"
MAC	9"	Maximum width	14"
Area	225 in ²	Maximum height	5.25"
Deflection	± 30°		
Wing		Landing gear	
Area	900 in ²	Height	7.25"
Span	70"	Thickness	0.1875"
MAC	13.5"	Width	18.25"
Aspect ratio	5	Material	Carbon Fiber, Aluminum, Plastic
Sweep angle (LE)	0°		
Incidence angle	3°		
Tip Chord	10"		
Root chord	15"		

5.2 AIRCRAFT STRUCTURES

5.2.1 Fuselage

Per the decision matrix, the fuselage was designed as a blended form between the wings. This has the obvious advantage of reduced interference drag but also provides more benefits due to the width of the fuselage. A larger total wing area can be achieved by bringing the width up to 20% of the wingspan. This is because the maximum linear dimension of the wing panels is limited to the maximum dimension of the box: 28.5 inches. By spreading the wingspan among both the wing panels and the fuselage, more wing area can be fit in the box, and a heavier payload can be carried during Mission 2. The box dimensions determine the length of the fuselage. As such, the fuselage measures 28 inches in length, with 10 inches forward of the main wing, in the interest of balance about the desired CG.

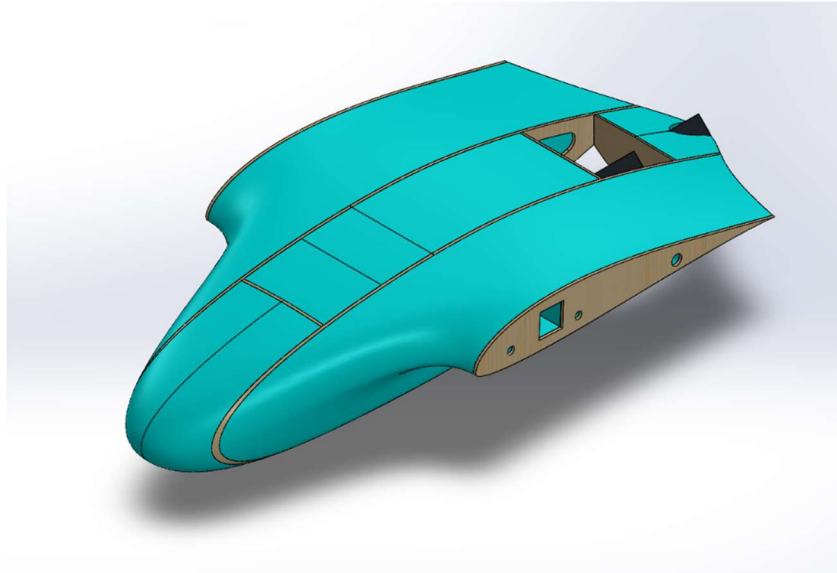


Figure 25. Detailed fuselage design

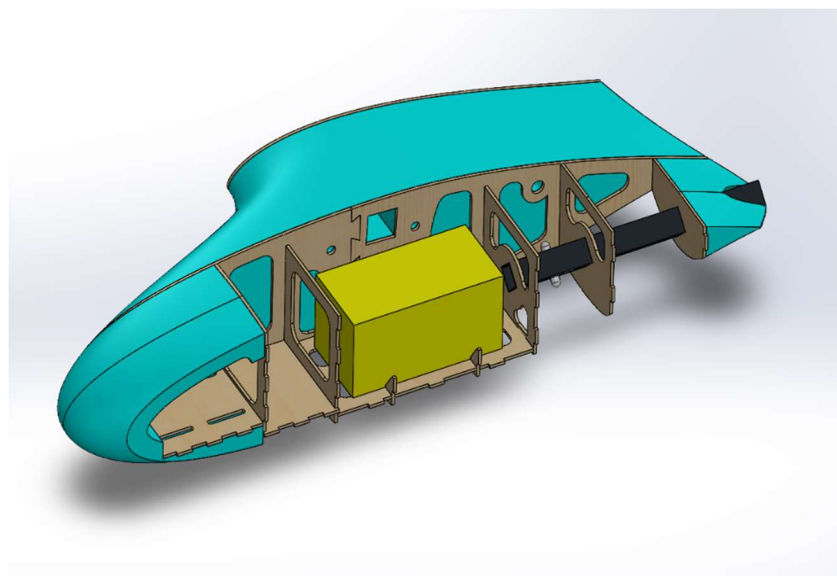


Figure 26. Fuselage inner structure

A 3 mm birch plywood skeleton creates hard points for the critical fuselage connections, such as the landing gear and tail boom. An aerodynamic foam block surrounds the skeleton, which provides a blended transition from the center profile to the root airfoil. The electronics package payload (shown in yellow) consists of a laser-cut birch plywood box filled with steel weights as desired. The payload is located at the CG, such that it causes minimal CG displacement when equipped. A 1" gap exists between the payload and the two adjacent bulkheads, allowing for CG adjustment during Mission 2. The gap can be filled with foam blocks of varying dimensions to prevent undesired translation of the payload.

5.2.2 Wings

To exceed the structural performance achieved in testing and maintain control-surface deflection, the developed wing design utilizes several integral features implemented to provide both increased elasticity and rigidity to the wing assemblies. The structure utilizes a single-layer composite skin of 12K T-700 spread tow triaxial weave reinforcement with a fiber orientation of -60/0/60 degree that is bonded to the sub-assembly. The final design of the sub-assembly consists mainly of XPS foam sections and an enhanced wooden sub-frame. The sub-frame is integrated into the Wing Attachment Sub-system by way of the ribs that are adhered to the internal CF tubes. The wing includes five stringers made of 5 mm unidirectional carbon fiber strips. Control surfaces and servo doors pivot on a composite KEVLAR live-hinge.

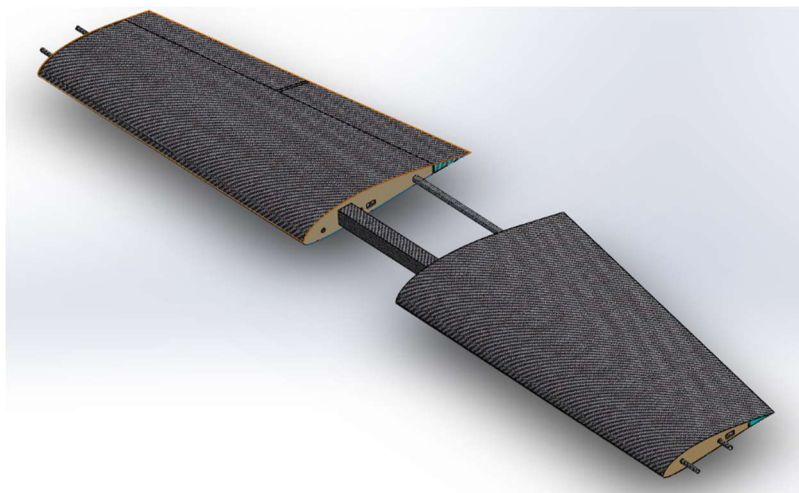


Figure 27. Detailed final wing design

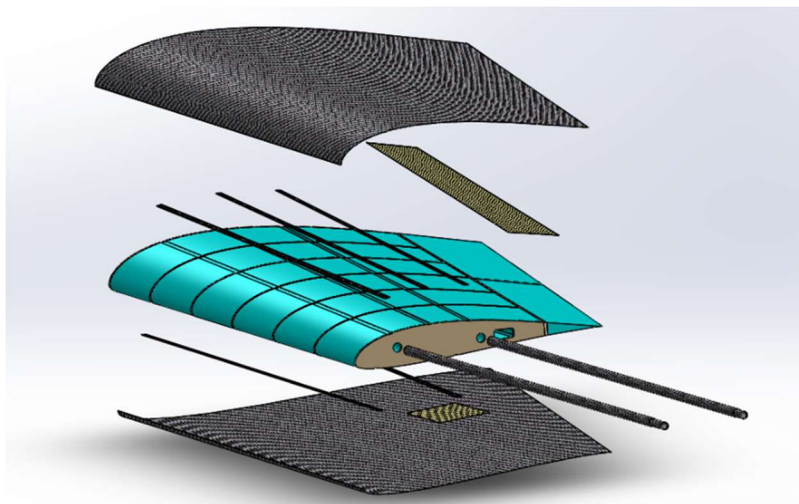


Figure 28. View of inner detailed wing structure

5.2.3 Empennage

The primary focus when designing the empennage is lightness. Therefore, the choice of material and amount of material used is carefully considered. The empennage is out of laser-cut balsa wood. The tail is permanently attached to the empennage and will be installed on the aircraft as a single assembly. The empennage features a slide-and-lock mechanism. It slides from the rear of the aircraft through the tail boom. Two detent pins embedded on the tail boom will be compressed during installation. Once the empennage slides into place, the detent pins will be released, preventing translational motion of the tail assembly. Rotation is prevented by leveraging the non-rotational property of a square boom.

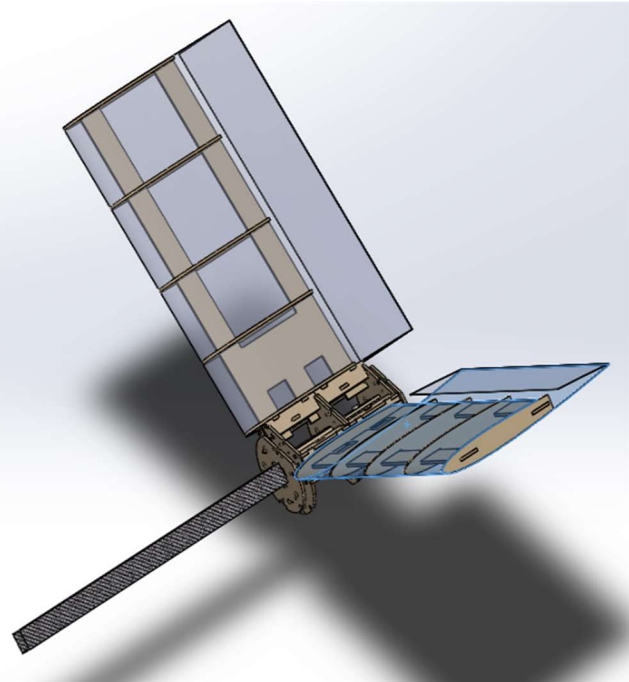


Figure 29. Image of Tail Assembly

5.2.4 Landing Gear

Finite Element Analysis was run on the landing gear to analyze how the sub-system would react under a large force. The force was equivalent to 100 pounds and was applied to the top of the rail to mimic the forces from the fuselage, wings, and other components. The Von Mises plot below shows the high-stress points at the Cam Clamps and the wheels. Since the wheels are made of flexible polyurethane foam tires, the forces can be transferred into the tires, lowering the maximum stress points at the wheels. Our factor of safety equated to 1.39, resulting in a safe design.

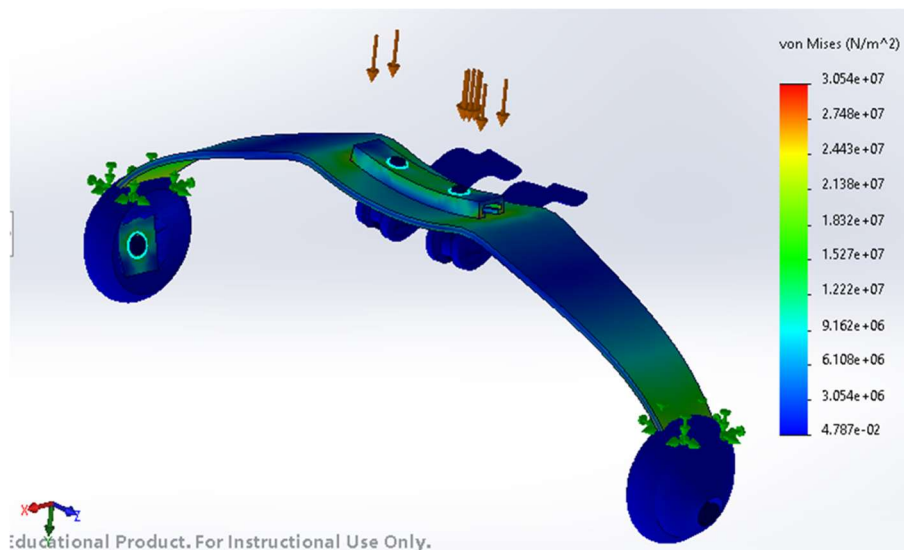


Figure 30. FEA Von Mises Stress plot of final landing gear design

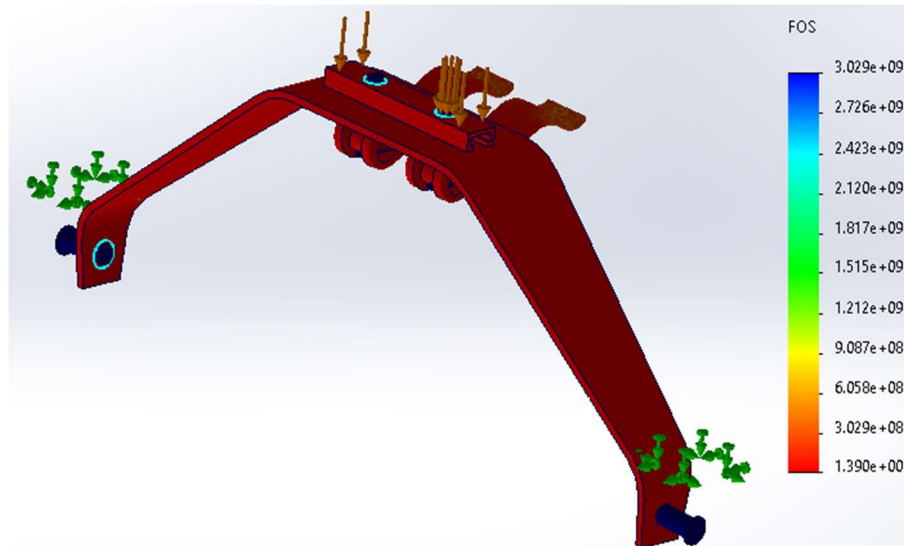


Figure 30. FEA factor of safety (FOS) plot of final landing gear design

5.2.5 Nacelles

The nacelles are made from a 1 in carbon fiber tube that is a 2x2 twill weave biaxial. A laser printed wood engine mount is attached on the front of the nacelle for the propeller, is Kevlar reinforced, and attached to the tube with an 8-32 screw. The engine nacelle tail cone is made from lightweight PLA. The wingtip to tube mount, the antenna clamp assembly, and counterweight adapter assembly are 3D printed with carbon fiber reinforced nylon. The entire mount is held in place via thru holes that are pierced by the threaded carbon fiber tubes that run through both wings and the fuselage. When the threaded carbon fiber tubes are tightened with the cam clamps as shown in Figure 31, it puts the entire system in compression from wingtip to wingtip.

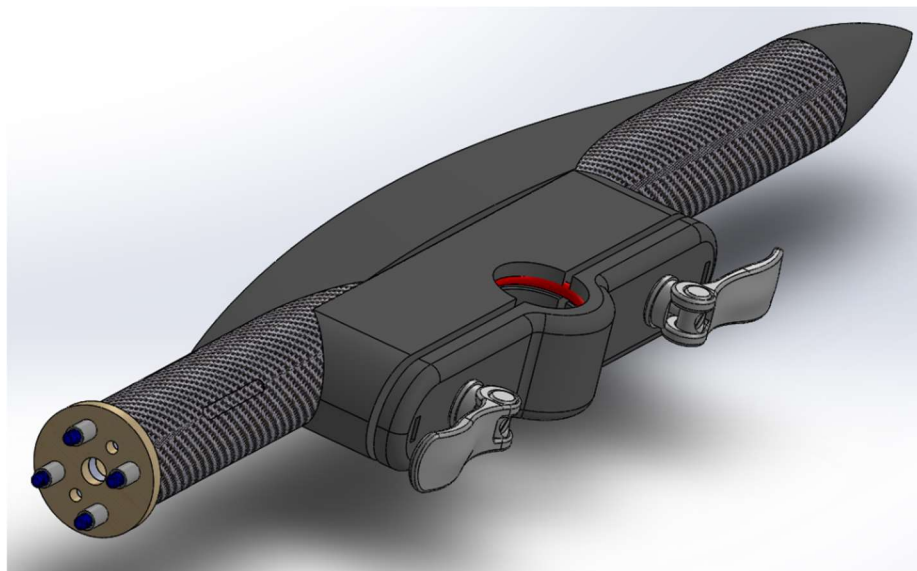


Figure 31. Motor Nacelle design

5.3 DETAILED SUBSYSTEM DESIGN, ARCHITECTURE, AND INTEGRATION

5.3.1 Detailed Packaging Container System

The dimensions of the shipping container were primarily driven by the goal of maximizing wing area. To optimize the volume within the competition limits, main assemblies were considered for fitment. The package container's primary dimension of a 19.5-inch width is driven by the nested wing chords. The height of the nested chords in addition to the height of the remaining components results in the secondary dimension of a 13.5-inch height. The final dimension of total box length is determined by the remaining allowance drives the individual wingspan of 29.0-inches.

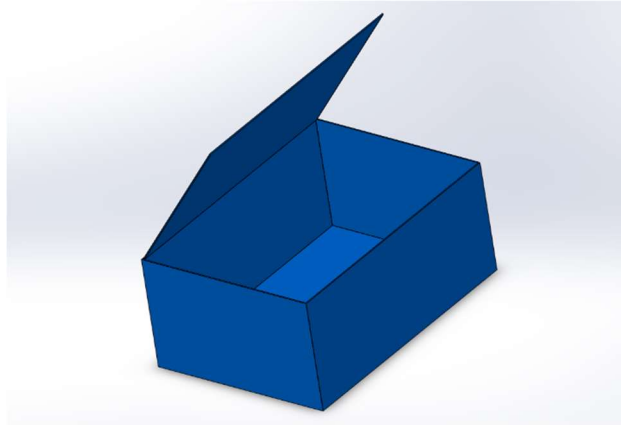


Figure 32. Final container design

5.3.2 Structural Attachment System

To meet the container size and assembly time requirements, a modular structural system was chosen with quick-connect attachment sub-systems designed for the performance needs at each inter-assembly joint.

5.3.2.1 Detailed Main Landing Gear Attachment Sub-System

The main landing gear attachment consists of an integrated aluminum rail and clamp system. Using a pair of manually operated cam lever clamps situated in the mounting plate of the landing gear, the T-bolt of each clamp is inserted into the fuselage-mounted rail until the gear is centered under the aircraft and fixed by clamping down.

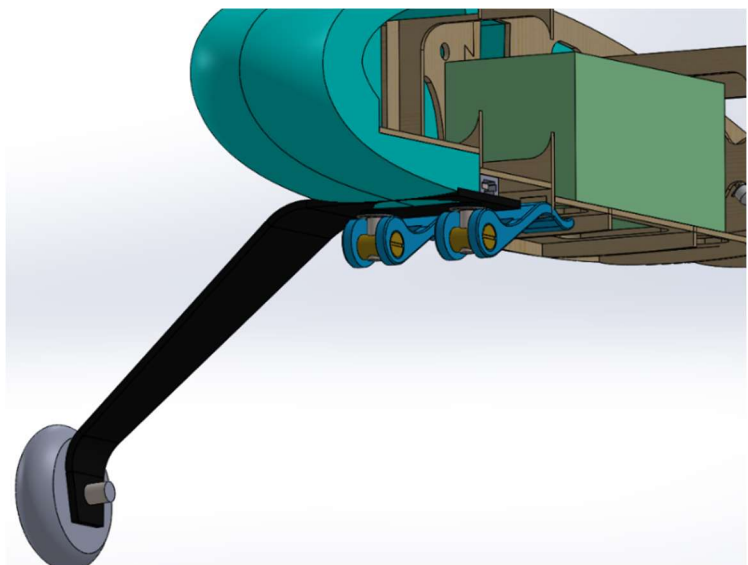


Figure 33. Landing gear attachment sub-system

5.3.2.2 Detailed Tail Boom Attachment Sub-System

Attachment of the fuselage assembly and empennage assembly to the 22mm CF tail boom is accomplished by a spring-locking tube pin system. The tail boom interfaces a wooden four-walled structure made of 3mm birch plywood integrated into each assembly. To fix the linear motion, the square boom is fabricated to be fitted with 8mm spring-locking pins which extend into the walled interfaces at fabricated mounting holes when the boom is inserted.

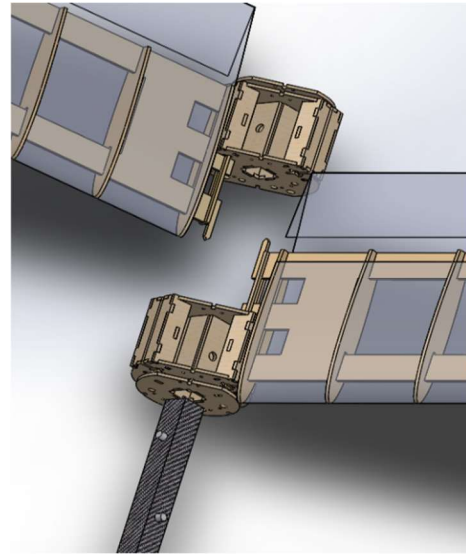


Figure 34. Tail Boom Attachment sub-system

5.3.2.3 Detailed Wingspan Attachment Sub-System

An integrated clamping system was employed for the assemblies spanning the planform, including structural elements within the wing and fuselage assemblies. The main assemblies each incorporate a set of annular-nested unidirectional CF shaft sections that interface at the joints with internally mounted M3 threaded fastener studs. The Wingspan Attachment Sub-system, integrated with the embedded Antenna Sub-system, is clamped at one end by a set of washers and threaded fasteners and at the opposing end by a pair of cam handle clamps.

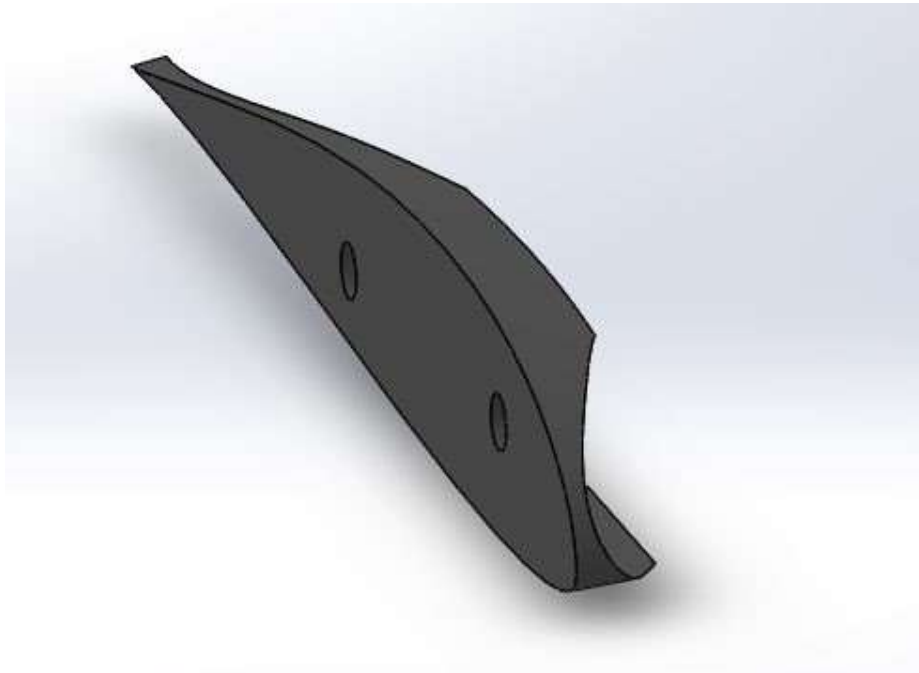


Figure 35. Wingspan attachment sub-system

5.3.2.4 Detailed Antenna Sub-System

The antenna adapter/counterweight sub-system is integrated into the unidirectional CF 7.4mm shaft connectors that are used for the wingspan attachment sub-system. This allows for the pipe used as our antenna to be inserted into the cylindrical section and tightened in place when the shaft sections are tightened down. This antenna mount is made of Carbon Fiber Nylon.

A counterweight will be attached to the wingtip opposite the jamming antenna mounted in mission 3. The addition of the counterweight will make the weight distribution symmetric about the aircraft's longitudinal axis. It will also counteract the yaw instability created by the antenna's drag.

A plate made of aluminum will be used as the counterweight. The height of the plate is limited by the wingtip chord maximum height, and the thickness of the plate is constrained by the thickness of antenna adapter. However, the length may be varied up to 20 in (twice the wingtip chord). The rectangular design allows the team to vary the total volume of the plate in order to match the antenna's weight. Given that aluminum has a density of 2.7g/cm³, a relationship between antenna length and plate length was determined. The dimensions of the 3 counterweights based on antenna length are the following:

Table 17. Plate dimensions in relation to antenna length (all units in inches)

Plate and Antenna Dimensions			
L_{antenna}	12	24	30
L_{plate}	6.561	13.122	16.402
h_{plate}	1		
t_{plate}	0.25		

The final design is capable of mating with the wingtip of the aircraft in the same way as the antenna adapter. Both components are shown in the following images:

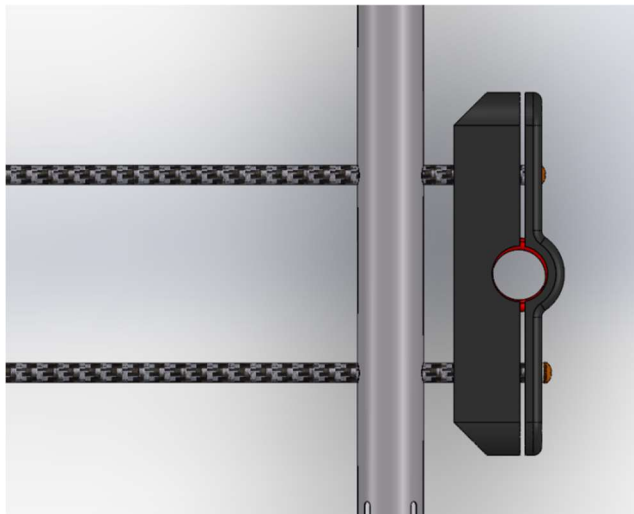


Figure 36. Detailed antenna adapter design

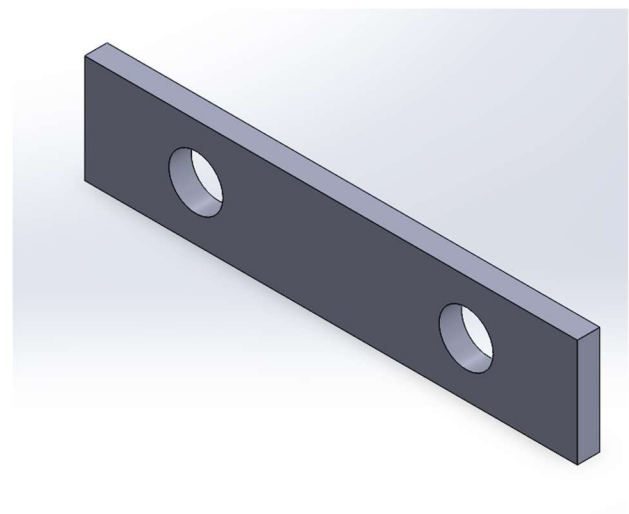


Figure 37. Detailed counter-weight design

5.3.2.6 Propulsion System

The final propulsion system configuration is a dual wingtip mounted propeller system consisting of two counter-rotating APC 8x8 propellers attached to two T-Motor Cine 66-925kv motors. The motors are mounted on the left and right-side leading-edge wing tip mounts. The motors are each controlled by Hobbywing Skywalker 60A ESCs. The five servos, as described in section 4.2.4.3, along with the ESC's are connected to an AR8360T DSMX 8-channel receiver with built-in gyro stabilization. The receiver and servos are powered by an E-flite 1300mah 2s LiPo pack, and the motors are powered by a 6s 4500mAh LiPo pack. A 100A fuse acts as an arming plug and is placed on the positive terminal of the propulsion battery pack to protect the circuit from overloading. The ESCs are placed in the nose to help the aircraft balance on an acceptable CG. Additionally, voltage losses are much smaller along the 3-phase side, so keeping the single-phase wires as short as possible makes sense, which conveniently puts the ESCs near the battery. The figure below shows the schematic and configuration of the propulsion system.

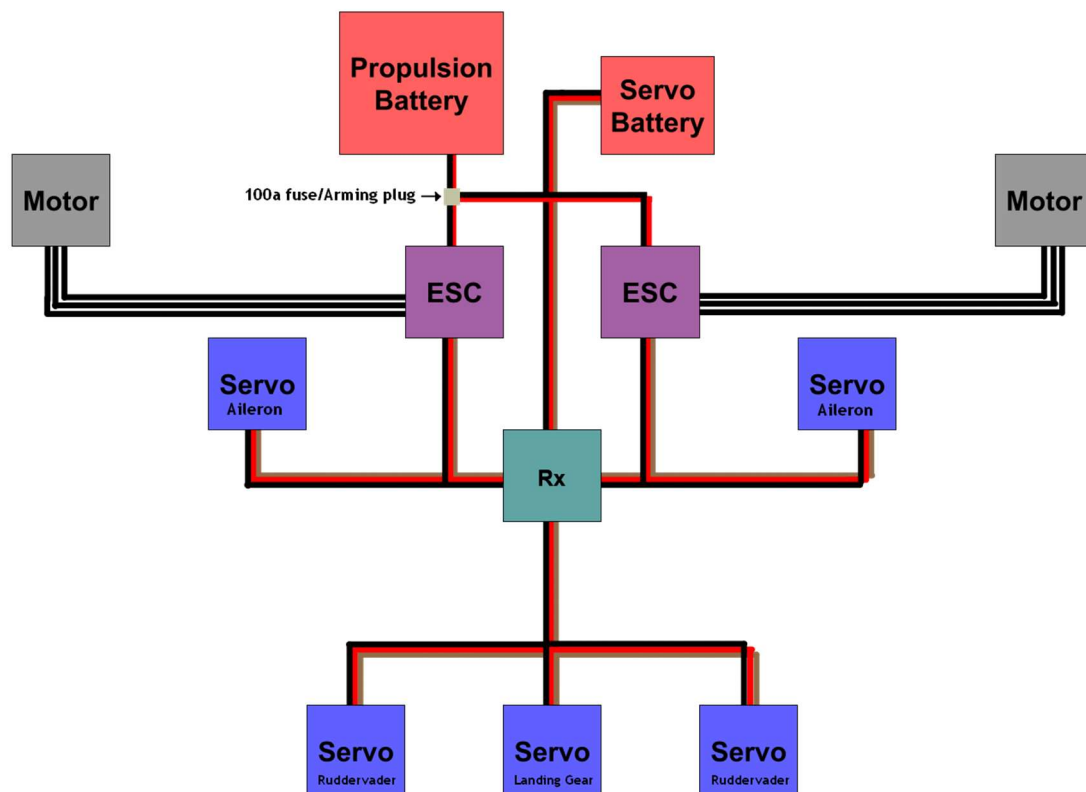


Figure 38. Propulsion system schematic

5.3.3 Ground Test Fixture

The ground test fixture consists of two symmetrical wooden support stands. Each test stand is based around two 2x4 in (nominal size) wood planks that are the vertical components. Two plywood cuts acting as base supports that prevent the vertical component from leaning are fastened to a bottom wood foundation and the vertical planks. Near the top of each stand are two 8 mm through holes for the arrow shaft spars holding the plane for the GM. Additionally, because of the ambiguity of the test surface interface term defined in the rules, two potential ledges can be adopted: the 1-inch-long ledge supports the weight at the nacelle, and the 3.5-inch-long ledge extends past the wingtip. The ledges have a 2-in tall layer of XPS foam.

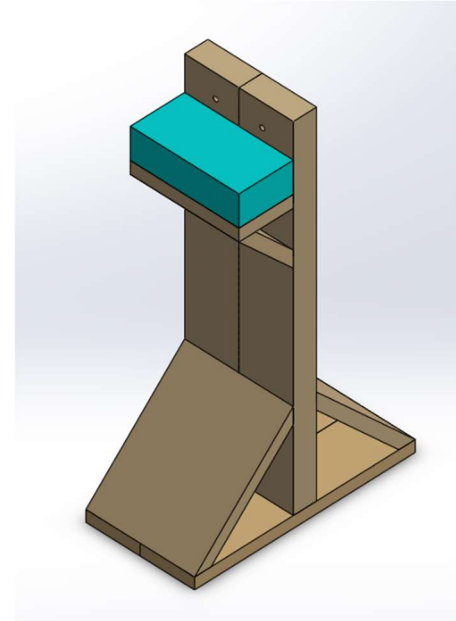


Figure 39. Ground test fixture

5.4 Weight and Balance

A scale was used to determine the weight of propulsion, avionics, and mission components such as motors, ESCs, batteries, and servos. SolidWorks [11] was used to estimate the weight and CG locations of parts not yet built, i.e., final fuselage, wing, landing gear, antenna adapter, and others. The placement of each item in the aircraft was done in XFLR5. The location of the items was iterated multiple times to get the overall CG location of the aircraft to the desired static margin percentage position shown in Table [X]. Figure 40 show the component placement of the aircraft in mission 1:

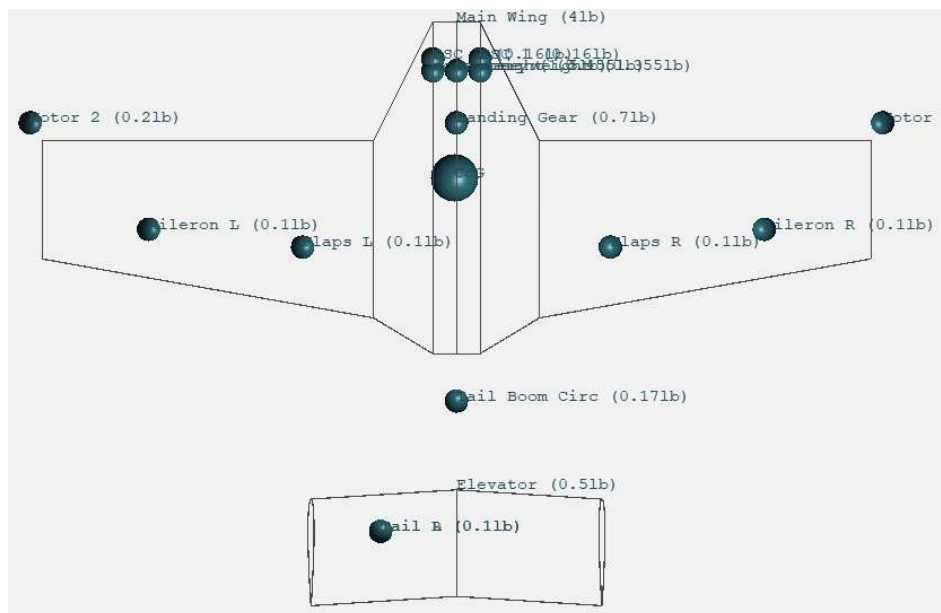


Figure 40. CG location of all components in aircraft in XFLR5

Each component's weight and CG values are described in the table below. All CG locations are relative to the leading edge of the wing:

Table 18 . Stability and inertia properties of aircraft in XFLR5

Component	Weight [lbs]	CG _x [in from LE]
Mission 1		
Fuselage	1.5	-3.9
Wings	2	-5.3
Major wing spar	0.66	-3.75
Minor wing spar	0.15	-10
Tail	0.5	-34
Tail boom	0.18	-22
Landing gear	0.75	1.5
Propellers	0.084	0.75
Motors	0.4	0.5
Nacelles	0.31	-4.5
ESCs	0.32	6.9
Propulsion battery	1.5	5.9
Avionics Battery	0.12	5.9
Receiver	0.0625	
Aileron Servos	0.2	-7.5
Flap Servos	0.2	-9
Tail Servos	0.2	-33
Mission 2		
Electronic Package	6.4	-4.55
Mission 3		
Jamming Antenna	0.16	-3
Counterweight	0.16	-3

The total aircraft weight, CG location, and the percent static margin in terms of MAC chord with respect to the neutral point for each mission are the following:

Table 19. Weight and balance properties of aircraft

Mission	Weight [lbs]	CG _x [in]	Static Margin [%]
M1	9.14	4.201	13.13
M2	15	4.368	12.19
M3	9.46	4.220	13.48

5.5 AIRCRAFT FLIGHT PERFORMANCE

With our preliminary performance estimation already done, we can compare it with the final performance estimation with the same representative parameters. The table below details the estimated final flight performance of Hammerhead X-1 in all of its missions. Obtained results were validated by flight tests:

Table 20. Weight and balance properties of aircraft

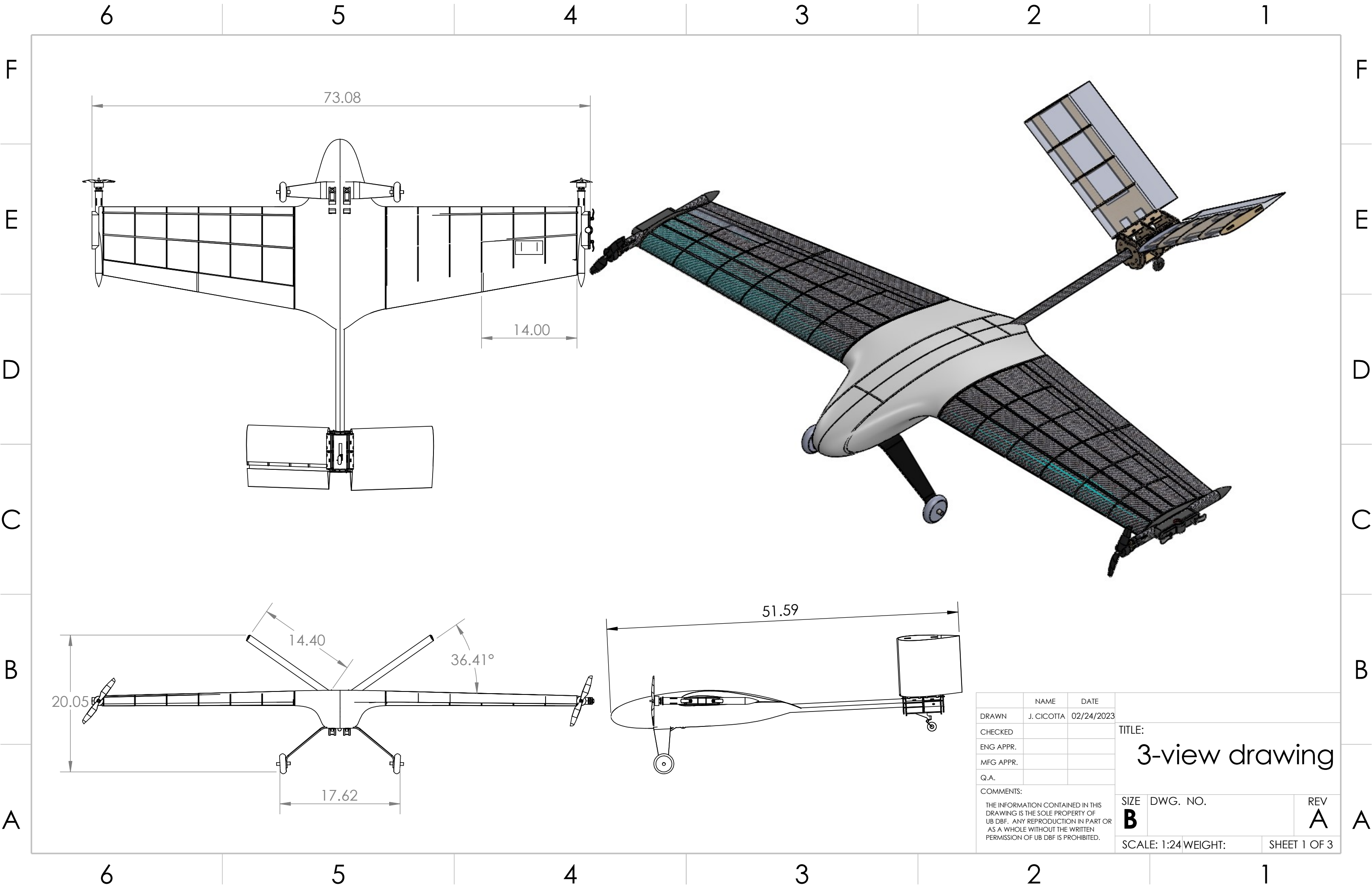
	Mission 1	Mission 2	Mission 3
Payload weight	0	6.8 lb	0.1824 lb
Takeoff gross weight	9.00 lb	15.8 lb	9.1824 lb
Takeoff Distance	19 ft	53 ft	20
Stall Speed	18.9 mph	25 mph	19 mph
Average Cruise Speed	40 mph	56 mph	65 mph
Lap time	66 s	47 s	40 s
Mission duration	3.3 mins	10 mins	2 mins
Number of laps	3	12	3
Personal mission performance	1	12 laps x 6 lbs	30" x 120s
Maximum estimated mission performance	1	15 laps x 12 lbs	39" x 120s
Normalized personal mission score	1	1.4	2.77
Total personal flight mission score	5.17		

5.6 AIRCRAFT MISSION PERFORMANCE

Hammerhead X-1's final performance is calculated and estimated based on the final configurations for the aircraft along with the derived final flight performance. The following table presents the mission performance of the final design. Throughout the iterative design process, we found that it was possible to increase the estimated total personal mission score by a total of 0.322 points.

Table 21. Ground mission aircraft performance

	Assembly Task	Hammerhead X-1	Best Assumed Time	
GM	Unloading for Box	13s	10s	
	Wing Attachment	180s	150s	
	Tail to Boom Attachment	13s	15s	
	Assemble Tail Boom to Fuselage	7s	5s	
	Landing Gear Attachment	23s	15s	
	Total Time	236s	185s	UB DBF GM Score
	$W_{test}/W_{aircraft}$	6.78	10	0.678



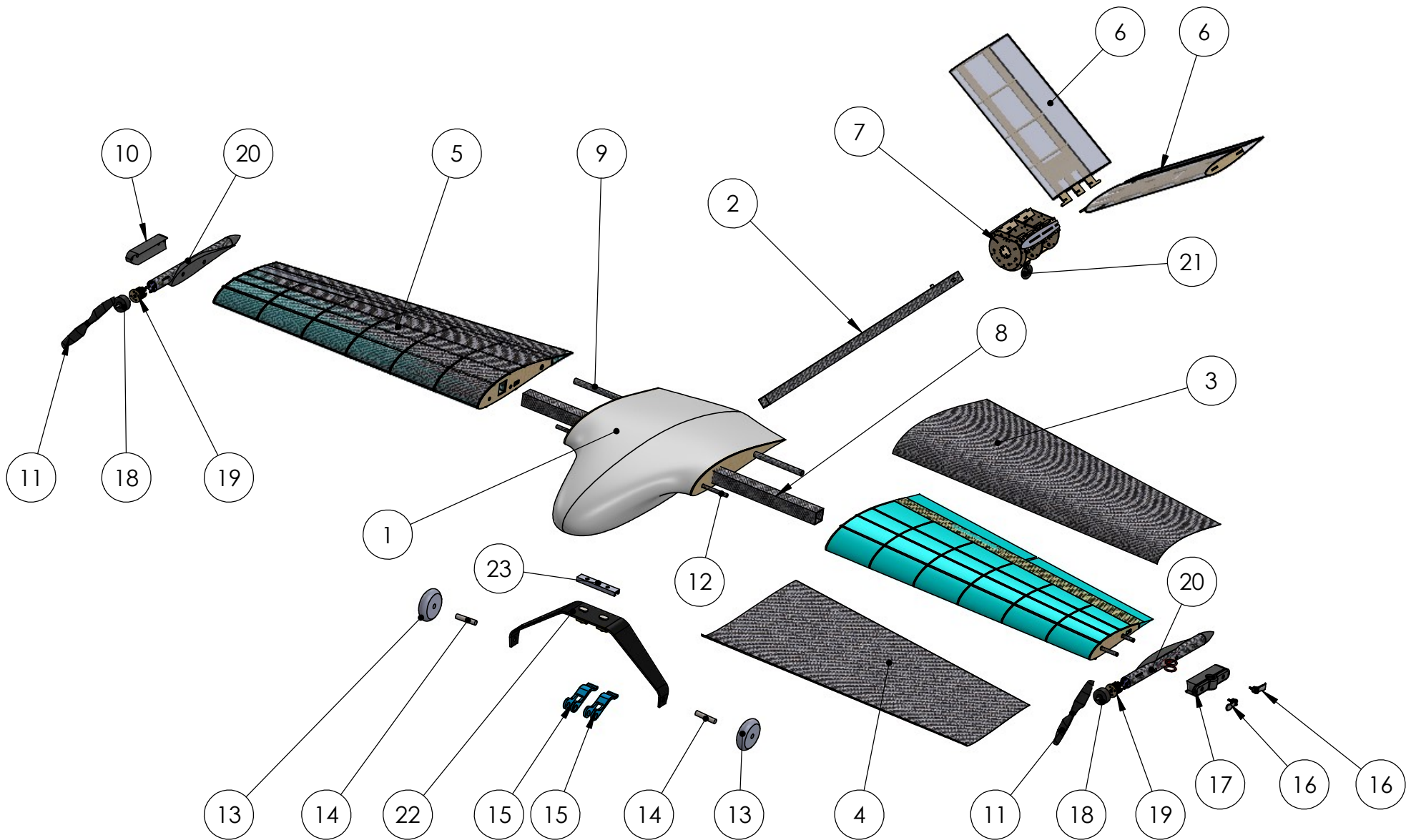
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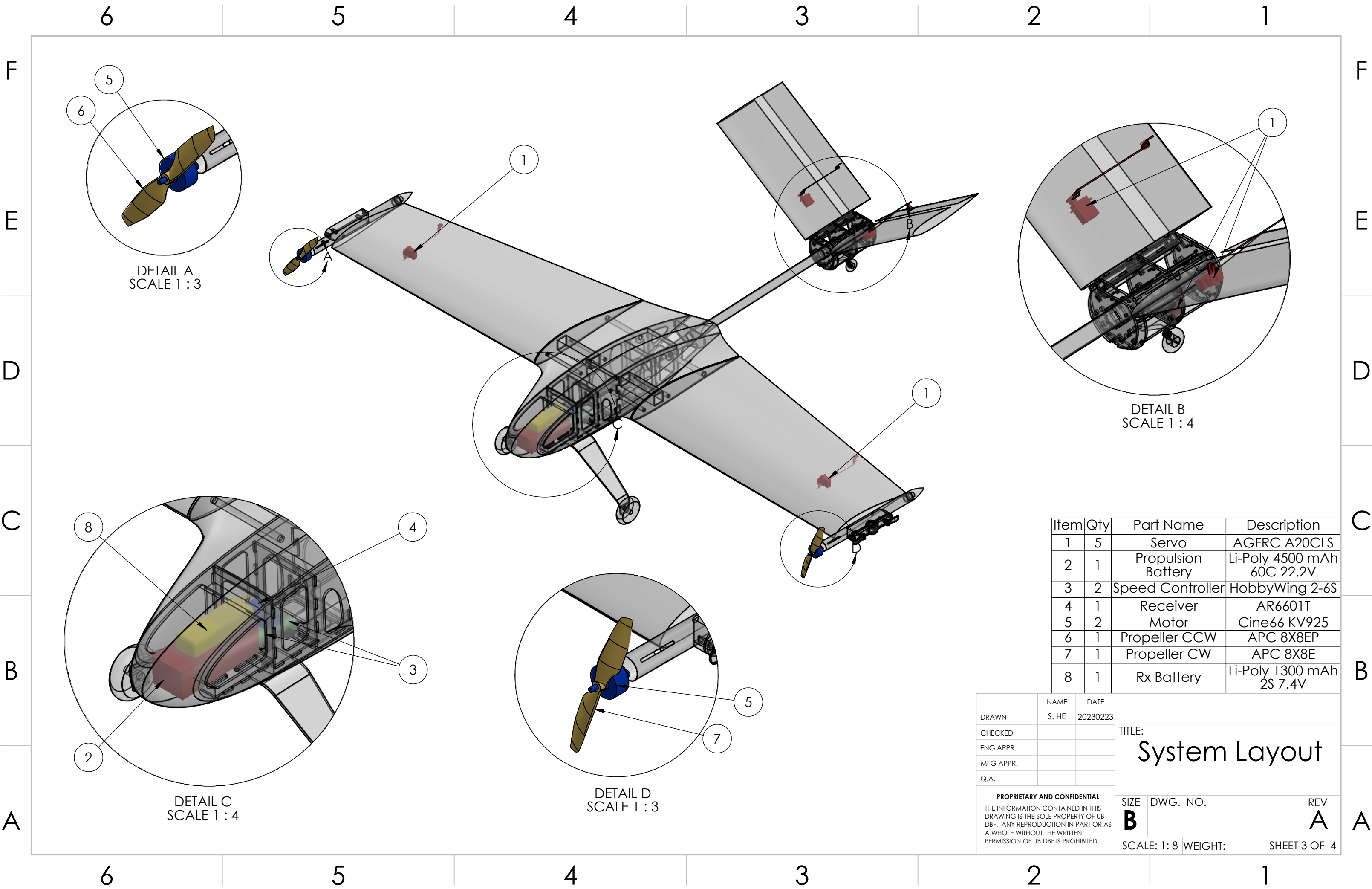
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Part No.	Quantity	Part Name
1	1	Fuselage
2	1	Tail Boom
3	1	Left Wing Upper Skin
4	1	Left Wing Lower Skin
5	1	Right wing Assembly
6	2	Tail Sufaces
7	1	Tail Hub
8	1	Main Wing Spar
9	1	Seondary Wing Spar
10	1	Counter-Weight Adapter
11	2	Propeller
12	1	Front Attachment Spar
13	2	Wheels
14	2	Axle
15	2	Cam Clamp
16	2	Cam Clamp
17	1	Antenna Adapter
18	2	Motor
19	2	Motor Mount
20	2	Nacelle
21	1	Tail Wheel
22	1	Landing Gear
23	1	Landing Gear Rail



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		TOLERANCES:	CHECKED					
		FRACTIONAL ±	ENG APPR.					
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		THREE PLACE DECIMAL ±	COMMENTS:				SCALE: 1:12 WEIGHT: SHEET 1 OF 1	
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		MATERIAL						
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APPLICATION		DO NOT SCALE DRAWING						



Item	Qty	Part Name	Description
1	5	Servo	AGFRC A20CLS
2	1	Propulsion Battery	Li-Poly 4500 mAh 60C 22.2V
3	2	Speed Controller	HobbyWing 2-6S
4	1	Receiver	AR6601T
5	2	Motor	Cine66 KV925
6	1	Propeller CCW	APC 8X8EP
7	1	Propeller CW	APC 8X8E
8	1	Rx Battery	Li-Poly 1300 mAh 2S 7.4V

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Q.A.			SIZE B DWG. NO. REV A		
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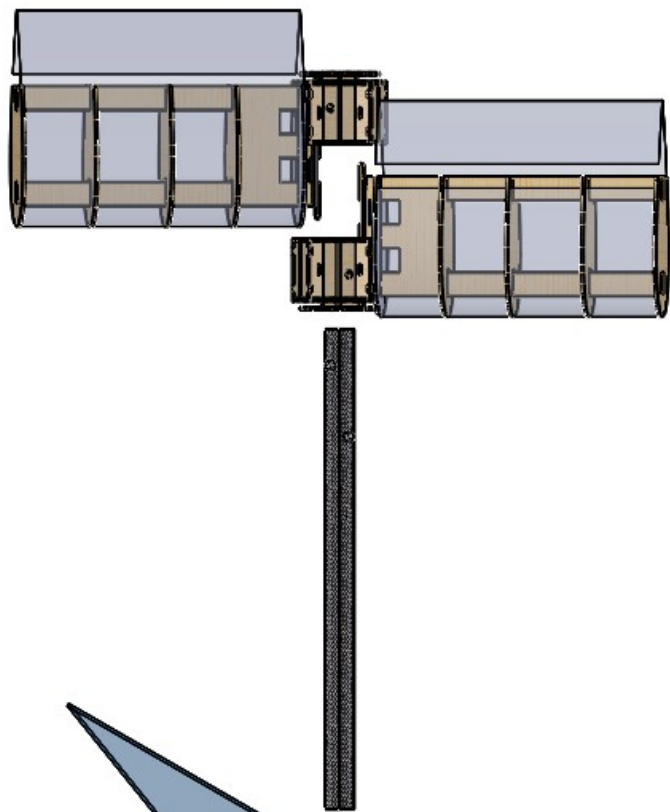
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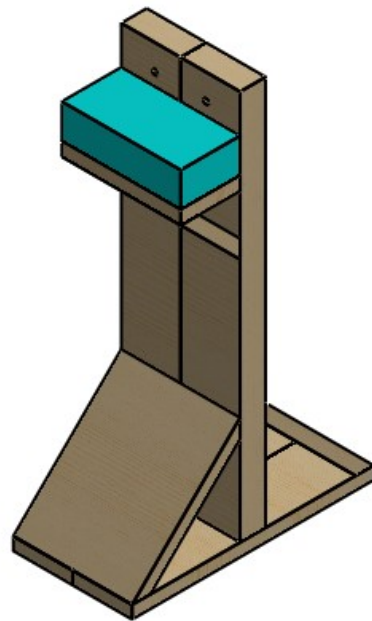
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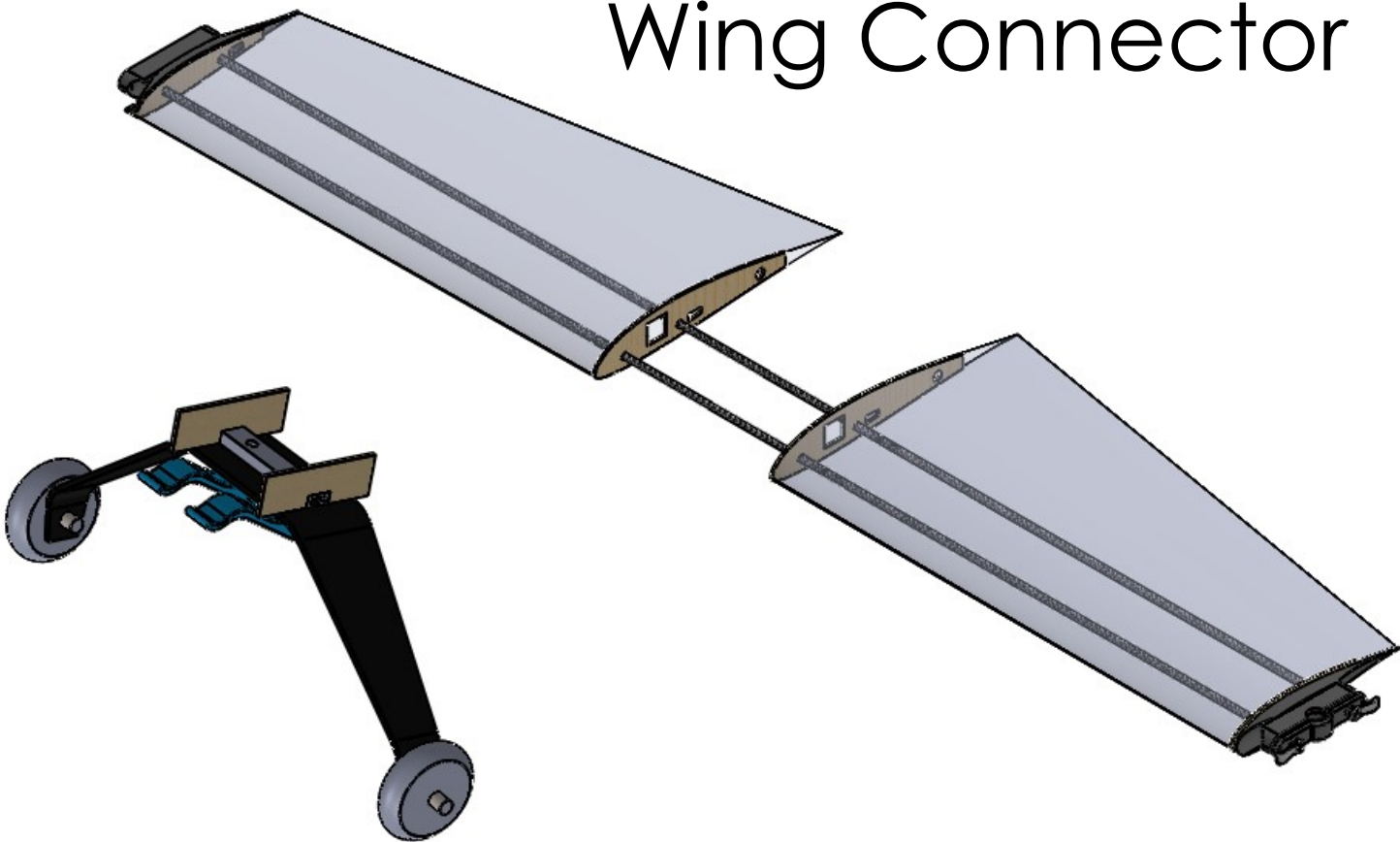
Tail Connection



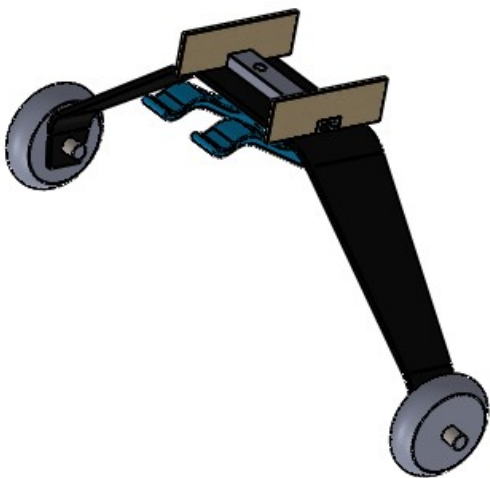
Test Fixture



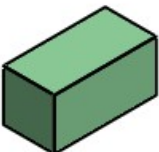
Wing Connector



Landing Gear



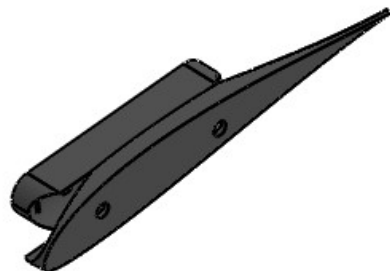
Payload



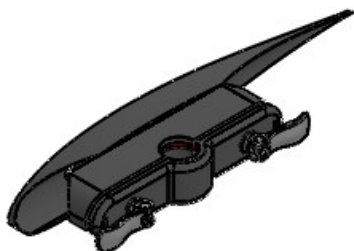
Antenna



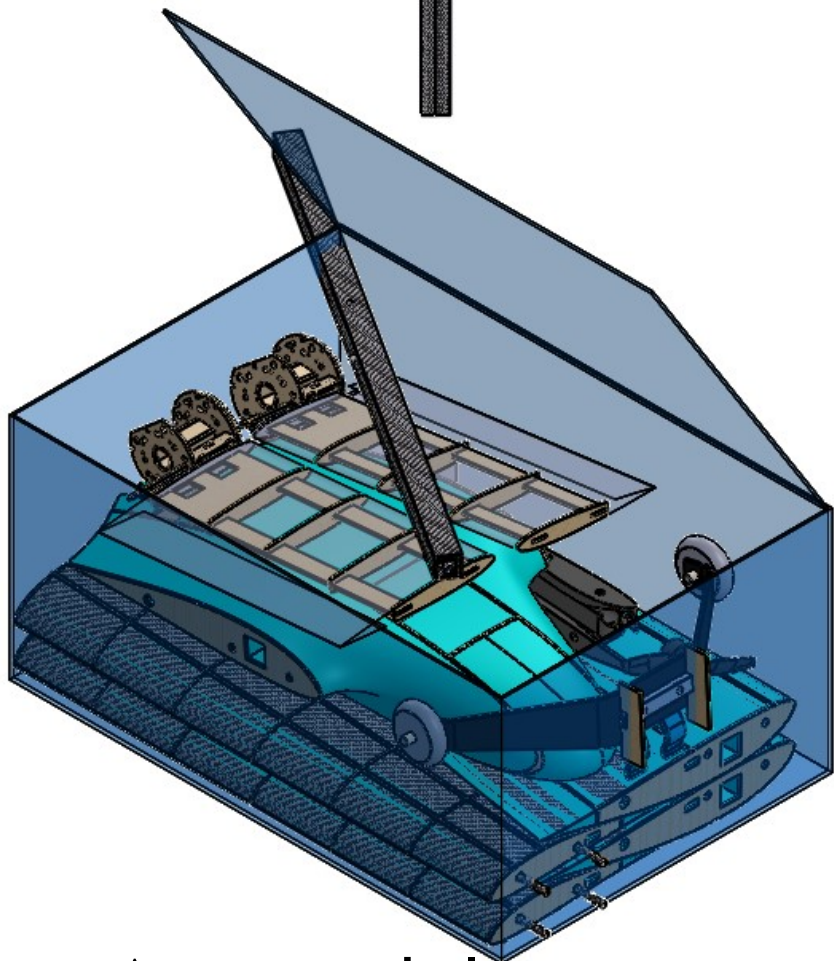
Counter Weight



Antenna Mount



Box Assembly



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CHECKED					
ENG APPR.					
MFG APPR.					
Q.A.			REV		
COMMENTS:					
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6.0 MANUFACTURING PLAN

Various manufacturing processes being developed were evaluated to produce major aircraft assemblies, as necessitated by objectives and project developments. The main section assemblies include the fuselage, wings, empennage, nacelles, and landing gear.

6.1 Manufacturing Milestone Chart

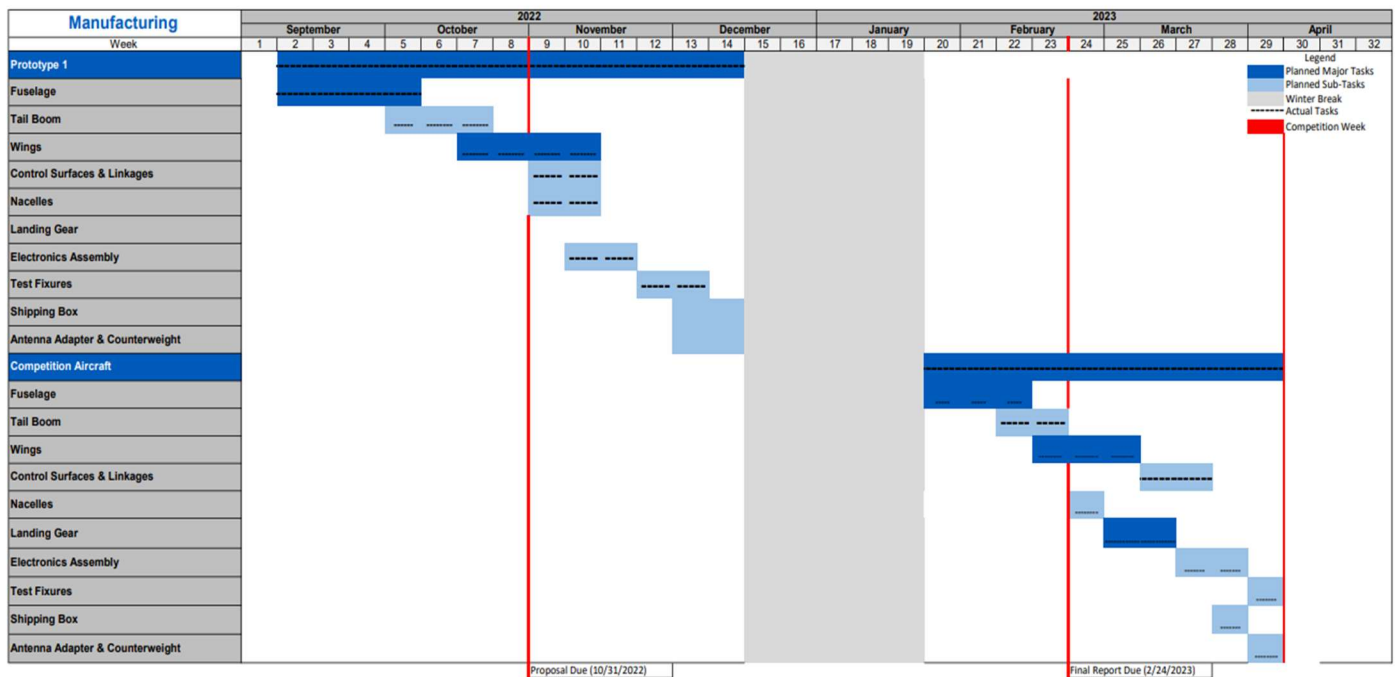


Figure 41. UB Manufacturing Gantt Chart

6.2 Investigated Manufacturing Processes

6.2.1 3-D Printing

3-D printing offers the capability for rapid and inexpensive prototyping of unique geometries of parts and tooling. Material filaments used include PLA, PETG, CF-Nylon, and TPU. Components produced via additive manufacturing must consider the adhesion and orientation of layer lines regarding the directionality of expected loads exerted on the part, particularly out-of-plane forces.

6.2.2 Balsa/Plywood

Balsa and plywood built-up production offers the capability for lightweight components with increased strength were applied at a considerably low cost. Laser CAD is the primary means of cutting wood, yielding parts with greater accuracy and precision than cutting manually. Wood assemblies are adhered to at the joints by wood glue or cyanoacrylate glue. The structure is then wrapped in a heat-shrinking film backed by a heat-activated adhesive. Built-up wood construction is low-cost and offers high strength-to-weight; however, durability and assembly time must be considered.

6.2.3 CNC Hot-wire

CNC hot-wire cutting allows to produce lightweight forms with low costs and high repeatability. A 4-D CNC sweeps a nichrome hot-wire through expanded polystyrene (XPS) foam stock, carving out forms made of single-curved surfaces. This process requires consideration of CAM operations, part geometry, and surface finish.

6.2.4 CNC Routing

CNC routing offers the capability to produce complex components and tooling with accuracy and a high degree of repeatability. Production of parts via this process allows for both 2-D and 3-D operations. Materials used in this process primarily include composite panels and XPS foam; metals such as aluminum can also be milled. Considerations regarding CAM operations, part geometry, and surface finish must be considered.

6.2.5 Composites Vacuum Bagging

Vacuum bagging composites offer the capability for high strength-to-weight and relatively durable fiber-reinforced polymer (FRP) composites. Fiber reinforcement available includes fiberglass, KEVLAR, and carbon fiber. The polymer matrix used in composite layups is PRO-SET LAM-145 Thixotropic Laminating Resin. The process requires expendables, including layers of peel/ply, breather/bleeder, and bagging. High material costs and moderately developed experience levels are the primary considerations relevant to this manufacturing process.

6.2.6 Foam Core Composites

Foam core composite manufacturing can produce high-load structures at a relatively low weight, with high durability FRP composite forms. Foam cores are produced via CNC router or CNC hotwire cutting operations. Then a Fiber reinforcement is adhered to the core and encapsulated in the polymer matrix through a vacuum bagging operation. Unique integrated structures are available such as active KEVLAR hinges. High material costs and moderate experience levels are the main considerations relevant to this manufacturing process.

6.2.7 Composite Molding

Composite molding manufacturing offers the capability to produce high-load structures at a relatively very low weight. Foam molds are produced via a CNC router or CNC hotwire cutting operation. A vacuum bagging process is required. Molded composite skins and beam structures allow for high-performance hollow construction methods. High material costs and developing experience levels are the main considerations regarding this manufacturing process.

6.3 Manufacturing Processes Selected

6.3.1 Wings

The wings are manufactured employing foam core composites with a variety of added reinforcements. Foam wing sections are cut by hotwire CNC and then glued together with laser-cut wood wing ribs. Wingtip and wing-root rib interface modules are attached before the grooves for stringers are cut into the foam. Unidirectional carbon fiber strips are inserted into the slots and grooves of the ribs and foam, respectively. The wing structure is covered in a base layer before applying KEVLAR hinge sections, then wrapped in a single layer of 3K 0°- 60° weave carbon fiber via a vacuum bagging operation.

6.3.2 Fuselage

The fuselage is a glass fiber-reinforced polymer (GFRP) unibody manufactured primarily utilizing foam core composites along with a wood sub-frame. Forms are cut from XPS foam stock by a CNC router operation and glued together using gorilla glue with 3mm birch plywood sub-frame components cut using a Laser CNC operation. The 3-d printed CF-nylon interface modules for the tail boom and wings are attached using LOCTITE 5-minute epoxy. The completed sub-frame is then prepared for a vacuum bagging operation. A base layer of epoxy resin is applied to the surface and allowed to reach the B-stage, where it begins to get tacky. The hatch reinforcement and KEVLAR hinge are pressed onto the base layer before a single layer of fiberglass type is applied and wetted, followed by vacuum bagging. After curing, trimming, and cutting the hatch, the surface is sanded before applying a spray-on UV protective coating.

6.3.3 Empennage

The empennage is fabricated using a built-up construction of 3-mm birch plywood cut using a Laser CNC operation. The stabilizer structure consists of laser-cut wood ribs that are interlocked and glued into a plate. Furthermore, the assembly is sealed and reinforced with a 2 oz/sq., plain weave glass fiber composite skin. Each stabilizer structure is adhered to a tail boom interface hub. Finally, the tail boom interface hubs are locked onto the tail boom utilizing a spring-locking tube pin that allows the vertical structures to lock into the opposing hub in the same direction.

6.3.4 Landing Gear

The landing gear is a GFRP bow-shaped beam structure manufactured using a composite molding operation. The single-curve mold is cut from XPS foam stock using a hotwire CNC operation. The beam structure is a panel of uniform thickness along the curve made from 24 layers of fiberglass type wetted and cured under vacuum.

6.3.5 Ground test fixture

The test stands are constructed using woodworking techniques: the base planks and vertical pine planks are straightened with a table saw and bandsaw and smoothed with a belt sander before being glued

together and cured for 24 hours. The angled plywood pieces are cut at 45 degrees using a table saw and screwed into the ledge, the vertical planks, and the base planks for support. The potentially applicable ledge has hotwired CNC-cut XPS foam glued on top to cushion the wingtips. The holes for the connection interface are drilled using an M8 drill bit on a drill press.

6.3.6 Packaged Container

The box will be constructed of 4-mm thick corrugated polypropylene sheets reinforced with ladder mesh.

7.0 TESTING PLAN

7.1 TESTING SCHEDULE GANTT CHART

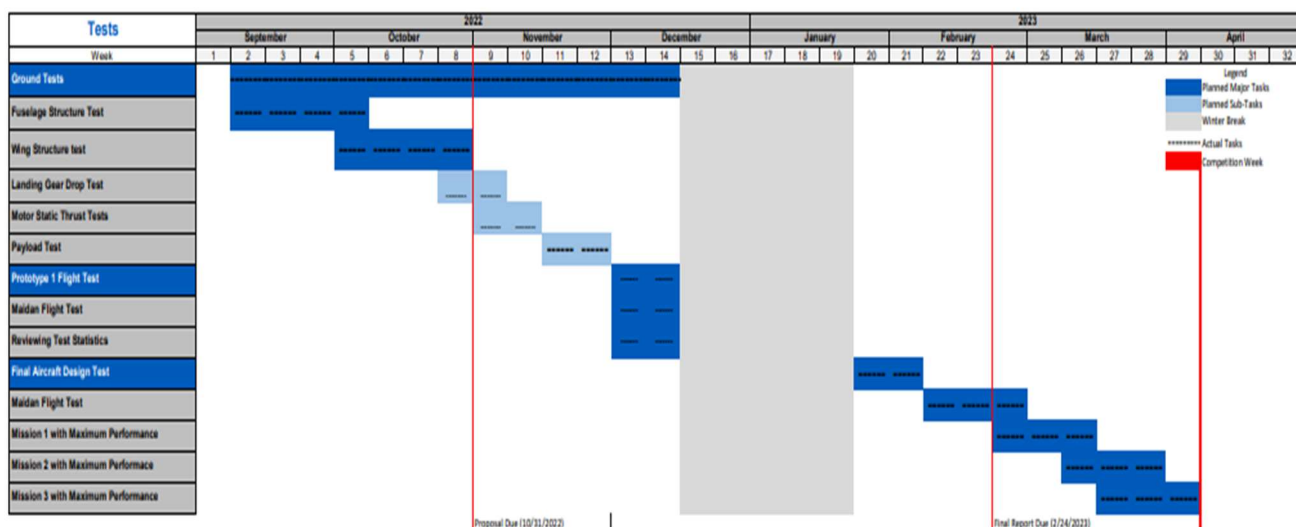


Figure 42. Testing Plan Gantt chart

The testing plan included preliminary testing of carbon fiber composite structures as well as aircraft prototype testing.

7.2 COMPONENT TESTING

7.2.1 Wing Structure Test

This year is the first time that UB DBF uses foam composites to manufacture an aircraft. Therefore, multiple XPS foam wings of different lengths with carbon fiber composite skins were manufactured and tested. The wings were fixed at the root chord and load was applied in increments at the wingtip. After each increase in load the deflection was measured. It was determined that the carbon fiber skin layup over foam does extraordinarily well at distributing loads.



Figure 43. Carbon fiber composite wing test

7.2.2 Static Propulsion Test

The propulsion test allowed us to calculate the maximum current and static thrust to validate our ESC selection and expectations for projected take-off thrust. Static thrust, power drawn, and rpm measurements were taken at 10% TX throttle inputs for three different propellers with a single motor configuration. The motor was fastened to a thrust test stand containing a load cell connected to a 24-bit precision ADC (HX711) and Arduino for data display shown in Figure 44. To calibrate the Arduino before the thrust readings were recorded, 10 reference masses hanging from a pulley were used to compute the linear best fit between the weight loading and ADC readings. The power drawn was calculated as the product of voltage and current readings from a wattmeter connected in series with the battery, and rpm was recorded using a tachometer.

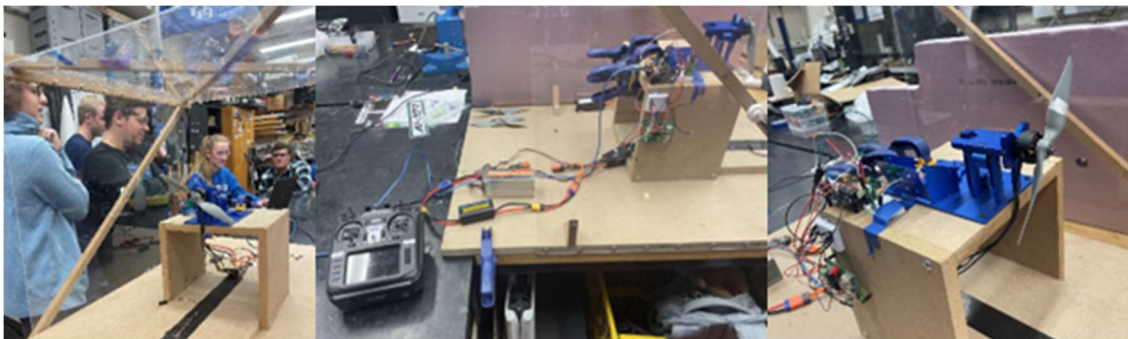


Figure 44. Static thrust setup

7.2 PROTOTYPE TESTING

7.2.1 Version 1 Summary

The Version 1 test flight was conducted in less-than-ideal airfield conditions, with a pilot lacking sufficient experience, which resulted in a stall and subsequent crash. Additionally, flight recording hardware was

damaged and rendered unusable. However, some valuable data was still recovered, and is documented in the below table:

Table 22. V1 Test flight data

	Mission 1
Takeoff Gross Weight	9lb
Takeoff Distance	3.5m
Stall Speed with Flap Deployed	25m/s
Average Cruise Speed	20 m/s
Lap Time	18s
Mission Duration	60s

Version 2's flight test was followed by the recruitment of a more experienced pilot, and a larger flight location with more space for longer approaches and higher flight speeds. It was hypothesized that the deployment of the large flaps may have placed the tail in a turbulent wake, which would explain why the stall was unrecoverable. As such, Version 2 features a larger wing and thicker airfoil, which eliminates the need for flaps.

7.2.2 Weighted wingtip test

A weighted wingtip test was performed on the Version 1 aircraft to determine the maximum load it could take before fracture. The airplane was held at the wingtips and test weight was applied in the outer surface of the fuselage section in increments.

7.3 V2 FLIGHT TESTING PLAN

Testing of Version 2 will begin immediately upon completion of the aircraft. The goal of Version 2 testing is to better understand the details of the aircraft's performance. This will be accomplished by implementing an Arduino-based sensor suite, including a pitot tube, IMU, voltage sensors and current sensors. The pitot tube and current sensors are crucial because the data obtained will help the team better understand dynamic propeller performance, which is a critical parameter in propulsion system design. The IMU sensors provide data on acceleration and angle of attack. The former can be used to design structures tailored to the inertial loads they experience during flight, and the latter can be used to correlate total drag with angle of attack.

7.4 CHECKLISTS

Table 23. Standard checklist tables

Pre-flight checklist - PHYSICAL				Pre-flight checklist - CONTROLS			
Item		Task		Item		Task	
Airframe	Wings	Check for cracks in skin, Kevlar, make sure cam clamp is tight		TX Battery	TX Battery above 60%		
	Tail	Check for cracks in skin, Kevlar, make sure spring clip is secure		System is ON	Power on TX, power on RX/servos, insert arming plug (in that order!)		
	Landing gear	Check for cracks, make sure cam clamps are tight		RX/TX	Range Check		
	Fuselage	Check for cracks in ribs, make sure hatches are locked		Failsafe	Throttle closed, Elevator up, right rudder, right aileron, flaps down		
	Nacelles	Check motors aren't wobbly, all parts are secured		Check Gyro	Visual confirmation of CORRECT control surface response to disturbance		
	CG	Balance the aircraft on the marked location – must sit LEVEL		Check Controls	Visual confirmation of CORRECT control surface and throttle response to input		
Electronics	Wires	Ensure no servo wires are loose, all wires secured					
	Propulsion battery	Check battery is strapped, plugged in, and FULLY CHARGED					
	RX battery	Check battery is strapped, plugged in, and FULLY CHARGED					
	Servos	Control linkages tight, control horns secured					
	Motors, props	Check for damaged props, grinding motors, and loose nuts					

8.0 PERFORMANCE RESULTS

8.1 Subsystems Performance Results

8.1.1 Wing structure test

Structural testing is performed to ensure that the airplane can withstand aerodynamic forces encountered during flight. A wing tip loading test was performed using foam board test fixtures to determine the maximum strength of the wings. During the test, weight was incrementally added until the wing skin failed. Simultaneously, the deflection of the plane, modeled as a simply supported beam, was recorded at each weight interval to evaluate the greatest g-force the wings withstood before permanent deformation. Failure occurred due to fractures which appear to have developed due to the opening in the composite skin accommodating servo hatch doors.



Figure 45. Wing structure test

8.1.2 Static Thrust Test

A static thrust test described in section 7.4 was conducted to gather data on the performance of each propeller being considered. The propellers considered were 9x4.5, 8x8, and 8x6, which were tested using a CINE66 motor. The static thrust test determined each propeller's thrust, current, and power draw. Along with this, the results from testing demonstrated that all three propellers could produce enough thrust for the plane to accelerate and climb, as the static thrust produced is more than $\frac{1}{3}$ of the plane's weight. Based on the results in Figure 46, the 9x4.5 propeller produces more thrust than the 8x8 and 8x6 propellers due to its lower pitch. The 9x4.5 propeller also draws around the same current and power as the 8x6 at similar throttle inputs. While the 9x4.5 propeller seems to be the best choice for our plane, the data only represents a static thrust test, not a dynamic thrust test. When testing the 9x4.5 propeller, the motor started to overheat at higher throttle settings, making it a less-than-ideal choice for our propulsion system. Due to the 9x4.5 propeller overheating, this leaves us with the 8x8 and 8x6 propellers. The 8x8 and 8x6 propellers underperform in the static thrust test due to the higher pitch and low airspeed that causes the propellers to

stall. REF 13] However, at higher airspeeds, the performance of the propellers should increase due to the increased airflow over the propellers. At higher airspeeds, the 8x8 propeller is more efficient than the 8x6 propeller due to its higher pitch, allowing the plane to travel further per revolution of the propeller. Due to the team not having the proper equipment to perform a dynamic thrust test safely, we could not gather any data about the dynamic thrust. Instead of a wind tunnel, the team placed a box fan in front of the testing enclosure to simulate airflow yielding an increase in performance. Because of this, the team decided to use the 8x8 propeller as it produced the most desirable results.

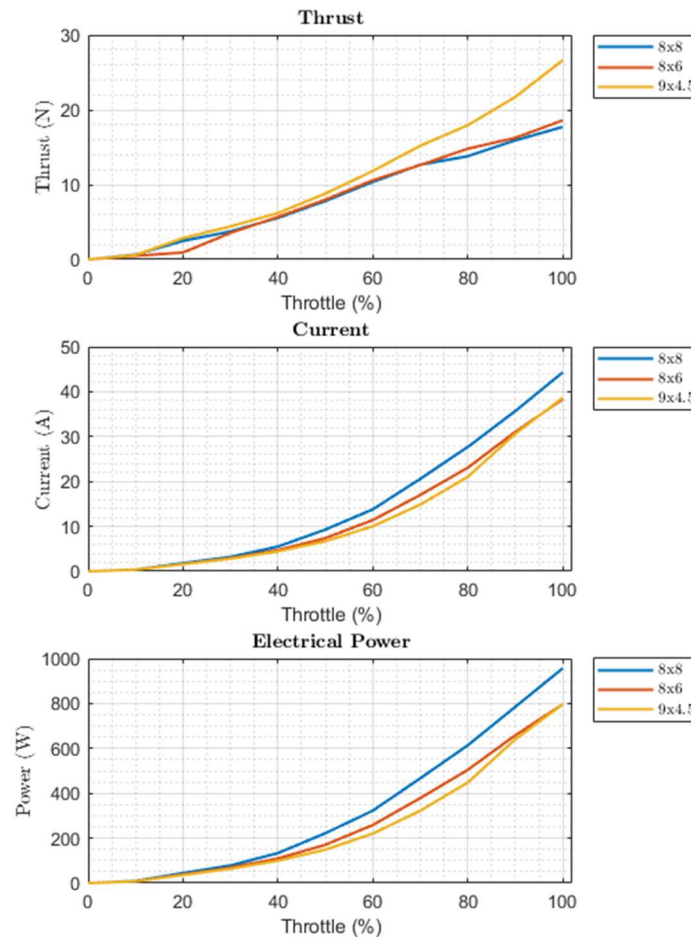


Figure 46. Static Thrust Test Results

8.2 System Performance

A series of tests were carried out to ensure aircraft performance, including timed ground mission simulations, fail-safe checks, pre-flight checks, and flight tests. The configurations of the mission-ready aircraft are noted in table 23. The timed assembly staging mission was simulated, and the expected assembly time is denoted in table 24.

Table 23. Configurations of the mission-ready aircraft

Parameter	Quantity	Specification
Battery Propulsion	1x	4,500 mAH 6S Li-Po
Receiver Battery Pack	1x	1300 mAH 2S Li-Po
Receiver Control	1x	2.4 GHz 8-Channel Spektrum Reciever
Electric Motor	2x	T-Motor CINE 66-925
Speed Controller (ESC)	2x	Hobbywing Skywalker 60 Amp
Propeller M1, M2, M3	2x	8 x 8 (Pitch x Diameter)
Empty Weight	N/A	9 lb

Table 24. Timed assembly staging mission

<i>Assembly Step</i>	<i>Avg. Measured Time</i>
Unloading for Box	14.2 s
Wing Attachment	67.34 s
Tail to Boom Attachment	14.78 s
Assemble Tail Boom to Fuselage	12.23 s
Landing Gear Attachment	13.82 s
Total Time	122.37
% Improvement	33.85 %

8.3 Results, Predictions, and Improvements

Testing and research results directed design changes to improve flight characteristics, structural performance, and sub-system functionality. Preliminary structures testing, shown in figure[7.XXX], found the primary mode of failure to be buckling under compression on the upper surface when exceeding a 30-pound load. Composite structures research found that a 0/60-degree fiber exhibited greater resistance to buckling versus the 0/90 fiber employed in the prototype [REF 12]. These findings lead design changes to the composite skin which is now reinforced by a 3.54 oz/sq yd triaxial weave CF fabric. The structural testing of the prototype up to 62 pounds discovered that the servo hatch doors introduce a point of stress concentration on the wing's tension side that can lead to a catastrophic failure. To mitigate this contribution to failure the wing was reinforced with unidirectional CF stringers on the lower surface. In combination with the stringers on the upper surface, the application aims to increase torsional resistance.

The prototype empennage had a very robust composite construction weighing an actuated 1.1 lbs. This mass was considered over-built, and a replacement was deemed necessary. The final design of the empennage is constructed of laser cut wood and has a reduced inertial impact on longitudinal stability.

The initial engine configuration housed the propulsion power storage in the wingtip mounted nacelles. However, during flight testing the roll rates and corresponding control inputs were analyzed and determined to have demonstrated an undesirable responsiveness, and it was determined to relocate the propulsion batteries inward to the nose of the aircraft.

The wingspan of the final unmanned aerial system increased due to an allowance in the linear dimension facilitated by spatial re-configuration of the box fitment. The final wing design increased to 28 inches from root to tip, an addition that represents a 6-inch increase to the span.

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