# The University of Tennessee, Knoxville

## 2023 AIAA Design, Build, Fly Competition

## Abbreviations, Acronyms, and Symbols

| Phrase | Abbreviation |
|---|---|
| **American Institute of Aeronautics and Astronautics** | AIAA |
| **Angle of Attack** | $\alpha$ |
| **Aspect Ratio** | AR |
| **Center of Gravity** | CG |
| **Coefficient of Lift** | $C_L$ |
| **Coefficient of Drag** | $C_D$ |
| **Computer Aided Design** | CAD |
| **Density** | $\rho$ |
| **Design, Build, Fly** | DBF |
| **Drag** | D |
| **Electronic Speed Controller** | ESC |
| **Expanded Polystyrene** | XPS |
| **Finite Element Analysis** | FEA |
| **Ground Mission** | GM |
| **Induced Drag** | $C_{Di}$ |
| **Lift** | L |
| **Lift to Drag** | L/D |
| **Matrix Laboratory** | MATLAB |
| **Mean Aerodynamic Chord** | MAC |
| **Mission 1** | M1 |
| **Mission 2** | M2 |
| **Mission 3** | M3 |
| **Load Factor** | n |
| **National Advisory Committee for Aeronautics** | NACA |
| **Neutral Point** | NP |
| **Planform Area** | Sref *or* S |
| **Polylactic Acid** | PLA |
| **Polyvinyl Chloride** | PVC |
| **Radio Control** | RC |
| **Root Chord** | Cr |
| **Steady Level Flight** | SLF |
| **Tip Chord** | Ct |
| **University of Tennessee, Knoxville** | UTK |
| **Velocity** | V |
| **Wingspan** | b |
| **2 Dimensional** | 2D |
| **3 Dimensional** | 3D |

# 1 Executive Summary

This report provides a detailed account of the design, manufacturing, and testing of the University of Tennessee, Knoxville's (UTK) submission for the 2023 Design, Build, Fly (DBF) competition hosted by the American Institute of Aeronautics and Astronautics (AIAA). UTK's submission for this competition is named Sailfin, inspired by the profile of the aircraft. All aircraft components, including a duplicate set of wings, must fit inside an airline checked baggage compliant box with characteristics set by AIAA; the box must be within 62 linearly constrained inches and have a maximum weight of 50 lbs. The aircraft must also take off in 60 ft or less on a paved runway and complete 4 missions (one ground, three flight) as described below:

- **Ground Mission (GM):** Structural Margin Demonstration **-** After successful completion of the technical inspection, the aircraft will be suspended from its wingtips while in Mission 2 configuration, which correlates to its heaviest payload configuration. Additional weight is applied at the team's discretion or until the 10 min mission duration expires.
- **Mission 1 (M1):** Staging Flight – The plane must takeoff within 60 ft and fly 3 laps of the predetermined flight course within 5 min without any payload on board.
- **Mission 2 (M2):** Surveillance Flight – The plane must takeoff within 60 ft while carrying an "electronics box" with minimum dimensions of 3 in x 3 in x 6 in and a payload that weighs, at minimum, 30% of the gross vehicle weight. The aircraft is to complete as many laps as possible during a 10 min time frame. The objective of the mission is to maximize the product of laps flown and weight of payload carried.
- **Mission 3 (M3):** Jamming Flight – The plane must takeoff within 60 ft while flying with a 0.5 in Schedule 40 polyvinyl chloride (PVC) jamming antenna fixed to a single wingtip. The jamming antenna must project vertically from the wing with no surface area extending below the wing's lower surface. Moreover, the flight time must not exceed 5 min. The goal of this mission is to minimize the flight time for three laps while maximizing the length of the antenna.

Sailfin has been designed and optimized to maximize scoring in all four missions. To achieve the 60 ft takeoff restriction and provide sufficient internal spacing for the electronics box the design employs a high-mounted wing with a 55 in wingspan. The aircraft produces a thrust-to-weight ratio in the Mission 1 configuration of approximately 1.39 which, coupled with the large wingspan, helps to meet the takeoff requirement as well as yield competitive flight speeds.

The aircraft was designed with an actuating vertical tail that optimized the total aircraft length and vertical tail size. With the incorporation of an articulating vertical tail instead of the standard rudder system, the lift-generating surface drastically increased. This increase in the lifting surface allowed for a smaller moment arm between the center of gravity (CG) of the aircraft and the vertical tail while still providing a significant counter moment for a competitively-sized jamming antenna during Mission 3.

## 2 Management Summary

### 2.1 Team Organization

The UTK DBF team consists of ten seniors majoring in aerospace engineering, an experienced faculty advisor, and twelve underclassmen ranging from freshmen to juniors. The team is led and organized by seniors; membership is open to students of all levels. The team employs a vertical leadership structure system, as shown in Figure 2.1, which promotes fluent communication, team collaboration, and accountability. During initial team formation, senior students are organized into sub-teams and assigned leadership roles, where membership is reflective of individual knowledge and expertise. The students then collaborated with other sub-teams to ensure cohesion and continuity. After seniors established the sub-teams, underclassmen were given the opportunity to join teams fitting individual interests and the ability to switch between sub-teams as the need arose.

### 2.2 Design Personnel & Assignment Areas

The UTK DBF team consists of two leadership roles and five sub-teams. This tiered leadership system is shown in Figure 2.1. The chief engineer organizes and facilitates meetings and performs other administrative tasks including setting deadlines and ensuring proper task distribution. Additionally, the chief engineer provides technical guidance and focus to each sub-team. The secretary manages travel, budgeting, and supply orders. Each sub-team oversees a specific design component of the aircraft with the computer aided design (CAD) team providing models for each component allowing for integration and cohesion between the sub-teams.

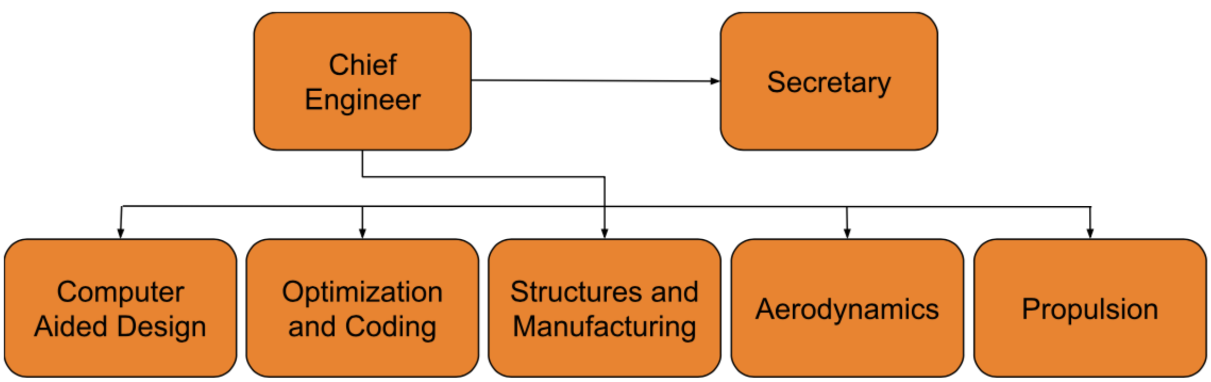



**Figure 2.1.** Team Organization Chart

### 2.3 Gantt Chart

The UTK DBF team utilizes a Gantt chart in order to maintain organization and execute proper time management. This chart, simplified for readability, can be seen in Figure 2.2, which provides deadlines for all major design milestones, testing, and competition deliverables.

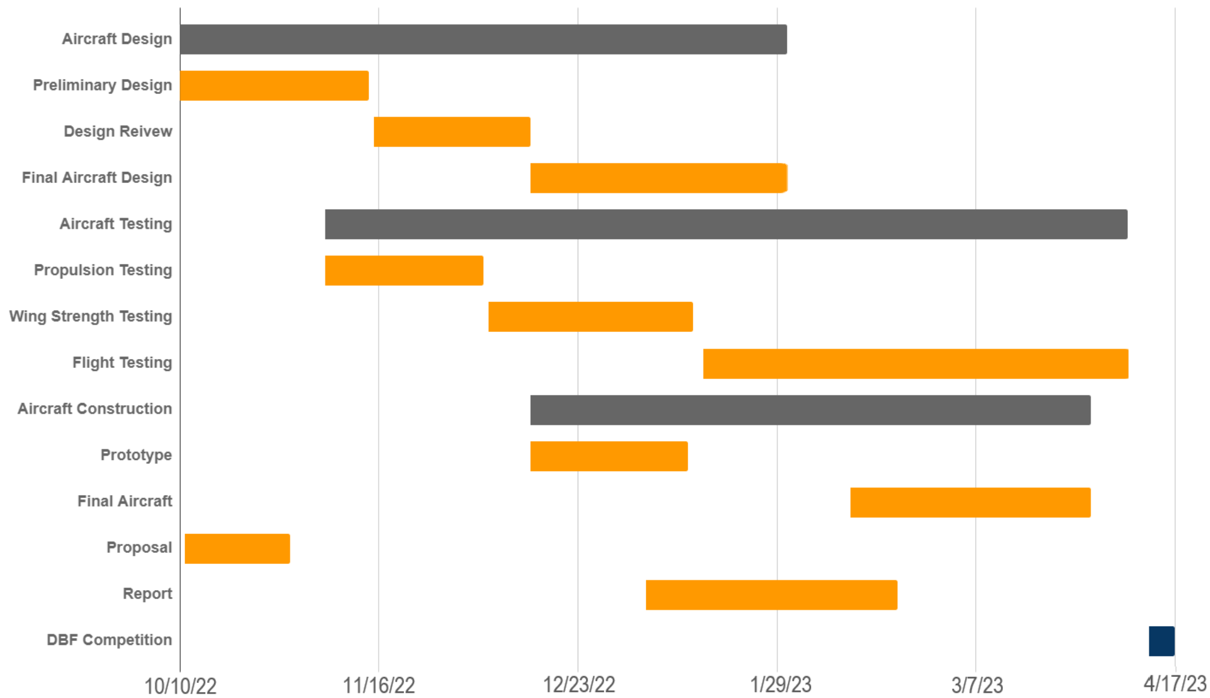



**Figure 2.2.** Gantt Chart

## 3 Conceptual Design

For the conceptual design, the team analyzed the AIAA provided aircraft requirements and the individual mission requirements. The mission scoring equations were then evaluated over many weeks to aid the team in selecting an aircraft design that could maximize scoring for the competition aircraft.

### 3.1 Mission Requirements

As discussed in Section 1, the 2023 AIAA DBF competition is divided into four missions: one ground mission and three flight missions. The flight course for the 2023 competition can be seen below in Figure 3.1. The overall objective of the competition is to design, build, test, and fly an aircraft that can successfully perform under the various constraints of the AIAA mission requirements. The aircraft must fit in a box with dimensions no larger than 62 linear in, weigh no more than 50 lbs, operate from a paved runway, takeoff in 60 ft or less, and carry all payloads fully internally. The specified requirements for each individual mission are laid out in Table 3.2.

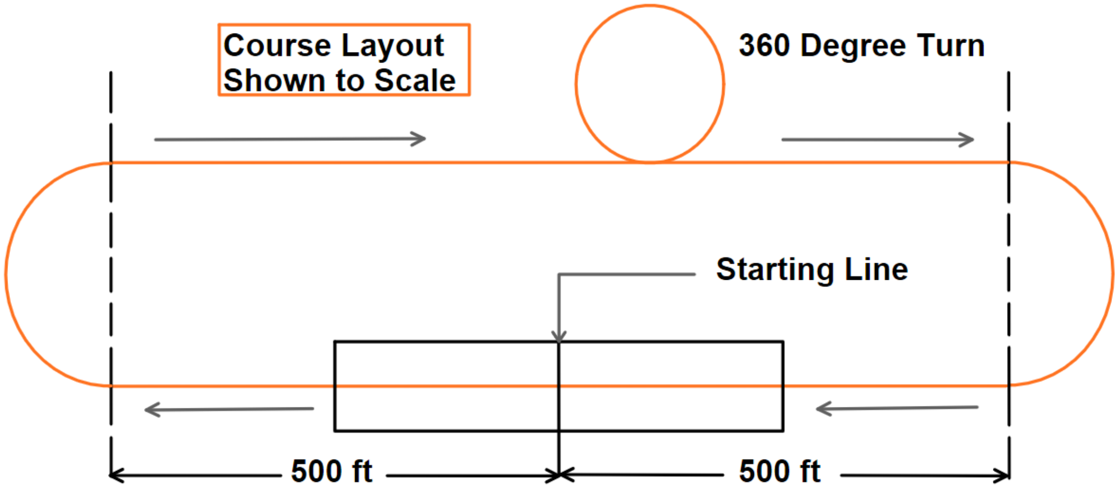



**Figure 3.1.** 2023 AIAA DBF Flight Course [2]

**Table 3.2a.** 2023 AIAA DBF Mission Requirements

| Mission | Requirements |
|---|---|
| **Ground Mission:** Structural Margin Demonstration | **1.** Pilot & assembly crew member may participate<br>**2.** Aircraft must enter staging box inside the closed shipping box<br>**3.** Team will flip a coin x2 to determine wing set components used.<br>**4.** Assembly member will assemble plane and install heaviest payload configuration as declared in tech inspection.<br>**5.** Pilot verifies all flight controls are working properly<br>**6.** Assembly crew member will install structural test fixture onto wing tips.<br>**7.** Assembly crew member applies test weights to the center of the fuselage until max weight is called or time expires.<br>**8.** While under test weight and on fixture, pilot verifies flight controls are still functioning. |
| **Mission 1:** Staging Flight | **1.** Aircraft must enter staging area inside the closed shipping box<br>**2.** Team will flip a coin x2 to determine the wing set components used<br>**3.** Takeoff in 60 ft or less<br>**4.** Must complete 3 laps within 5 min flight window<br>**5.** Must complete a successful landing |

**Table 3.2b.** 2023 AIAA DBF Mission Requirements Continued

| Mission | Requirements |
|---|---|
| **Mission 2:** Surveillance Flight | **1.** Minimum payload of 30% gross vehicle weight, minimum dimensions of 3 in x 3 in x 6 in<br>**2.** Aircraft must enter the staging box inside the closed shipping box<br>**3.** Team will flip a coin x2 to determine the wing set components used<br>**4.** Takeoff in 60 ft or less<br>**5.** Complete maximum amount of laps in 10 min time window<br>**6.** Must complete a successful landing |
| **Mission 3:** Jamming Flight | **1.** Payload is the jamming antenna<br>**2.** Aircraft must enter staging box inside the closed shipping box<br>**3.** Team will flip a coin x2 to determine the wing set components used<br>**4.** Jamming antenna must be mounted on the side of the vehicle opposite of flight safety line in the direction of takeoff<br>**5.** Takeoff in 60 ft or less<br>**6.** Must complete 3 laps within 5 min flight window<br>**7.** Must complete successful landing |

### 3.1.1 Scoring Summary

The final score for the competition is determined by Eq. 1.

$$\textit{Score} = \textit{Written Report Score} \cdot \textit{Total Mission Score} \qquad \text{Eq. 1}$$

Where *Written Report Score* is the score given based on the quality of the final submitted design report and the *Total Mission Score* is a sum of all the mission scores given by Eq. 2.

$$\textit{Total Mission Score} = GM + M1 + M2 + M3 \qquad \text{Eq. 2}$$

### 3.1.2 Mission Scoring

*Ground Mission: Structural Margin Demonstration*

For the Ground Mission, the goal is to demonstrate the structural margin of the airplane. The timed mission starts once the aircraft is inside the staging area. The wing set is then decided alongside the heaviest payload weight, additional testing weight, and test fixture. The Ground Mission aims to verify the structural integrity of the aircraft under increased loading, similar to Mission 2, while maintaining flight control functionality. The GM mission score is given by Eq. 3, where *UTK_(total test weight / max aircraft weight)* is the individual team's added weight to max aircraft weight. Additionally, *Max_(total test weight /*

*max aircraft weight)* is the highest added weight to max aircraft weight of all competing teams.

$$GM = [UTK\_(total\ test\ weight / max\ aircraft\ weight) / max\_(total\ test\ weight / max\ aircraft\ weight)] \quad \text{Eq. 3}$$

*Flight Mission 1: Staging Flight*

The objective of Mission 1 is to successfully takeoff within 60 ft and complete 3 laps within the given flight window of 5 min. There is no payload for this mission and the time starts once the aircraft throttle is advanced for take-off. Scoring for this mission is a pass-fail analysis; If the aircraft completes the flight landing safely within the time limit, **M1=1.** Failure to complete the mission results in **M1=0**.

*Flight Mission 2: Surveillance Flight*

The goal of this mission is to maximize the product of the number of laps flown in the given 10 min time window as well as maximize the payload weight. The scoring for this mission is given by Eq. 4 where *UTK_(#payload weight * # laps flown)* is the team's payload weight divided by the number of laps flown during the 10 min window and *Max_(#payload weight * # laps flown)* is the highest product of payload weight and the number of laps flown of all the competing teams.

$$M2= 1+[UTK\_(\#payload\ weight * \#\ laps\ flown) / Max\_(\#payload\ weight * \#\ laps\ flown)] \quad \text{Eq. 4}$$

*Flight Mission 3: Jamming Flight*

For this mission, the objective is to minimize the flight time of three complete laps while maximizing the length of the jamming antenna. The scoring for this mission is described in Eq. 5, where *UTK_(antenna length / mission time)* is the team's antenna length divided by the total mission time and *Max_((antenna length / mission time)* is the highest successful quotient of all teams.

$$M3 = 2 + [UTK\_\ (antenna\ length / mission\ time) / Max\_\ (antenna\ length / mission\ time)] \quad \text{Eq. 5}$$

### 3.2 Subsystem Design Requirements

During the design process, the team analyzed the AIAA provided rules and conducted a sensitivity analysis. From this, the team decided on basic requirements for every subsystem within the aircraft using a figure of merit analysis. Each sub-team was then put in charge of making the design selections that fell within the responsibilities of that team. Each sub-team ensured that the selected subsystem design met the requirements determined by prior analyses. These requirements are broken down for each sub-team in the following sections.

### 3.2.1 Computer Aided Design Team Requirements

The main responsibility of the CAD team was to create 3 Dimensional (3D) models of the aircraft and of each individual component. This team was also in charge of integration and continuity between subsystems. It was vital that each model be fully emulated so that the integration of the subsystems could be checked for any system interference. The CAD team also ensured that, as the systems were integrated, each component would fit into the airline compliant box while still maintaining optimal dimensions for each mission. Additionally, the team had to make certain that critical components inside the fuselage were accessible once the plane was fully manufactured.

A CAD model was also needed as a reference during the construction of the aircraft. The CAD team was tasked with modeling the fuselage and tail according to the optimized dimensions previously determined. The team's basis for these decisions was that they had to be designed for manufacturability with resources available to the team. The fuselage dimensions required enough clearance to fit the Mission 2 payload and all other flight components, while still meeting the design constraints set by the aerodynamics team.

The CAD team was also responsible for calculating the static margin of the plane. This was determined by finding the distance between the aerodynamic center and the CG of the aircraft for each mission configuration. The tail dimension selection process required that the vertical tail was large enough to counteract the yawing moment induced by the Mission 3 jamming antenna but small enough to minimize the drag created by the vertical tail. Additionally, it was required that the horizontal tail was the optimal size to keep the aircraft stable for Mission 1 and Mission 2. This was accomplished by setting the NP measurement at the wing quarter chord and back calculated the required horizontal tail volume. With the tail volume known and the horizontal tail construction material assumed to be ½ inch balsa, the chord and span lengths were constrained by aircraft geometry and shipping box dimensional constraints.

### 3.2.2 Structures and Manufacturing Team Requirements

The structures and manufacturing team focused on the selection of materials and processes that would be optimal for the construction of the plane, alongside overseeing the entirety of the manufacturing process. The fuselage material had to be lightweight, rigid enough to reduce the internal structure, and minimize the complexity of processing. The tail material needed to be very lightweight, simple to construct with dimensional accuracy, and to be constructed using readily available materials. The wing material also needed to be very lightweight to minimize the overall weight, while passing the wing tip loading test and supporting the addition of the jamming antenna in Mission 3. This team was also in charge of designing an easily manufacturable landing gear that would provide structural rigidity under the weight of the aircraft.

### 3.2.3 Aerodynamics Team Requirements

The aerodynamics team was responsible for airfoil selection, wing geometry, fuselage shape, tail design, and aerodynamic performance analysis. The requirements for the selected airfoil were that it maximized the wings' lift coefficient and was tolerant to manufacturing error. The wing geometry necessitated a wing design that would generate sufficient lift to support the estimated weight of the aircraft and payload while maintaining a takeoff distance of less than 60 ft. In addition, the wing geometry needed to minimize the induced drag ($C_{Di}$) and account for the asymmetric drag induced by the Mission 3 jamming antenna. The fuselage shape required that the cross-sectional area was minimized while still allowing space for the Mission 2 payload and other components. Additionally, it was necessary that a tail was designed capable of offsetting the flight instabilities caused by the addition of a wingtip antenna in Mission 3 while maintaining dimensional constraints and minimizing drag characteristics. The aerodynamics team continually updated and ran a Matrix Laboratory (MATLAB) based simulation of the aircraft's aerodynamic performance using Mission 2 and Mission 3 constraints to improve design developments.

### 3.2.4 Propulsion Team Requirements

The propulsion team was responsible for the design selections of the propeller, motor, electronic speed controller (ESC), control servos, and batteries. It was desired that the propeller operate at peak efficiency at the estimated cruise speed for each mission. The motor was chosen to provide maximum power for propulsion within the constraints of the battery. The ESC is needed to handle the voltage and current delivered to the motor. The control servos had to be strong enough to actuate their respective control surfaces precisely and reliably. Additionally, it was necessary that the batteries contain a high power-to-weight ratio as well as the maximum allowable amount of energy of 100 Wh.

### 3.2.5 Optimization and Coding Team Requirements

The optimization and coding team's main responsibility was to perform the vehicle's sensitivity analysis and run virtual simulations. The sensitivity analysis was a vital tool for making preliminary design choices before vehicle prototyping. MATLAB script files were created to simulate and analyze mission scoring based on each team's parameters. Structures and manufacturing, aerodynamics, and propulsion teams collaborated to propose configurations to be tested for predicted scoring by the optimization and coding team.

## 3.3 Considered Solutions

Regarding potential constraint solutions, the team considered various aircraft configurations to maximize the theoretical competition score. The methodology used to select initial aircraft configurations began with a figure of merit analysis. This process began with the potential fuselage, wing, tail, landing gear, and drag counteraction methods being discussed in a formal group setting. All team members then voted to decide which designs would be used for the proposed prototype. The prototype vehicle was then constructed according to the selected configurations and then flight tested so that improvements to the final design could be considered and made where necessary.

### 3.3.1 Figures of Merit

The figures of merit analysis consisted of a team effort to propose possible aircraft configurations. The proposed components were then voted on so that the theoretical benefits of the configuration aligned with the mission requirements and would allow for the best possible score at the competition. The below figure, Table 3.3a - 3.3f, represents the potential configuration options that were voted upon by each team member.

Table 3.3a represents the potential fuselage configurations considered for the initial prototyping phase. This section of the figures of merit analysis consisted of three potential fuselage designs with their listed advantages and disadvantages according to theory. Each team member weighed the advantages and disadvantages, resulting in a conventional, package-conscious fuselage with a detachable, tapered tail design. This decision is influenced by the ease of manufacturing and the need for the fuselage to fit as one connected piece within the airline complaint box. Moreover, the fuselage is designed to hold the package weight for Mission 2 approximately at the quarter chord of the wing, which limits changes to the CG between aircraft configurations.

**Table 3.3a.** Figures of Merit Table

| | Idea | Advantages | Disadvantages |
|---|---|---|---|
| **Fuselage Design** | Blended Wing | Reduced Drag | Difficult fit within box, complex manufacturing, might not gain drag reduction |
| | Package Conscious Fuselage with Tapered Tail | Easy to keep CG in front of NP | Less storage space, difficulty placing of components, may increase drag due to body shape |
| | Detachable Tail with Conventional Fuselage | Shorter fuselage length allows for easier packaging | Additional point of failure from attachment point |

The second portion of the figures of merit analysis involved weighing the advantages and disadvantages of potential wing design parameters and configurations. The primary considerations included the mounting configuration of the wings to the fuselage and the wings' aspect and taper ratios. Given the information in Table 3.3b, it was decided that prototyping would commence with a high wing mounting on the fuselage and a low aspect ratio (AR) wing section. The high wing posed the least amount of interference with the electronics package, as opposed to the mid and low-wing mounting positions, which would sit on or near the bottom surface of the fuselage. A high-wing mount would also be more aerodynamic and require less structural interfacing than a bi-wing construction. The low AR configuration was chosen due to its ease of fitting in the airline-compliant box, ease of manufacturing, and structural stability.

**Table 3.3b** Figures of Merit Table

| | Idea | Advantages | Disadvantages |
|---|---|---|---|
| **Wing Position** | High | Stability, ground clearance | Less ground effect during takeoff / landing |
| | Low | Ground effect | Side area needed to mount wings, needs dihedral for stability |
| | Mid | Places spar at the strongest point in the fuselage | Wing spar interferes with package |
| | Bi-Wing | Greater lift from same top-down projection | Increased drag, would double wings in box |
| **Wing Parameters** | High AR (>4) | Less induced drag | Greater moment arm, difficulty fitting in the box, less structurally sound |
| | Low AR (<4) | Smaller moment arm, Easier to fit in the box, More structurally sound | More induced drag, large chord length needed for Mission 2 |
| | Taper Ratio | Lighter overall weight (slight) | Eliminates asymmetric wing idea, difficult to manufacture, less wing area, less lift |

Potential landing gear configurations were another consideration in the figures of merit analysis. The two styles of landing gear proposed were taildragger and tricycle configurations. Ground clearance is of the utmost importance for the vehicle due to the need for large propellers that can provide adequate thrust to carry Mission 2's payload weight. Therefore, ground stability was decided to be of lesser importance which allowed the team to agree on the tail dragger configuration. This allowed for the greatest possible propeller ground clearance.

**Table 3.3c.** Figures of Merit Table

| | Idea | Advantages | Disadvantages |
|---|---|---|---|
| **Landing Gear Style** | Tail Dragger | Lighter, increased ground clearance, reduced drag | Ground loop, less ground stability in wind |
| | Tricycle | Increased ground stability in wind, reduces ground loop | Wheel-barrowing, increased weight, more complex, less ground clearance |

Next, the team considered potential motor configurations. The three configurations considered were a single front-mounted engine, dual engines mounted on the wing sections, and a single pusher configuration with the motor mounted aft of the fuselage. Weighing the theoretical benefits and drawbacks of the proposed ideas, the team decided upon a single front-mounted motor configuration. The front-mounted configuration would only require a single battery, allowed for ease of manufacturability, and kept the CG forward on the vehicle. The proposed dual engines were discarded due to the difficulty of interfacing the engines into the wing sections. Likewise, the pusher configuration was omitted due to the fact that it would not interface well with the tail dragger landing gear previously selected, and the CG would be moved aft.

**Table 3.3d.** Figures of Merit Table

| | Idea | Advantages | Disadvantages |
|---|---|---|---|
| **Motor Configuration** | Tractor | Single battery, Easier construction | Limited power from one motor |
| | Dual Engine | Increased power, Redundancy, Lack of yaw control for Mission 3 | Increased weight, more complex and expensive, increased difficulty manufacturing wings |
| | Pusher | Reduced drag from horizontal tail surfaces, No prop wash over wings | CG further back, may requires tricycle type landing gear, requires twin boom tail to avoid engine |

Another consideration for the figures of merit analysis was the correction method for the moment caused by the antenna introduced in Mission 3. Being the primary variable of a successful Mission 3 flight, the team heavily weighed the theoretical benefits and drawbacks of each potential design configuration with the support of MATLAB script analysis. The drag plate and two motor concept were the first ideas to be omitted, given the exact weight for the drag plate would require meticulous calculation to avoid introducing another source of instability during flight. The two motor concept had been previously discarded in the motor configuration analysis but also discarded in this analysis due to throttle control needing to be autonomously coded into the flight control system. Without the programming of the throttle control, the two-motor system poses the risk of overcomplicating the flight control system. Additionally, the drag plate was later deemed illegal by AIAA rule clarification [3]. The oversized rudder was discarded, given that the rudder and vertical tail design would need to be egregiously large to counteract the moment produced by a competitively sized antenna.

**Table 3.3e.** Figures of Merit Table

| | Idea | Advantages | Disadvantages |
|---|---|---|---|
| **Antenna Moment Correction Method** | Actuating Vertical Stabilizer | Increased yaw control, large antenna | Single hardpoint, complicated servo placement, weight |
| | Drag Plate | Act as antenna counterweight, reduces tail size, easy to manufacture | Increased overall drag of the aircraft, reduces efficiency and possibly top speed |
| | Oversized Rudder | Simple to manufacture | Increased drag, shorter antenna |
| | Two Motor System | Direct yaw control from throttle balance | Increased weight, extra wiring in wings, CG issues |
| | Tail Rotor | Reduced tail size, adjustable yaw control | CG further back, complex, draws power from main battery |

The tail rotor was proposed with the idea that another propulsive system would be placed inside the vertical tail for yaw control, like a helicopter. The actuating vertical tail was posed such that the entire vertical tail would be attached to a servo and rotate, effectively making the vertical tail act as a rudder for increased yaw stability. Both configurations were then evaluated using MATLAB script files; these performance outputs can be found in section 3.4. Theoretically, both moment correction methods posed similar maximum composite scores, allowing the optimization team to determine that ease of manufacturability would be the final consideration for the moment correction method. The actuating vertical tail was ultimately chosen as the moment correction method, given the decision that a secondary propulsion system would not be added, along with ease of manufacturability.

The final consideration from the figures of merit analysis concerned the potential tail configurations of the aircraft, which can be seen in figure 3.3f. Conventional H, V, and T-tails were considered for the aircraft. The main drawbacks of the H, V, and T-tails were their reduction in ease of manufacturability as well as incurred necessity of studier construction materials. Sturdier construction materials would in turn add more aft weight, moving the CG of the vehicle back. For these reasons, a conventional horizontal and vertical tail section was chosen.

**Table 3.3f.** Figures of Merit Table

| | Idea | Advantages | Disadvantages |
|---|---|---|---|
| **Tail Design** | Conventional | Ease of manufacturing | Taller tail to counteract yaw moment may have difficulty fitting in the box |
| | V-Tail | Less parasite drag | Difficult to make, not flying fast enough for parasite drag to have as much of an effect |
| | H-Tail | Offset rudders induce moment to counteract antenna drag, lower tail height | Horizontal tail must be stronger/heavier (moves CG back), harder to construct, multiple vertical rudder servos needed |
| | T-Tail | Allows for NP changes, elevator above downwash, more consistent control | Have to run wires to elevator servos all the way up the tail, stalls at a lower AOA than most |

For the initial prototyping phase, the team weighed the advantages and disadvantages listed in Tables 3.3a-3.3f for the configuration of the plane and decided to construct a conventional, package-conscious fuselage with a tapered tail and a low AR, high-wing placement design. The landing gear decided upon was a taildragger configuration with a single motor mounted in the center of the fuselage’s front face. A conventional tail style was selected in order to utilize rotation of the entire vertical tail, which would eliminate the need for a conventional rudder. This overall design was established because it allowed for the best theoretical mission scores and ease of manufacturing.

## 3.4 Sensitivity Analysis

To analytically maximize mission scoring, the optimization and coding team performed a two-stage sensitivity analysis. The first stage of this sensitivity analysis consisted of varying parameters determined to be vital to the success of Mission 2 and Mission 3, as the score increment increase in these missions would allow the team to maximize the overall flight score of the vehicle. Starting with an individually designed plane, the team utilized the design characteristics of this vehicle as a baseline for the sensitivity analysis. The analyzed parameters were as follows: wing chord, wingspan, and vertical tail chord in inches. The variance of the parameters allowed the optimization team to produce a baseline 2D line plot of how a percent increase or decrease in vital mission parameters would affect flight mission scoring. It should be noted that the team assumed a full flight duration of 10 min and 5 min for Mission 2 and Mission 3, respectively, as well as limiting the data of each respective varied parameter to a maximum value based on constraints of the airline checked baggage; additionally, Mission 1 is omitted from the analysis due its binary scoring procedure. The findings shown in Figure 3.2 reveal that increasing all three critical parameters would produce a maximized theoretical score while still being constrained by the components fitting correctly into the airline checked box.

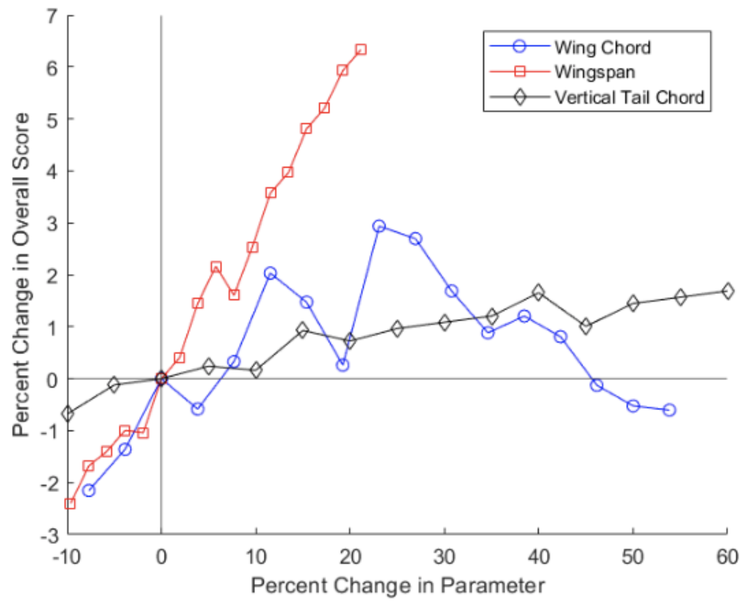



**Figure 3.2.** Initial Parametric and Scoring Analysis

The optimization team then used a secondary sensitivity analysis to investigate further the parameters shown in figure 3.2 by considering a varying moment arm of the aircraft's tail section. The secondary analysis produced an idealized version of the aircraft providing a tangible starting point for prototyping and eventual finalized construction. The optimization and coding team then created MATLAB script files incorporating the configuration specifications according to the figures of merit analysis with the added analysis of the top two considered antenna moment correction methods; the articulating vertical tail and tail rotor concepts.

The secondary sensitivity analysis utilized MATLAB script files to iterate through the aforementioned vital parameters to predict scoring values for Mission 2 and Mission 3 and a composite predicted score assuming successful flights of all three missions.

### 3.4.1 Mission 2 Secondary Analysis

The first portion of the secondary analysis consisted of iterating through different wingspans and chord lengths for a Mission 2 score until a max weight was achieved while still allowing the vehicle to takeoff in the 60 ft constraint. This inherently allowed the estimated max package weight to be calculated. Another key element in the script file used for Mission 2 analysis was the overriding of the calculated thrust required at takeoff values. The script file allowed for the thrust at takeoff to be set to the maximum static thrust which was obtained through propulsion testing and reported in figures 4.3-4.5. Incorporating the static thrust testing values as the maximum achievable thrust for takeoff allowed the score modeling and package weight prediction to be considered an accurate approximation. The validation of these modeling techniques was further investigated through flight testing. Headwind affecting the vehicle's ability to carry large package weights was another consideration for the Mission 2 analysis. Within the Mission 2 script file, the calculated liftoff speed was varied with factors from 0 to negative 15 ft/s. This rough estimate allowed for the liftoff speed to account for various headwind conditions up to the average wind speed in April in Tucson, Arizona [4]. Table 3.5 displays that an assumption of a relatively low headwind, such as 5 ft/s, would allow the team to increase their declared max package weight by 2.1 pounds while requiring below average headwind.

**Table 3.5.** Predicted Maximum Package Weights at Varied Headwind Conditions

| **Headwind (ft/s)** | 0 | 5 | 10 | 15 |
|---|---|---|---|---|
| **Predicted Package Weight (lbs)** | 9.70 | 11.80 | 14.20 | 16.80 |

The antenna moment correction methods, discussed previously in Table 3.3f, posed no theoretical difference in Mission 2 estimated scoring. Therefore in the intermediate scoring analysis for the mission, plots for the articulating vertical tail and tail rotor configurations were created. According to this assumption, the plots showed no feasible difference in scoring for Mission 2 based on the moment correction method. The wingspan and chord were iterated through in the Mission 2 script file and found that the optimal measurements occurred at two points; a 55 and 57 in wingspan both with a 20 in chord. The following 3D surface plots represented the Mission 2 intermediate scoring analysis. Figures 3.3 and 3.4 respectively referenced the predicted Mission 2 scores for different wingspan and chord values.

Figures 3.3 and 3.4 show that Mission 2 required the largest possible chord length with peak scoring occurring at 55 and 57 in wingspans. Increased wingspan and chord length would allow the vehicle to carry a heavier package weight and takeoff in under 60 ft.

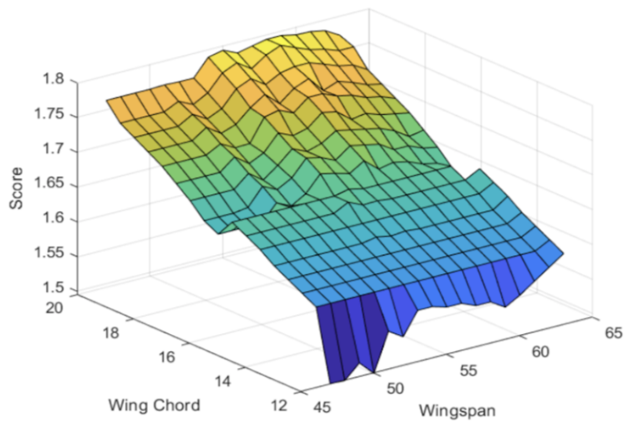



**Figure 3.3.** Predicted Change in M2 Score based on Wing Geometry (Articulating Tail)

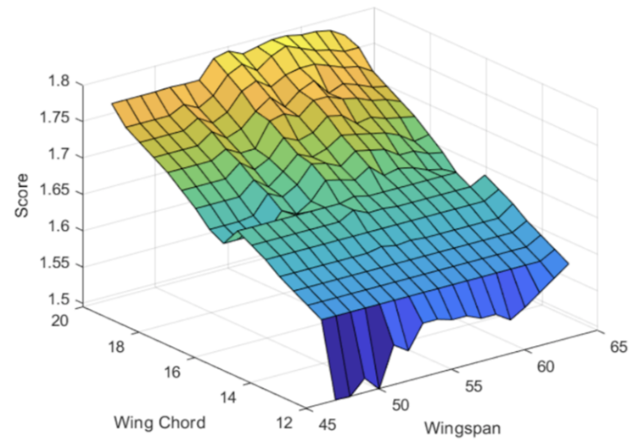



**Figure 3.4.** Predicted Change in M2 Score based on Wing Geometry (Tail Rotor)

### 3.4.2 Mission 3 Secondary Analysis

The second portion of the secondary analysis involved iterating through wingspans, chord lengths and antenna heights in order to predict intermediate scoring values for Mission 3. A MATLAB script file was created to mimic the scoring routines for Mission 2 with the change to incorporate the Mission 3 scoring equation. In order to remain consistent with the scoring routines of Mission 2, the Mission 3 scoring script also set the thrust at takeoff to the maximum static thrust achievable based on the propulsion test reported values in figures 4.3-4.5. However, due to the nature of the mission, the vehicle did not require maximum static thrust to takeoff in less than 60 ft. The figures produced by the code allowed the team to see a 3D visual representation of how wingspan and chord length affected Mission 3 predicted scoring. It should be noted that according to theory, the optimization team predicted that the highest Mission 3 score would come from the shortest wingspan and chord length as those parameters would create the smallest moment arm for the antenna and allow the vehicle to experience the least yawing moment possible. For the scoring analysis, both potential antenna moment correction methods were tested in the script file in order to see if there was a noticeable scoring difference between the methods. The results are seen in Figures 3.5 and 3.6. Figure 3.5 shows a visual representation of the wingspan and chord length's effect on Mission 3 performance for the articulating tail concept. As expected, the plot shows a downward trend in the score as the wingspan increases. This downward trend was expected as the distance to the wingtip directly relates to the induced yawing moment created by the antenna. Figure 3.6 represents the effect of wingspan and chord on Mission 3 scoring. Similar to the articulating vertical tail concept, the tail rotor concept displayed a maximum Mission 3 score at the shortest wingspan. This data validated the Mission 3 scoring model as it was consistent with the hypothesis of moment balances of the articulating vertical tail concept for Mission 3.

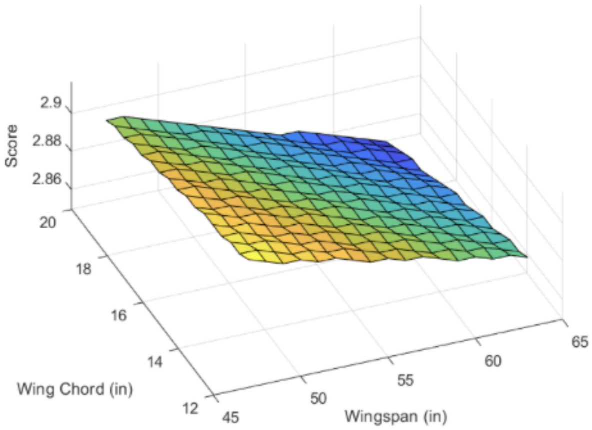



**Figure 3.5.** Predicted Change in M3 Score based on Wing Geometry (Articulating Tail)

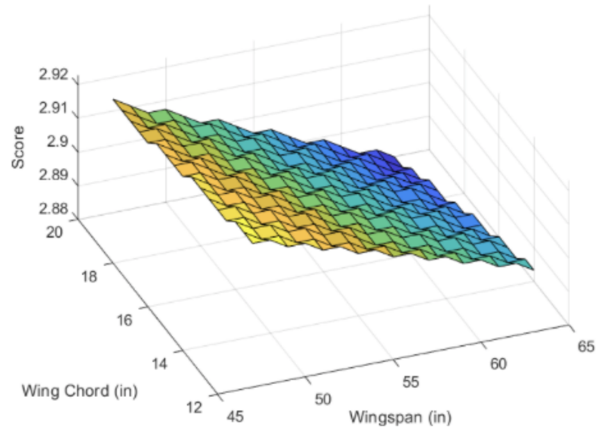



**Figure 3.6.** Predicted Change in M3 Score based on Wing Geometry (Tail Rotor)

### 3.4.3 Composite Scoring Analysis

After the optimization of both Missions 2 and 3, the intermediate predicted scoring values were then summed together for each wingspan and chord iteration. This analysis allowed the optimization team to produce a figure of total predicted mission scoring as a function of wingspan and chord. Plotting these data points on a 3D surface plot allowed the team to select a wingspan and chord length for initial prototyping. Figures 3.7 and 3.8 represented the composite scoring for both the articulating vertical tail and tail rotor concepts. Figure 3.7 shows the combined scoring analysis for the articulating vertical tail concept. This composite scoring analysis assumed successful and ideal flights of Missions 1, 2, and 3. From the plot, it was determined that while Mission 3 was worth more points, the variance in wing chord and wingspan had a greater effect on Mission 2 scoring resulting in the conclusion that the wingspan and chord of the vehicle should cater more to Mission 2. Figure 3.8 is a composite scoring analysis for the tail rotor concept. The plot assumed successful flights for Missions 1, 2, and 3. Analysis of the figures allowed the team to see that implementing a 55 in wingspan and 20 in chord for the wing sizing on the prototype vehicle would result in a max theoretical score. Furthermore, the analysis confirmed that the maximum score predictions for either of the tail concepts were approximately the same. Given similar mission scores for both methods, the manufacturing team determined the final prototyping concept. Their decision was based on which concept was easier to manufacture. Therefore, the articulating vertical tail was chosen.

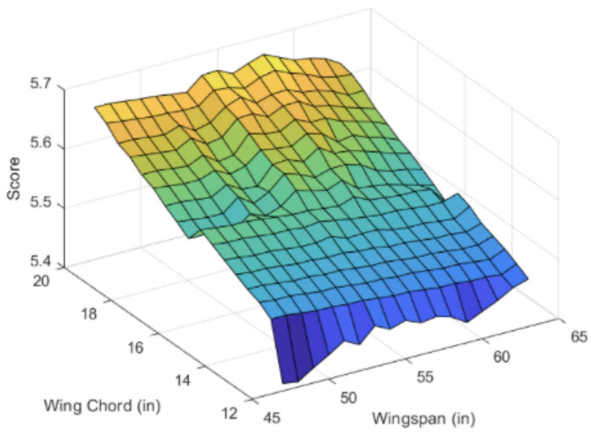



**Figure 3.7.** Composite Scoring based on Wing Geometry (Articulating Tail)

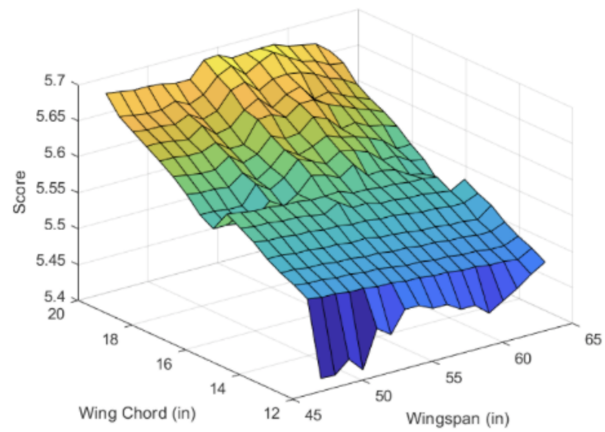



**Figure 3.8.** Composite Scoring based on Wing Geometry (Tail Rotor)

# 4 Preliminary Design

The preliminary design phase followed the conceptual design phase. The goal of this phase was to begin fabricating the overall design of the aircraft. Most importantly, the initial aircraft design was adjusted to ensure all mission requirements and design constraints were met with optimal performance.

## 4.1 Design/Analysis Methodology

During the preliminary design phase, larger design categories were broken down into smaller subsystems and examined to ensure each category performed optimally, given individual mission constraints. To test the overall design, test flights were performed at the end of the preliminary design phase and the results were used to determine protocols for further improvement of the aircraft. Design elements that cause divergence from expected theoretical performance values were observed from testing. These specific elements were then either redesigned or further optimized following the analysis methods described earlier. Overall, the methodology surrounding the design process was highly iterative and focused on optimizing as many parameters as possible to achieve high mission scores.

## 4.2 Design/Sizing Trades

### 4.2.1 Airfoil Selection

Airfoil selection was crucial given the strict mission requirements. The aircraft must take off within 60 ft while carrying a payload in Mission 2 and still being able to support the jamming antenna introduced in Mission 3. To meet these requirements, a high-lift airfoil was desired. However, with limited manufacturing abilities, the airfoil type was restricted in complexity. Based on the flight profile, including speed, altitude, Reynolds number, and faculty recommendation, the PSU94-097 depicted in Figure 4.1 was chosen as the airfoil for the aircraft.

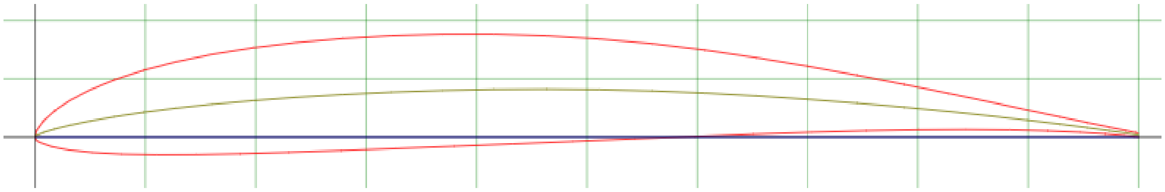


**Figure 4.1.** PSU94-097 Airfoil Shape [5]

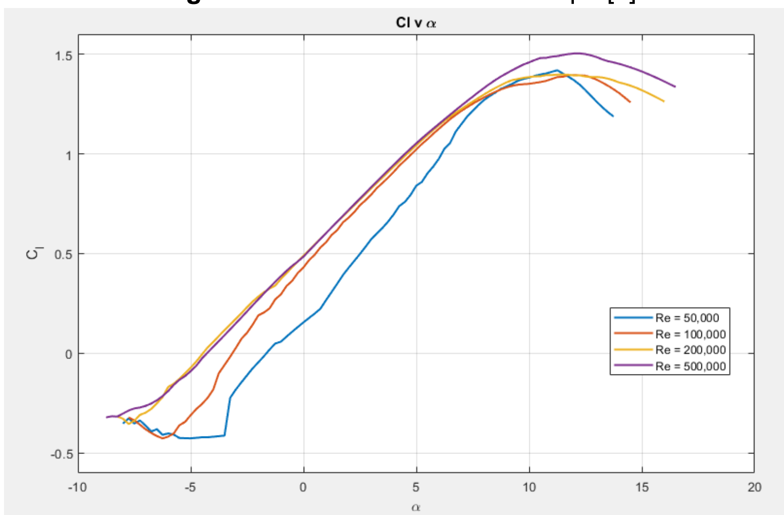



**Figure 4.2.** $C_l$ vs. α for the PSU94-097 [5]

The selected airfoil has a high maximum lift coefficient ($C_{l,max}$ = 1.4), as seen in Figure 4.2, which is necessary to execute the 60 ft takeoff distance with a maximum payload. The high lift combined with feasible manufacturability made the PSU94-097 the optimal choice for the given mission requirements.

### 4.2.2 Wing Sizing

After selecting the PSU94-097 airfoil, the size and taper ratio of the wing had to be determined. These were critical factors in ensuring multiple mission requirements were met - most importantly, the 60 ft takeoff distance. The takeoff distance is inversely related to the size of the wings; thus, the size of the wing was maximized using the sensitivity analysis discussed in Section 3.4. Additionally, a wing with no taper was selected for ease of manufacturability. The selected dimensions are shown in Table 4.1 below.

**Table 4.1.** Wing Dimensions

| | |
|---|---|
| **Wingspan** | 4.58 ft |
| **$C_t$** | 1.67 ft |
| **$C_r$** | 1.67 ft |
| **S** | 7.64 $ft^2$ |
| **AR** | 2.75 |

### 4.2.3 Fuselage Sizing

The fuselage was designed to minimize unnecessary weight and drag while still being structurally sound. Additionally, great attention was given to ensuring a secure connection between the wing and tail, given they are detachable to fit within the airline compliant box. Since the aircraft has large wings, the fuselage needed to be long enough to accommodate the 1.67 ft wing chord (C). A blended wing-body design was adopted to further reduce the drag caused by a boxy fuselage and increase aerodynamic efficiency. This changes the upper portion of the fuselage to have smooth contours that mesh seamlessly with the wings and fuselage. Mission 3 requirements also proved to be an important factor in the fuselage design. To eliminate the effects of a shifting CG caused by an increase in payload, the fuselage was designed to accommodate the payload box in a position that is located at the unloaded CG. With all of these design considerations, a package-conscious fuselage with a tapered tail shape was adopted. This design presents a thicker, boxlike mid-section with decreasing thickness towards the nose and tail.

### 4.2.4 Vertical Tail

The vertical tail design was a critical component of Mission 3. To counteract the yaw induced by the antenna in Mission 3, considerable effort was put into finding a solution that would maximize antenna height while minimizing drag. It was determined that an oversized vertical tail, capable of pivoting about its aerodynamic center, was the optimal solution in contrast to a conventional tail rudder. During preliminary calculations, it was determined that the conventional tail with rudder design required a considerable increase in size to offset relatively small changes in antenna height. A 50% deflection limit was used to counteract antenna yaw and allow additional control authority throughout the flight. In comparison, the ability to pivot the entire vertical tail allowed for smaller deflection angles that could counteract the yawing moment generated by longer antenna lengths. Additionally, using an actuating vertical tail required a shorter distance from the airplane's CG to the vertical tail's center of lift. This reduction in the distance directly affects the total fuselage surface area, reducing total skin friction drag. A NACA 0009 airfoil was used to improve drag characteristics and reduce flow separation compared to a standard balsa buildup design

### 4.2.5 Propulsion

Using manufacturer suggestions and general knowledge about mission requirements, two motors were considered. The LiPo battery selection was straightforward due to the 100 Wh constraint imposed by the AIAA for the DBF competition. The Thunder Power RC TP300-8sE55 3300 mAh 29.6 V 8s LiPo battery was chosen and tested with the Scorpion SII-4025-300kV motor while the Thunder Power RC TP4400-6sE55 4400 mAh 22.2V 6s LiPo battery was chosen and tested with the SII-4025-330 kV and E-flite Power 60 motors. The tests were conducted on a test stand consisting of an Arduino and a 10 kg load cell attached to a mount that held the motor. The following motors and their corresponding specifications can be seen in Table 4.2 below.

**Table 4.2.** Tested Motor/Battery Specifications

| Motor/Battery | | |
|---|---|---|
| | **E-flite Power 60** | **Scorpion SII-4025-330 kV** |
| **Max Power (W)** | 1800 | 2000 |
| **Battery Name** | Thunder Power RC TP4400-6sE55 | Thunder Power RC TP300-8sE55 |
| **Voltage (V)** | 22.2 | 29.6 |

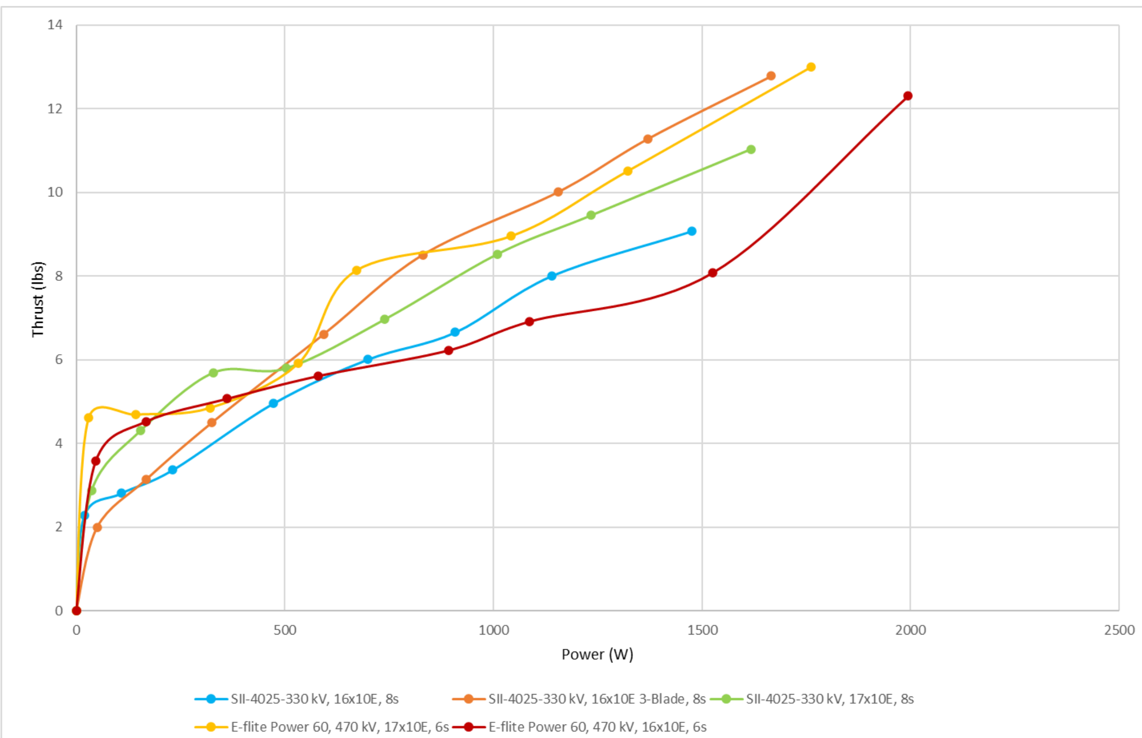



**Figure 4.3.** Power vs Thrust for E-flite Power 60 and Scorpion SII-4025-330 kV

From Figure 4.3, the maximum thrust for the Scorpion motor was 12.79 lbs at 1666 W with the 16x10E 3-blade propeller. The maximum thrust of the E-flite Power 60 motor was found to be approximately 13.01 lbs of thrust at 1761 W with a 17x10E propeller. This test proved that the E-flite Power 60 could produce slightly more thrust but the power needed would exceed the manufacturer's recommended limits. To stay within the manufacturer's power and amperage limits, a smaller propeller would be needed at the expense of thrust. For this reason, the Scorpion SII-4025-330 kV motor was determined to be the optimal motor choice. From the testing performed, the Scorpion SII-4025-330 kV motor best suited the mission requirements. Once the motor was chosen, different propeller configurations were tested. Using the same methodology as the motor testing, power vs. thrust was plotted with propellers measuring 16x8E, 16X10E, 17X10E, and 18x12E, and the results are shown below in Figure 4.4.

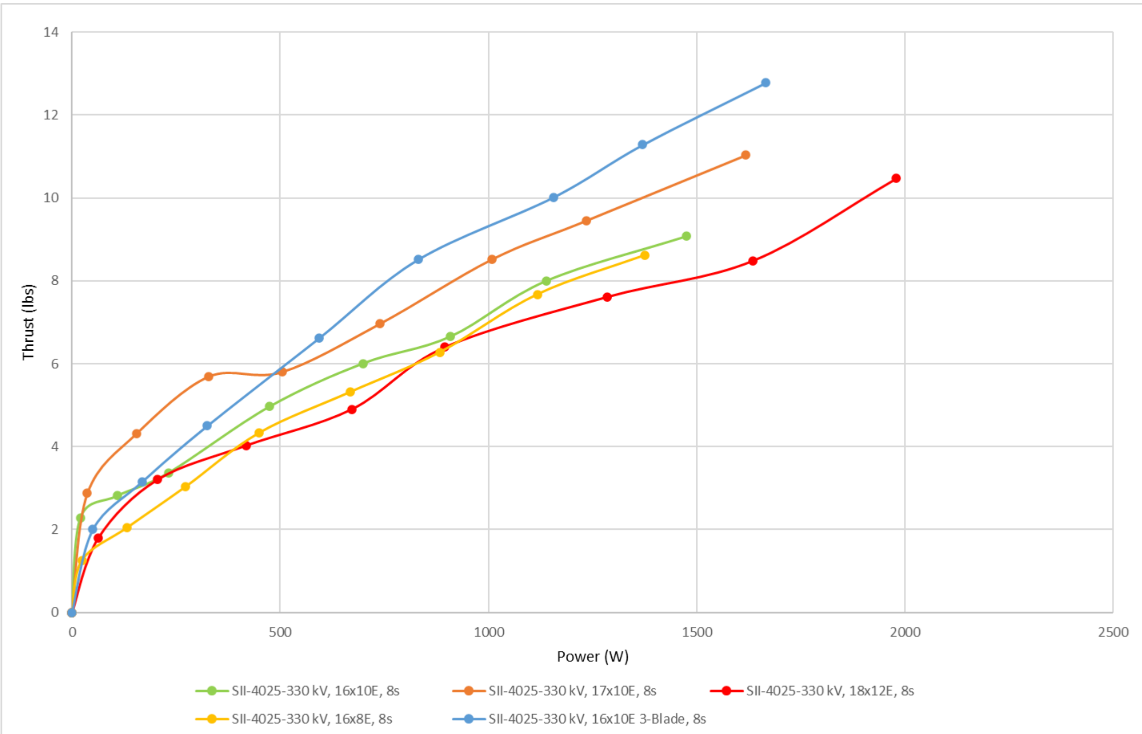



**Figure 4.4.** Power vs Thrust for SII-4025-330 kV with 16x8E, 16x10E, 17x10E, and 18x12E Propellers

It was observed that the larger and heavier propellers generally provided more static thrust given the low motor kV. From the graphs, the thrust and wattage for each propeller were pulled to compare performance, as seen in Table 4.2. From both Figure 4.4 and Table 4.3, the 16x10E 3-blade propeller produced the most thrust. However, the 17x10E produced a similar amount of thrust and is a more efficient propeller in real-world flight conditions.

**Table 4.3.** Maximum Static Thrust and Power Required Based on Propeller Size

| Propeller | Thrust (lbs) | Power (W) |
|---|---|---|
| 16x8E | 8.62 | 1375.90 |
| 16x10E | 9.08 | 1475.20 |
| 16x10E 3-Blade | 12.79 | 1666.60 |
| 17x10E | 11.03 | 1618.80 |
| 18x12E | 10.47 | 1979.60 |

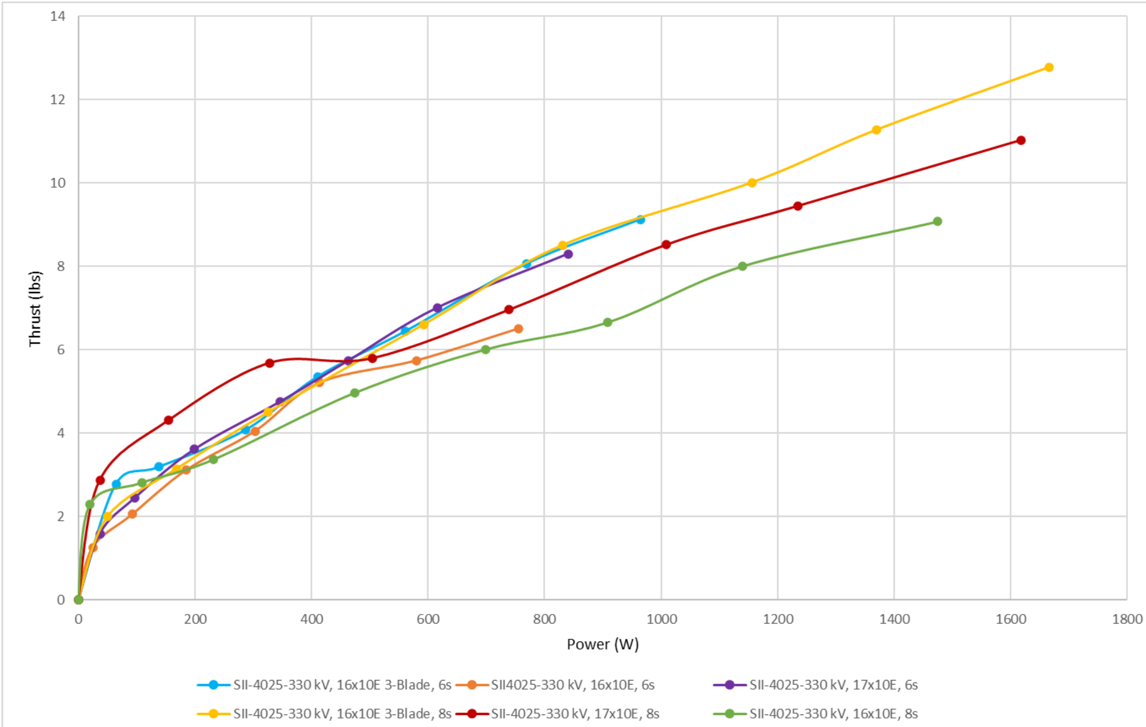



**Figure 4.5.** Power vs Thrust of Scorpion SII-4025-330 kV with 6s and 8s batteries

It was found that using the SII-4025-330 kV with the Thunder Power RC TP3300-8sE55 yielded significant static thrust increases when compared to the Thunder Power Power RC TP4400-6sE55 and validated the choice to use an 8s battery. Based on these tests, the propulsion system chosen was the Scorpion SII-4025-330 kV motor with APC 17x10E propeller powered by Thunder Power RC TP3300-8sE55 (97.68 Wh) battery and controlled by a Spektrum Avian 120 A ESC.

## 4.3 Performance Prediction Methodology

The aircraft's preliminary performance characteristics were predicted with a MATLAB-based airplane flight performance calculator. Table 4.4, as seen below, included two of the more important performance predictions; maximum lift to drag ratio and cruise speed. As it pertains to most aircraft, flying at the maximum lift to drag ratio is ideal as it increases range. However, given the nature of the competition and missions, flying as fast as possible was seen to be more important than flying at the max range condition.

**Table 4.4.** Performance Parameters for Preliminary Design

| Performance Parameter | $C_{L_{max}}$ | $C_{L_{cruise}}$ | $C_{D_{cruise}}$ | $\frac{L}{D}_{max}$ | $\frac{W}{S}$ | $V_{cruise}$ (ft/s) | $V_{stall}$ (ft/s) | Gross Weight (lb) | Mission Score |
|---|---|---|---|---|---|---|---|---|---|
| **Mission 1** | 1.41 | 0.06 | 0.03 | 7.36 | 1.21 | 151 | 30.50 | 9.21 | 1.00 |
| **Mission 2** | 1.41 | 0.13 | 0.03 | 7.36 | 2.75 | 149.2 | 46.07 | 21.01 | 1.79 |
| **Mission 3** | 1.41 | 0.08 | 0.05 | 5.67 | 1.25 | 133.5 | 31.01 | 9.52 | 2.87 |

## 4.4 Drag, Lift, & Stability

### 4.4.1 Drag Analysis

The drag analysis of the aircraft entailed utilizing the predicted cruise speeds in accordance with the calculated drag coefficients on a per mission basis using MATLAB. These values for each mission were then plugged into Eq. 6 represented below.

$$D = \frac{1}{2}\rho V^2 S C_D \qquad \text{Eq. 6}$$

Table 4.5 presents the results of the drag prediction analysis for each mission. As seen in the table, Mission 3 produced the greatest drag due to the mission incurring the added drag of the jamming antenna. The data showed that the aircraft must overcome an estimated 6.26 lbs of total drag to complete each of the three missions successfully and that the moment correction method must account for roughly an additional 1.5 lbs of drag more than the base configuration of the aircraft.

**Table 4.5** Speed, Drag, and Drag Coefficient for Missions 1, 2, and 3

| Mission | Estimated Speed (ft/s) | $C_D$ | Drag (lbs) |
|---|---|---|---|
| 1 | 151 | 0.03 | 4.81 |
| 2 | 149.2 | 0.03 | 4.69 |
| 3 | 133.5 | 0.05 | 6.26 |

### 4.4.2 Lift Analysis

To estimate the lift on the aircraft, Eq. 7 was used.

$$L = \frac{1}{2}\rho V^2 S C_L \text{ , Where } L = W \text{ in } SLF \qquad \text{Eq. 7}$$

A MATLAB script file was written to find the optimal range of flight speeds for each mission. This was accomplished by calculating the lift coefficient at different speeds assuming steady level flight where the lifting force is equal to the weight. The drag polar equation was then utilized in a MATLAB script to calculate the drag coefficient for the given vehicle configuration based on the lift coefficient at each speed. The lift coefficients were then divided by the drag coefficients over a variety of speeds ranging from 0 to 225 ft/s. These calculations were repeated for all three missions to account for the difference in weights and antenna drag between missions. The L/D ratios for each mission are shown below in figure 4.6.

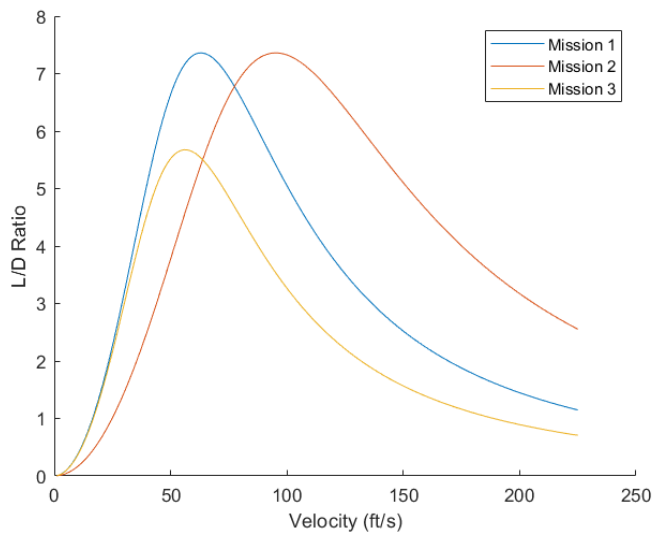



**Figure 4.6** - Lift to Drag Ratio for Various Flight Speeds

Due to the vehicle's weight changing greatly for Mission 2, different flight speeds are required for each mission to maximize the L/D ratio. For Mission 1 and Mission 3, the weight changed very slightly but the drag coefficient changed due to the incurred drag of the jamming antenna. This caused the ideal flight speed to decrease from Mission 1 to Mission 3 and the maximum L/D ratio to decrease considerably. For Mission 1 the predicted optimal flight speed range for the maximum L/D ratio was roughly 50 to 75 ft/s with the maximum value occurring at 60 ft/s. Mission 2 had a much higher weight for the total aircraft configuration and thus required a higher speed to achieve the maximum L/D ratio of the aircraft. Mission 2 predicted the optimal flight speed range was roughly 80 to 130 ft/s with the maximum value of the L/D ratio occurring at 100 ft/s. Mission 3 predicted an optimal flight speed of 40 to 75 ft/s with a maximum L/D ratio at 55 ft/s. However, due to speed being of greater importance, flying at the maximum L/D ratio would limit competition performance. Therefore, the team decided to fly as fast as possible at the expense of maximum L/D ratio.

### 4.4.3 Stability Analysis

The stability analysis of the aircraft entailed ensuring static stability of the vehicle in flight. In accordance with general aviation requirements, a static margin of at least five percent was met. Keeping the static margin within these requirements was theoretically simple due to the nature of the flight missions. Throughout the construction process of the aircraft, a CG calculator was used to determine where the CG would be when the vehicle was completely put together in Mission 1 configuration. Due to the slight amount of weight added for Mission 3, the CG of the vehicle was able to remain at least five percent in front of the neutral point. In order to keep this static margin for Mission 2, the package was placed in the vehicle directly below the original CG. This allowed for static stability of the aircraft in all three mission configurations.

### 4.5 Mission Performance Estimates

The vital parameters used to maximize the scores of each mission were determined by the sensitivity analysis discussed in Section 3.3. Before the analysis could be performed, the team discussed the rules established by AIAA, paying special attention to the mission statements and scoring rubric. The propulsion team then began a series of tests to determine the thrust produced by the motors. These results were used to select a motor/battery combination based on availability and the thrust requirements estimated by the optimization code. Mission 2 was the limiting case given the gross vehicle weight will be at a maximum, requiring the most thrust and highest takeoff speed. The estimated mission scores were found assuming maximum scores for the "best" team for each mission using thrust test data, assumptions of successful flight missions, and scoring analysis routines. It should be noted that these maximum scores were predicted to occur from different competition teams. This allowed for the acceptance that certain competition teams would optimize missions they assumed to be the most achievable. This allowed the UTK DBF team to predict scoring outputs with reasonable normalization factors, allowing for high competition scores without assuming the team would place first in every mission. These estimations were based on the intermediate and composite scoring outputs of the generated MATLAB routines using the previously optimized vehicle parameters as inputs.

For Mission 2, it was assumed that a team could build a plane with the thrust capacity to takeoff in the 60 ft distance constraint, incur wing loading during flight path turns, and land with a maximum theoretical package weight of 11.80 lbs. In order to remain within the takeoff distance on flight day, the optimization team recommended a maximum declared package weight of 10 to 11 lbs. Based on the results yielded, this package weight will be further tuned during flight testing. For Mission 3, it was determined that a team could successfully fly with a 22 in tall jamming antenna while still maintaining stability. The preliminary stability analysis, however, was primarily focused on finding a method to counteract a basic, drag inducing structure. This method would later be improved to lengthen the antenna used in Mission 3 and, as a result, increase Mission 3 scoring. Moreover, the optimization and coding team will further research modeling the likely 2 dimensional moment produced in the yaw and pitch axes by flying with a 22 in antenna. The modeling will be compared to flight test results of visible pitching moments. The pitching moment caused by the antenna's extension above the surface of the plane will further strain the elevators and their servo motors. This aircraft is intended to integrate design choices that allow for successful flight during all three missions (i.e., Ground Mission, Mission 2, and Mission 3). However, as typical with RC aircraft, construction methods introduce many errors to the theoretical baseline which could cause instability. Therefore, to build functionality into the scoring estimates, the optimization team included the use of a 90% theoretical maximum buffer on the predicted mission scores for Missions 2 and 3. Due to time affecting Missions 2 and 3 scoring, this implemented buffer allows for the pilot to make mission saving maneuvers at the expense of time. The predicted scores reported in Table 4.6 represent 90% of the maximum predicted scoring values to account for the pilot having to make costly maneuvers.

**Table 4.6.** Predicted Mission Scores

| Mission | 1 | 2 | 3 |
|---|---|---|---|
| **Theoretical Score** | 1.00 | 1.79 | 2.87 |
| **Actual Predicted Score** | 1.00 | 1.61 | 2.58 |

## 5 Detailed Design

While the preliminary design was a good starting point, there were many improvements to be made in the detailed design phase. Flight testing of the prototype showed that the 60 ft takeoff distance was reasonable; however, there were some minor, but notable issues during the first set of flight tests. These issues included stability, landing gear rigidity, and large amounts of drag. The large amount of drag was observed specifically near the nose of the plane and the location where the trailing edge of the wing met the fuselage. Therefore, increasing the torsional resistance of the vertical tail, improving the strength of the landing gear, blending the wing with the fuselage, and creating an aerodynamic fairing for the engine were prioritized in the transition between the preliminary design and detailed design.

### 5.1 Dimensional Parameters

**Table 5.1a.** Dimensional Parameters

| Wing | | Motor | |
|---|---|---|---|
| **Airfoil** | PSU 94-097 | **Model** | Scorpion SII-4025-330 kV |
| **Span** | 4.58 ft | **Effective kV** | 330 |
| ***MAC*** | 1.67 ft | **Power Rating** | 2000 W |
| **Planform Area** | 7.64 ft² | **No-Load Current ($I_0$)** | 1.71 A |
| ***AR*** | 2.75 | **Internal Resistance** | 0.03 Ω |
| **Incidence Angle** | -2° | **Weight** | 0.96 lb |
| **Static Margin** | 10.9% | | |

**Table 5.1b.** Dimensional Parameters

| Tail | | Control | |
|---|---|---|---|
| **Horizontal Span** | 1.90 ft | **Receiver** | NX10 10-Channel DSMX |
| **Horizontal Chord** | 0.75 ft | **Battery Model** | Thunder Power RC TP300-8sE55 |
| **Horizontal Tail Planform Area** | 1.36 ft² | **Cell Count** | 8s |
| **Incidence Angle** | 0° | **Pack Voltage** | 29.6 V |
| **Vertical Chord** | 1.00 ft | **Pack Weight** | 1.49 lb |
| **Vertical Tail Height** | 1.17 | | |
| **Vertical Tail Planform Area** | 1.17 ft² | | |
| **Fuselage** | | | |
| **Total Length** | 4.89 ft | **Nose Length** | 0.67 ft |
| **Tail Length** | 1.38 ft | **Width** | 0.33 ft |

### 5.2 Structural Characteristics/Capabilities

When designing the aircraft, consideration was given to the weight, manufacturing complexity, material strength, and mission performance. In the following sections, the materials used will be justified through finite element analysis (FEA) and practical testing of critical, load-bearing components concerning loading possible on the ground and in flight.

#### 5.2.1 Fuselage

The design of the fuselage required a significant amount of consideration as all other critical components of the aircraft are interfaced with it. The fuselage is a monocoque construction consisting of 3K plain weave carbon fiber and West Systems epoxy resin formed around a removable plug. This construction method created a rigid shell and required minimal internal structure, allowing for a compact frame to contain the electronics package that still meets the dimensional requirements. To reduce the form drag at the rear of the fuselage, the fuselage and wings blend together near the wing's trailing edge.

#### 5.2.2 Wings

The wings were constructed from an extruded polystyrene (XPS) foam core cut to shape with a hotwire cutter. A single ply of 3K plain weave carbon fiber was adhered with West Systems epoxy resin to the wing cores. The main spar, a 0.75 in carbon fiber tube located at the quarter chord, bears most of the structural loading transmitted from each wing. The FEA performed on the wing spar shows almost negligible deflection of 0.08 in steady, level flight in the heaviest configuration. Figure 5.1 shows a deflection of 0.46 in that would occur if the aircraft experienced a load factor of 5 in its heaviest configuration.

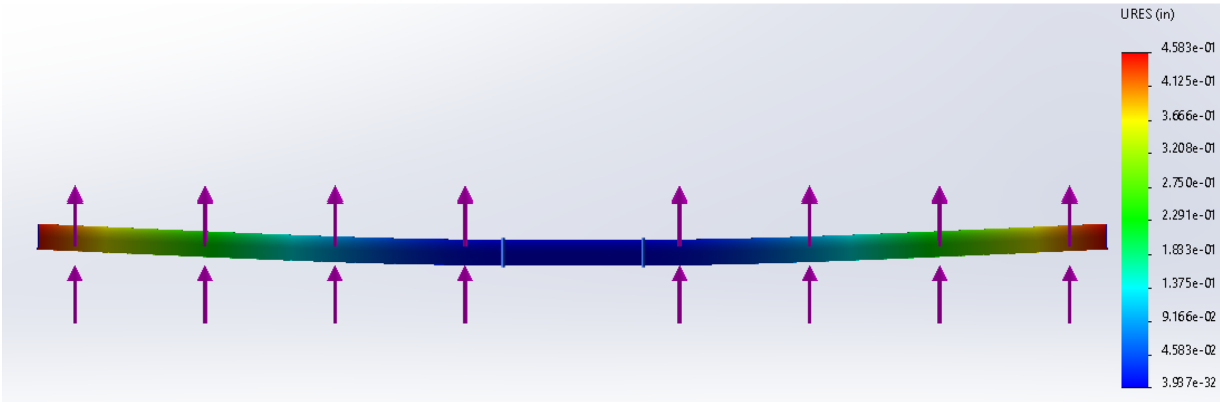



**Figure 5.1.** Wing Spar Displacement Under Maximum Loading Conditions

The main spar interfaced with the fuselage through the use of a matched fiberglass sleeve bonded to the fuselage in order to distribute loading. Alignment pins are located near the leading and trailing edge of the wing's root to ensure proper alignment as well as support against torsional loads caused by the aerodynamics of the wing. The wings are secured by a retention bolt located near the center of each wing's root.

### 5.2.3 Empennage

The tail section was constructed from XPS sheeting and then laminated in MonoKote. As the vertical stabilizer moves as a single unit in lieu of a rudder, plywood ribs are placed at the root and mid-span to provide additional support. These ribs distribute loads from the tail to the spar and allow for AOA control by way of rotating the spar. The stationary portion of the horizontal tail is held in place by a tab and slot system with a single retention bolt to reduce the aft weight of additional metal fasteners. To support the loading, the tail section spars run through a 0.75 in carbon fiber tube that protrudes from the rear of the fuselage. Electronics and retention collars are mounted within an aerodynamic

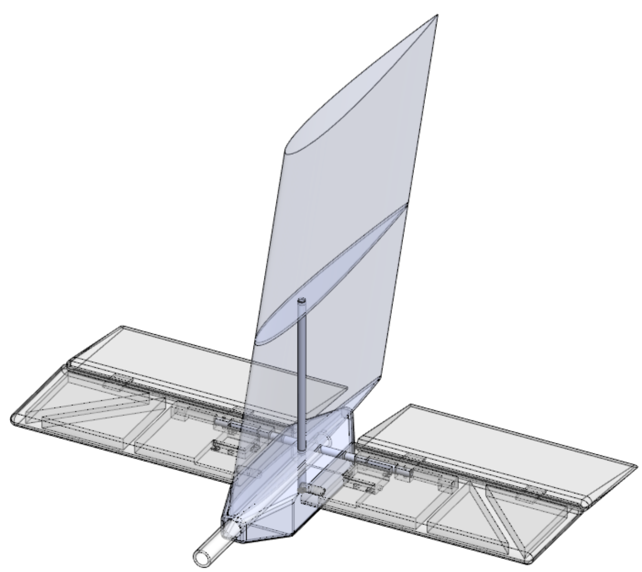


**Figure 5.2.** Tail Internal Structure

housing that is constructed from a single ply of 3K plain weave carbon fiber and West Systems epoxy resin.

### 5.2.4 Landing Gear

The design of the main landing gear required the consideration of several variables such as the propeller diameter, fuselage sizing, electronics package weight, Mission 3 ground stability, and CG of the aircraft. Taking these factors into consideration, the main landing gear was constructed using multiple layers of unidirectional and plain weave carbon fiber. The layers of unidirectional weave, oriented perpendicular to the aircraft centerline, provide tensile strength to resist outward stretch. The additional layers of 3K plain weave carbon fiber provide moderate isotropic tensile strength. By implementing carbon fiber in the component structure, the aircraft's overall weight was reduced and a more aerodynamic form was achieved. The landing gear will be mounted to the bottom of the fuselage under the location of the electronics package in order to support as much weight as possible during takeoff and landing. Due to the complex material makeup, the landing gear was practically tested by incrementally applying weight up to a maximum of 45 lbs, which resulted in a maximum deflection of 0.59 in. This condition simulates the force of an impulse of 30 lbs on landing.

### 5.2.5 Electronics Package and Retention System

The electronics package has a modular weighting system to save overall weight in the component box. The modular weight system consists of removable weights that can slot into receptacles symmetrically placed around the CG. Eye bolts with a 0.75 in inside diameter were used to assist the fuselage in supporting the cargo. As the eye bolts are part of the package itself, the weight of this attachment method was not considered. The retention system is not designed to carry 100% of the weight of the electronics package but will prevent the fuselage from bowing or breaking during high-g maneuvers. Figure 5.3 shows a 5 g loading condition with a max weight payload installed. The deflection of the electronics package will be negligible and is not expected to affect the fuselage negatively.

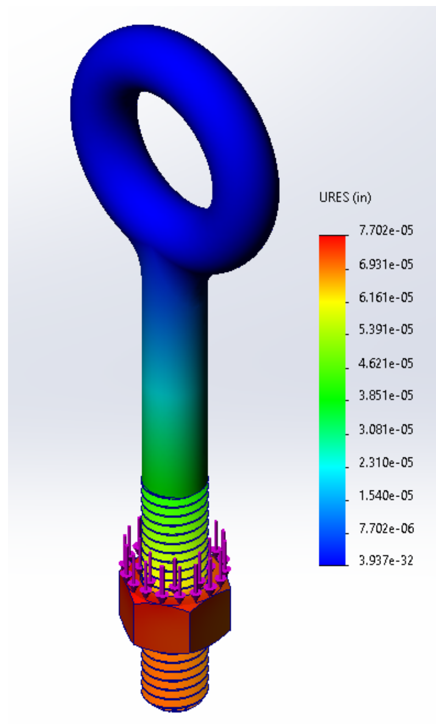



**Figure 5.3.** Displacement Analysis on Eye Bolt for Maximum Loading Conditions

### 5.2.6 Jamming Antenna Mounting System

During Mission 3, the weight of the components is less pertinent, for the aircraft is relatively close to an unweighted flight condition. The jamming antenna mounting bracket was not required to carry large loads and was thus 3D-printed from PLA. The bracket has countersunk bolt holes to reduce the drag caused by the fasteners that attach to the hard point contained in the wing. The hard points consist of 11 in long arrow shafts with the factory threads still intact. These arrow shafts are epoxied into the wings to assist in distributing the load away from the wing tip. Due to the anisotropic properties of 3D-printed objects caused by infill patterns and layer lines, the bracket was stress tested manually using a piece of 0.5 in Schedule 40 PVC pipe and a handheld spring scale. This manual testing revealed that the bracket could withstand approximately 40 ft-lbs of torque before failure. This is well above the expected load, so adjustments may be made to create a more weight-conscious design. The counterweight will consist of a similarly shaped component that has been weighted with lead shot.

#### 5.2.7 Capabilities

The aircraft is projected to fly missions at speeds between 133 ft/s and 151 ft/s. Structural analysis validates the design at the 5 g structural limit. The V-n diagram, Figure 5.4, shows the maximum possible stall limit, load factor against airspeed, and maximum allowable load factor. The Mission 1 cornering speed was found to be 72 ft/s and the maximum SLF speed was calculated at 160 ft/s. The never exceed speed was calculated at 172 ft/s. Flight within these limits will not lead to structural damage or aerodynamic flutter.

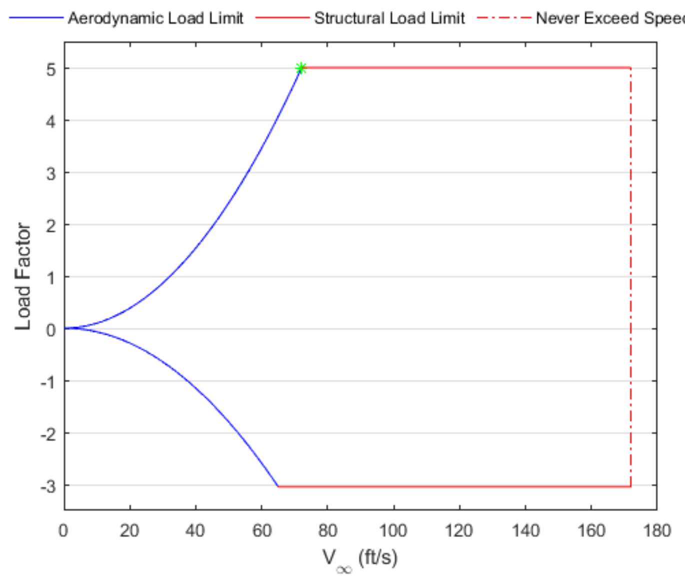



**Figure 5.4.** Load Factor vs Velocity

### 5.3 Systems and Subsystems Selection, Integration, & Architecture

#### 5.3.1 Propulsion

The propulsion system components outlined in Table 5.2 were selected to maximize available power and low speed thrust to achieve reliable takeoffs under 60 ft. The Thunder Power RC 8s 3300 mAh Elite Series LiPo measures in at 97.68 Wh, or just below the 100 Wh limit, and is rated for 181.5 A of continuous current. A higher voltage was targeted to decrease amperage draw for a given power setting for improved efficiency. The combination of the Scorpion SII-4025-330 kV motor and APC 17x10E propeller was selected to maximize static thrust for maximum takeoff performance and is within the manufacturer's recommended range. The manufacturer rates the maximum current draw of the motor at 75 A, which is well below the 120 A rating of the high voltage Spektrum Avian 120 A ESC selected. Additionally, a safety disconnect is wired in line with the flight battery and is accessible from the exterior of the aircraft.

**Table 5.2.** Major Propulsion System Components

| Component | Component Selection |
|---|---|
| **Motor** | Scorpion SII-4025-330 kV |
| **ESC** | Spektrum Avian 120 A ESC |
| **Battery** | Thunder Power RC 8s 3300 mAh 55C LiPo |
| **Propeller** | APC 17x10E |

### 5.3.2 Servos

The control surfaces are articulated by a combination of high voltage, mini, and standard size servos. The servos used are commonly found on model aircraft of the same scale and are known to be reliable with exceptional performance. Table 5.3 outlines the servo models used for each control surface.

**Table 5.3.** Servo Selections

| Control Surface | Component Selection |
|---|---|
| **Ailerons (2x)** | Bluebird BMS A920 (190 oz-in Torque @ 7.4 V) |
| **Elevators (2x)** | KST X10 (132 oz-in Torque @ 7.4 V) |
| **Vertical Stabilizer / Tail Wheel** | Bluebird BMS A920 (190 oz-in Torque @ 7.4 V) |

### 5.3.3 Electronics System

The electronics system for this aircraft is centered around a Spektrum AR10400T receiver coupled with a Spektrum NX10 transmitter. With the addition of a Spektrum Avian ESC, the remaining charge of the flight battery may be monitored through live telemetry data sent to the transmitter during endurance-based missions. Figure 5.5 shows critical interactions between all onboard electronics.

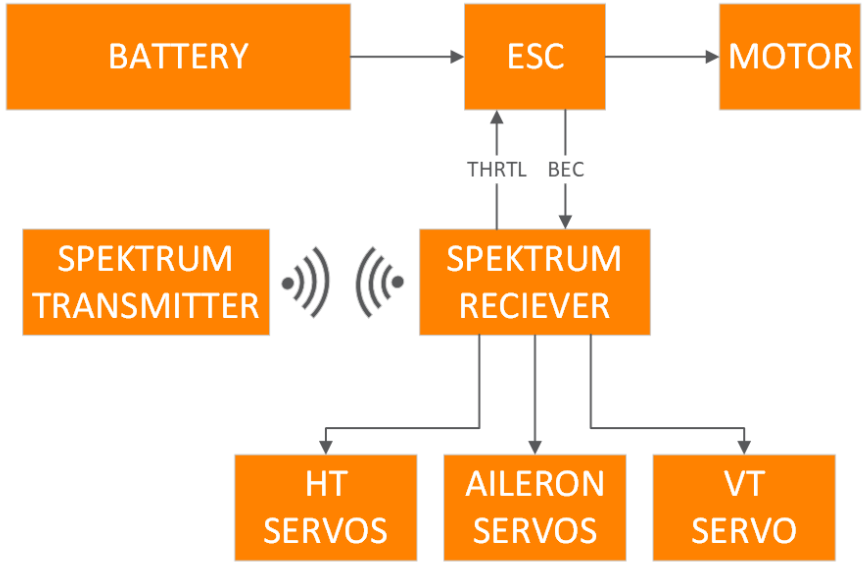



**Figure 5.5.** Electronics System Diagram

## 5.4 Weight and Balance

It is critical that the proper CG is maintained for aircraft stability. The CAD model was used to estimate the weight of individual flight components and then confirmed with physical prototype parts thereafter. The weight of critical components is described in Table 5.4 along with their respective locations from the firewall.

**Table 5.4a.** Weight and Balance

| Part | Weight (lb) | Distance from FW (in) | Effective Moment (in-lb) |
|---|---|---|---|
| Wings | 3.26 | 18.50 | 60.36 |
| Fuselage | 0.79 | 12.50 | 9.92 |
| Landing Gear | 0.45 | 8.50 | 3.80 |
| Battery | 1.44 | 3.00 | 4.32 |
| ESC | 0.49 | 4.50 | 2.18 |
| Motor | 0.98 | -1.38 | -1.35 |
| Receiver | 0.12 | 4.75 | 0.58 |
| Battery (Receiver) | 0.18 | 3.00 | 0.53 |
| Tail Spar | 0.22 | 26.50 | 5.83 |

**Table 5.4b.** Weight and Balance

| Part | Weight (lb) | Distance from FW (in) | Effective Moment (in-lb) |
|---|---|---|---|
| Vertical Tail | 0.34 | 46.46 | 15.67 |
| Horizontal Tail (with Servos) | 0.46 | 43.00 | 19.62 |
| Tail Box | 0.23 | 42.50 | 9.93 |
| Spar Joiner | 0.08 | 15.00 | 1.16 |
| Main Spar | 0.13 | 14.25 | 1.88 |
| Motor Mount | 0.04 | 0.05 | 0.00 |
| **Center of Gravity** | 9.21 | 14.60 | 134.44 |

### 5.5 Flight Performance Parameters

Given the component weights from Table 5.4 and sizing of parameters determined in the sensitivity analysis, preliminary performance parameters were able to be obtained. The values shown in Table 5.5 display the estimated flight performance. These numbers were determined by compiling and analyzing flight test data in conjunction with known performance estimates based on a MATLAB script.

**Table 5.5.** Mission-Based Performance Parameters

| Performance Parameters | $C_{L,Max}$ | $C_{L,cruise}$ | $(L/D)_{Max}$ | $(L/D)_{cruise}$ | W/S ($lbs/ft^2$) | $V_{Cruise}$ (ft/s) | $V_{Stall}$ (ft/s) | Weight (lbs) |
|---|---|---|---|---|---|---|---|---|
| **Mission 1** | 1.41 | 0.06 | 7.36 | 2.00 | 1.21 | 151 | 30.5 | 9.21 |
| **Mission 2** | 1.41 | 0.13 | 7.36 | 4.33 | 3.62 | 149 | 46.1 | 21.0 |
| **Mission 3** | 1.41 | 0.08 | 5.67 | 1.60 | 1.25 | 134 | 31.0 | 9.52 |

### 5.6 Mission Performance

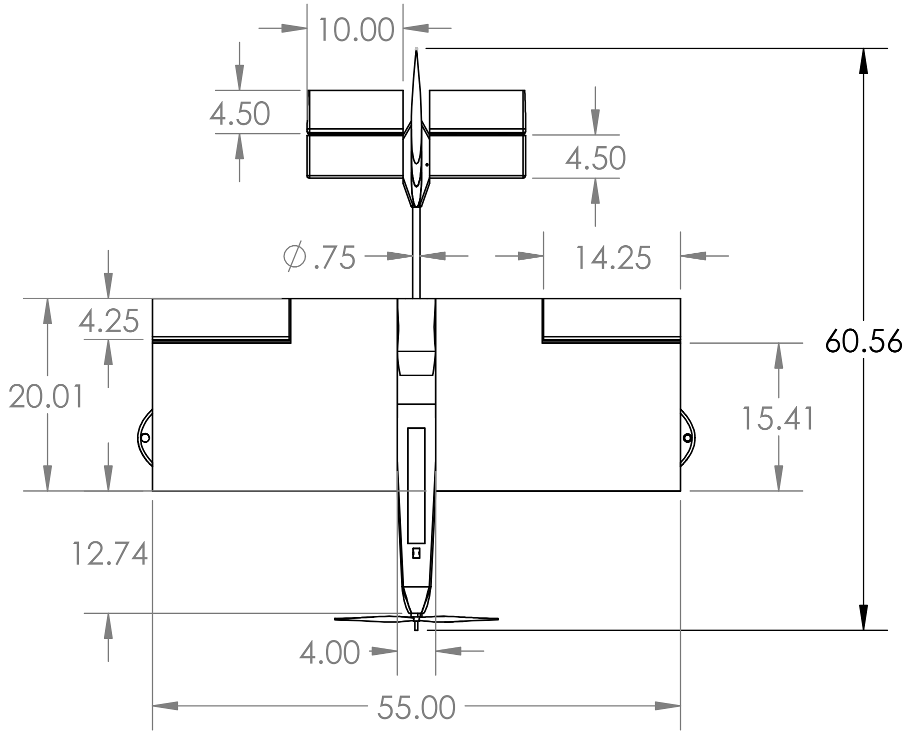
Mission performance was predicted by analyzing a combination of flight test data, ground test data, and simulated data. Table 5.6 displays the estimated mission performance for each mission assuming a maximum overall score of 1.61 on M2 and a maximum overall score of 2.58 on M3. These performance estimates were based on the previously reported 90% theoretical maximum predicted scoring values for the aircraft. This allows the pilot a buffer for mission saving maneuvers that would be costly in time. The Ground Mission scoring estimate was based on an addition of 20 lbs to the team's estimated fully loaded vehicle configuration. Assuming an added weight ratio of 3:1 to the maximum ground mission score during competition, the team predicted a Ground Mission score of 0.65.

**Table 5.6.** Expected Mission Performance

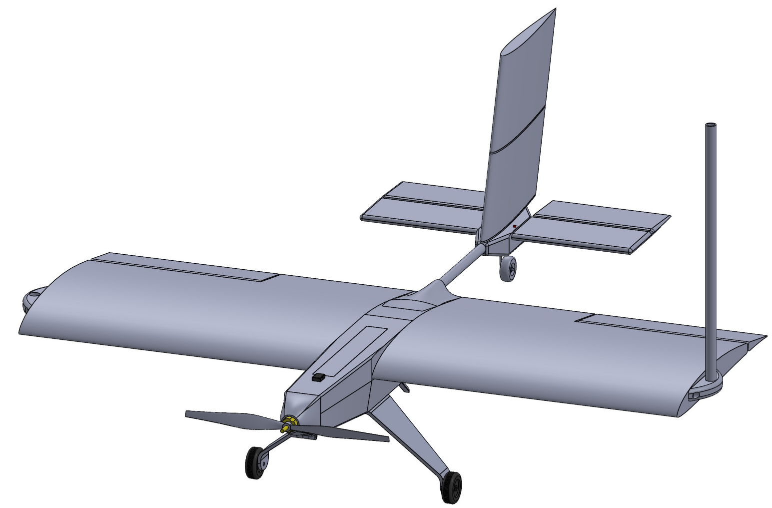
| Performance Parameter | Mission 1 | Mission 2 | Mission 3 | Ground Mission |
|---|---|---|---|---|
| **W (lbs)** | 9.21 | 21.01 | 9.52 | 41.01 |
| **Wing Loading (lbs/ft²)** | 1.21 | 2.75 | 1.25 | N/A |
| **Vstall (ft/s)** | 30.50 | 46.07 | 31.01 | N/A |
| **Vmax (ft/s)** | 151 | 149.2 | 133.5 | N/A |
| **Mission Score** | 1.00 | 1.61 | 2.58 | 0.65 |
| **Total Score** | 5.84 | | | |

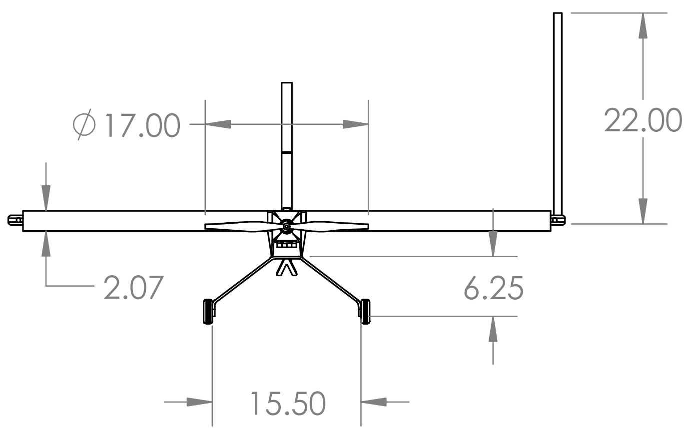
## 5.7 Drawing Package

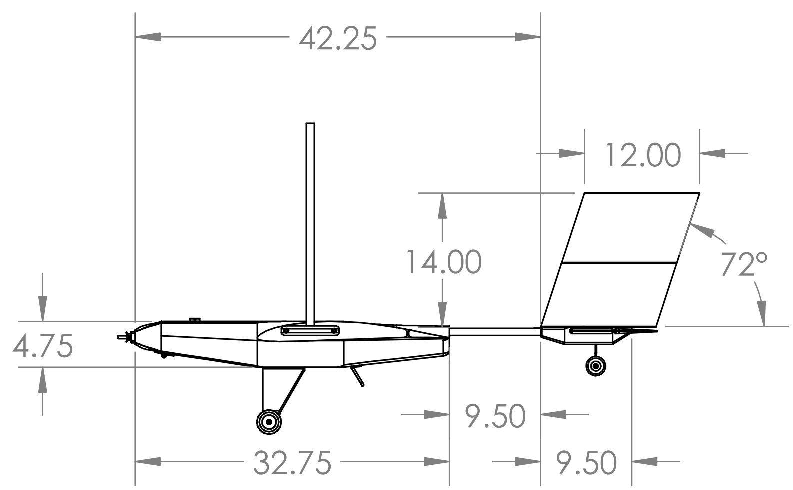
The next six pages contain the drawing package. This package contains a 3-view drawing of the finished plane, a drawing showing how the systems are arranged, a structural arrangement drawing, an electronics and payload drawing, and a drawing depicting the flight configuration for each of the three missions.




Dimetric View in 1:15 Scale

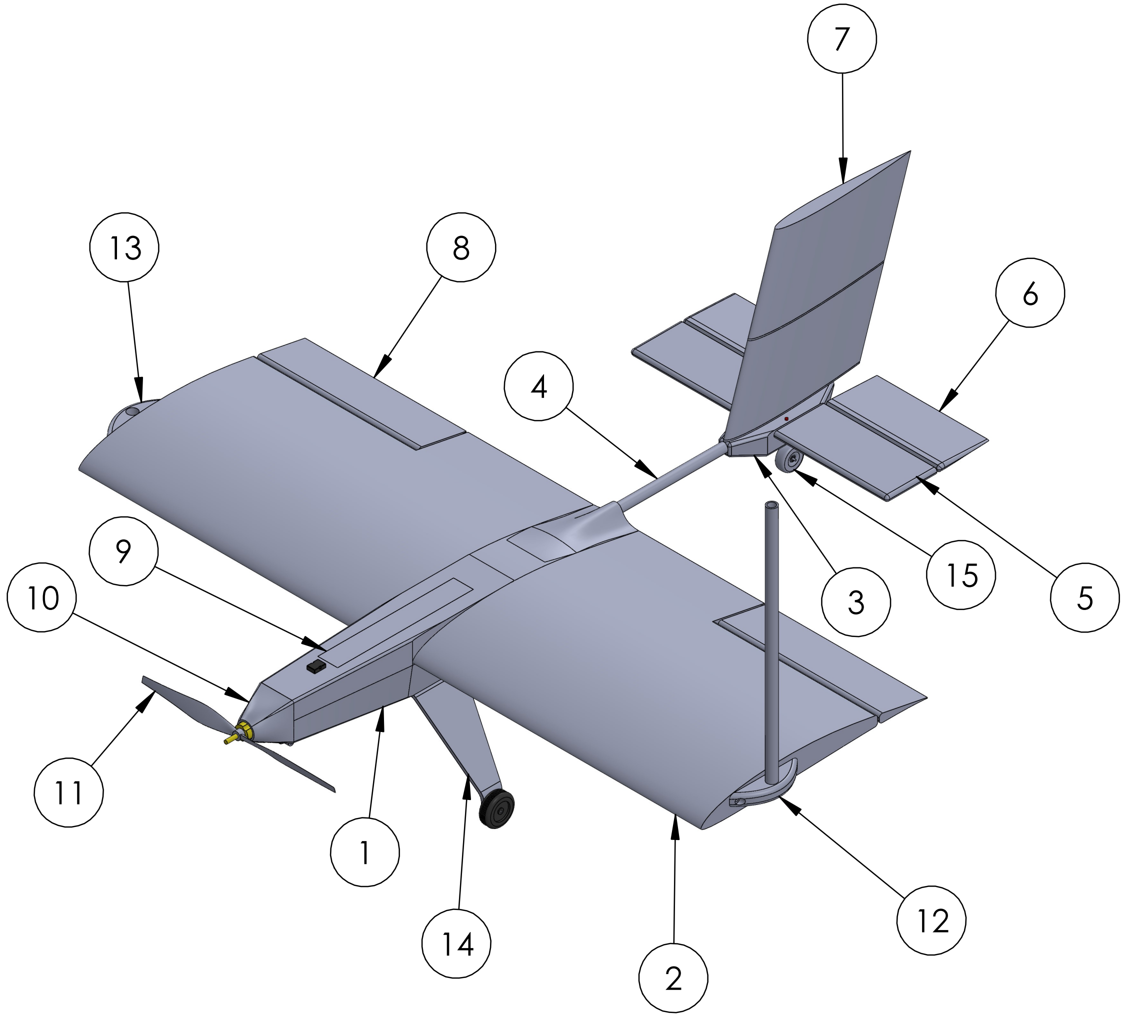





All Units in Inches & Degrees

| University of Tennessee - Knoxville DBF Team | | |
|---|---|---|
| SIZE A | DWG. NO. Overall Drawing | REV |
| SCALE: 1:20 | SHEET 1 OF 6 | |




| # | System Component | Material |
|---|---|---|
| 1 | Blended Wing Fuselage | 3K Plain Weave Carbon Fiber |
| 2 | PSU94-097 Wing | XPS Foam + 3K Plain Weave Carbon Fiber Wrap |
| 3 | Tailbox | 3K Plain Weave Carbon Fiber |
| 4 | Tail Spar | 3K Plain Weave Carbon Fiber |
| 5 | Horizontal Stablizer | Blasa Wood Build-Up and MonoKote Wrap |
| 6 | Elevator | Balsa Wood Build-Up and MonoKote Wrap |
| 7 | Vertical Stablizer | MonoKote Wrapped XPS Foam |
| 8 | Aileron | Foam + 3K Plain Weave Carbon Fiber |
| 9 | Access Hatch | 3K Plain Weave Carbon Fiber |
| 10 | Nose Cone | 3K Plain Weave Carbon Fiber |
| 11 | 17x10E Propellor | Nylon |
| 12 | Antenna Mount | PLA |
| 13 | Counter Weight | PLA |
| 14 | Main Gear | 3K Plain Weave & Unidirectional Carbon Fiber Mix |
| 15 | Tail Gear | Aluminum Shaft and Rubber Tire |

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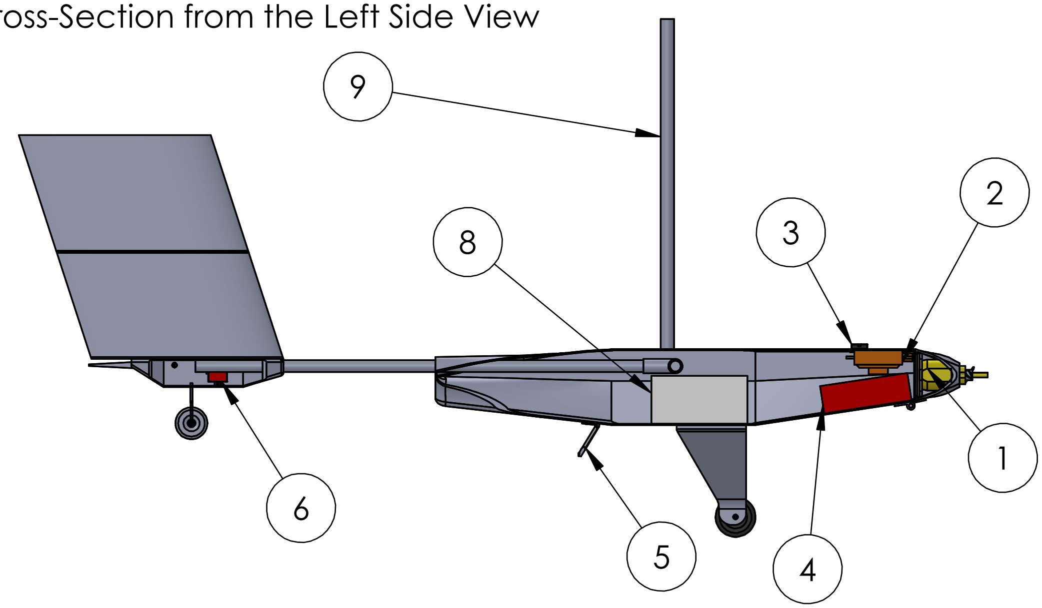
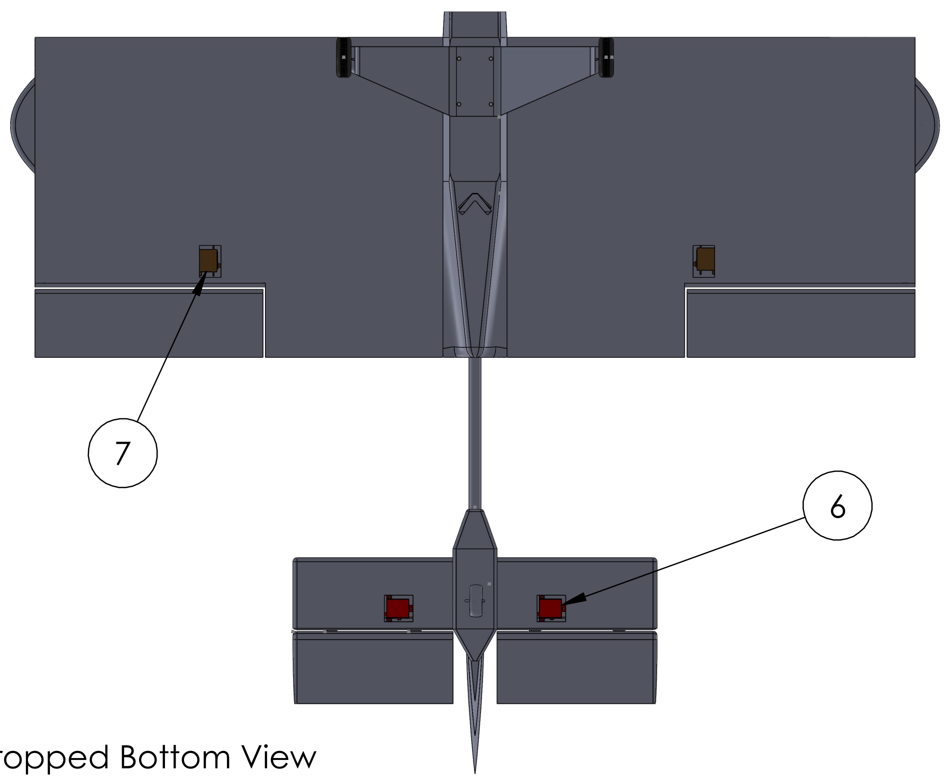
| SIZE | DWG. NO. | REV |
|---|---|---|
| A | Structures | |
| SCALE: 1:12 | SHEET 2 OF 6 | |

Cross-Section from the Left Side View




| # | System Component | Description |
|---|---|---|
| 1 | Motor | Scorpion SII-4025-330 kV |
| 2 | Electronic Speed Controller | Spektrum Avian 120 A |
| 3 | Receiver | Spektrum AR10400T |
| 4 | Battery | Thunder Power RC 8s 3300 mAh 55C LiPo |
| 5 | Receiver Mount | PLA 3D Printed Mount for Receiver Wires |
| 6 | Tail Servos | KST X10 (132 oz-in Torque @ 7.4 V) |
| 7 | Wing Servos | Bluebird BMS A920 (190 oz-in Torque @ 7.4 V) |
| 8 | Electronics Package | Mission 2 Payload |
| 9 | Jamming Antenna | Mission 3 Payload |




Cropped Bottom View

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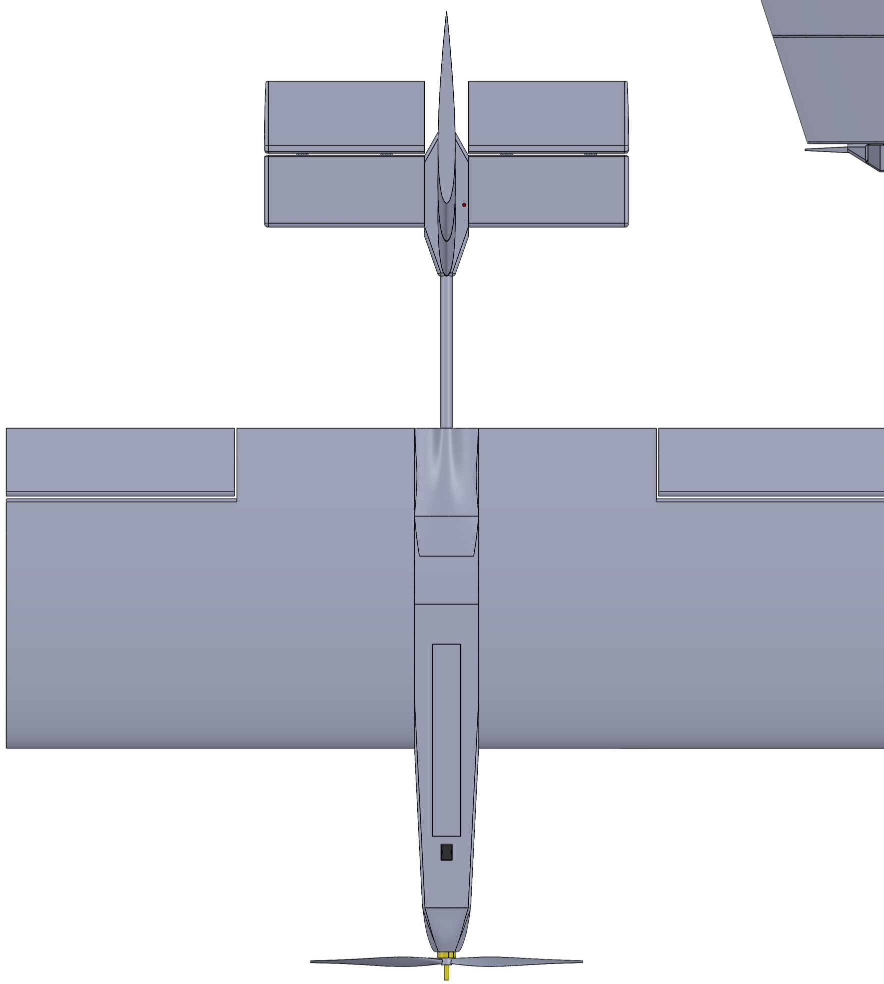
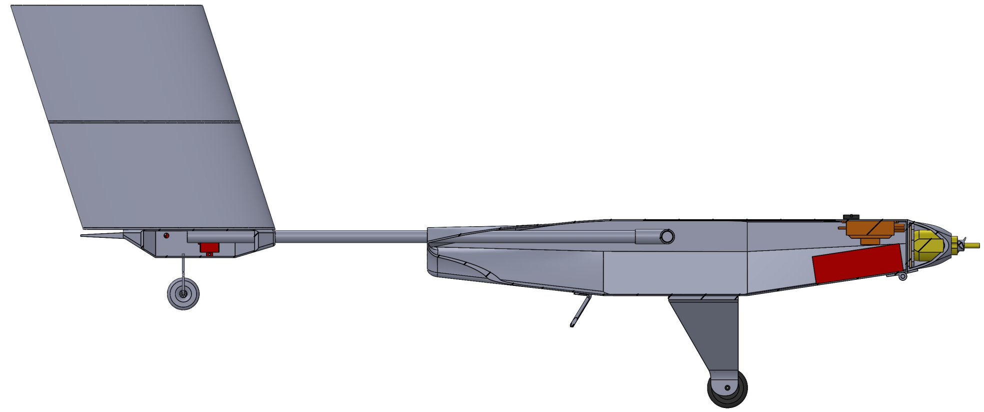
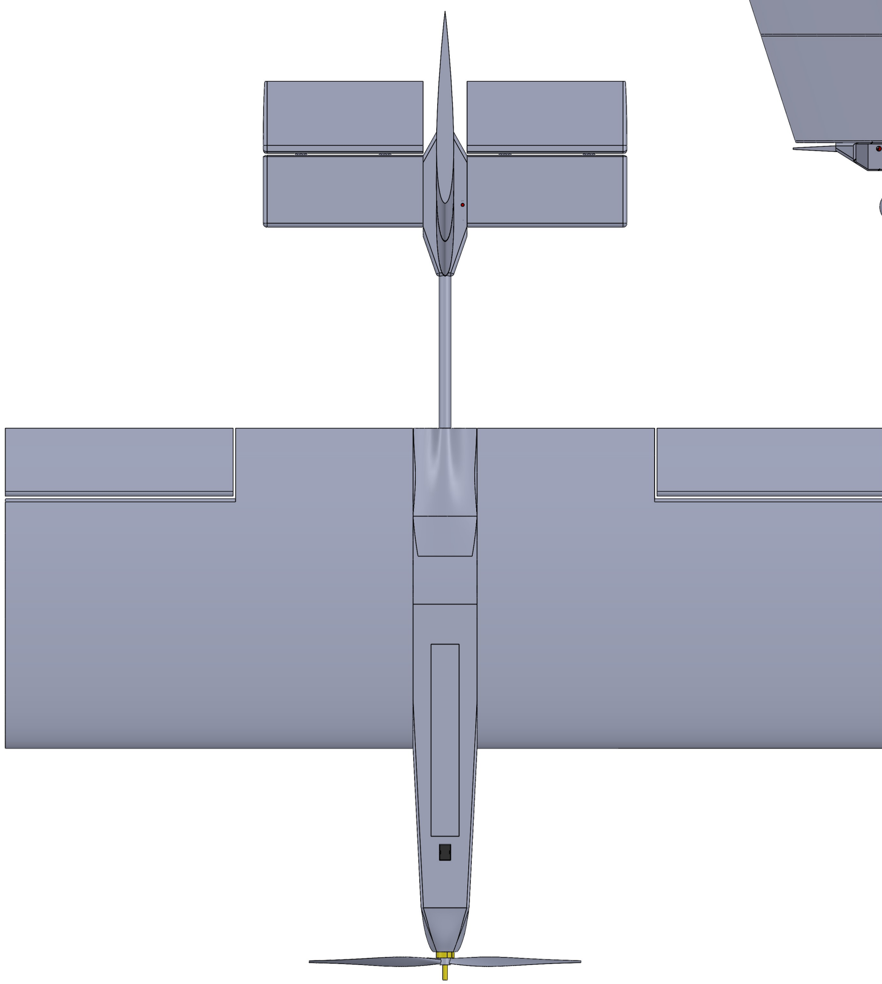
| SIZE | DWG. NO. | REV |
|---|---|---|
| A | Electronics & Payload | |
| SCALE: 1:12 | SHEET 3 OF 6 | |

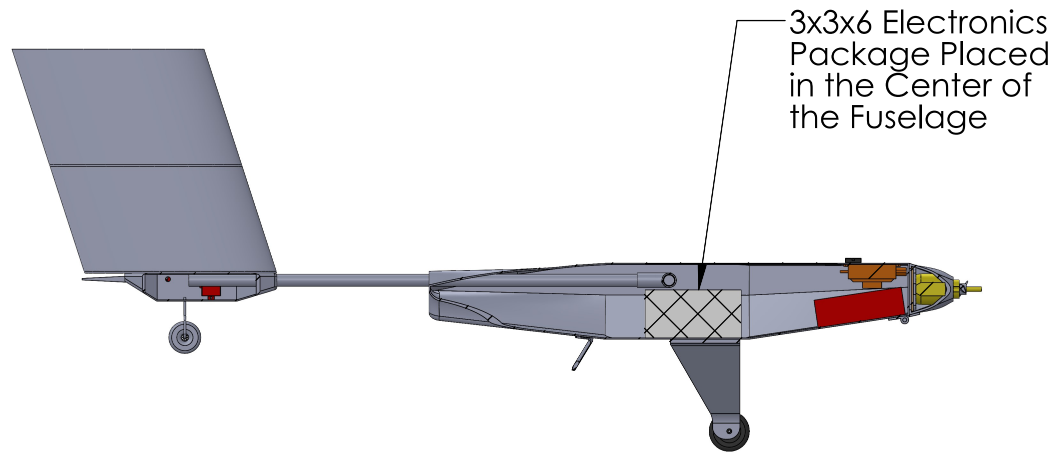




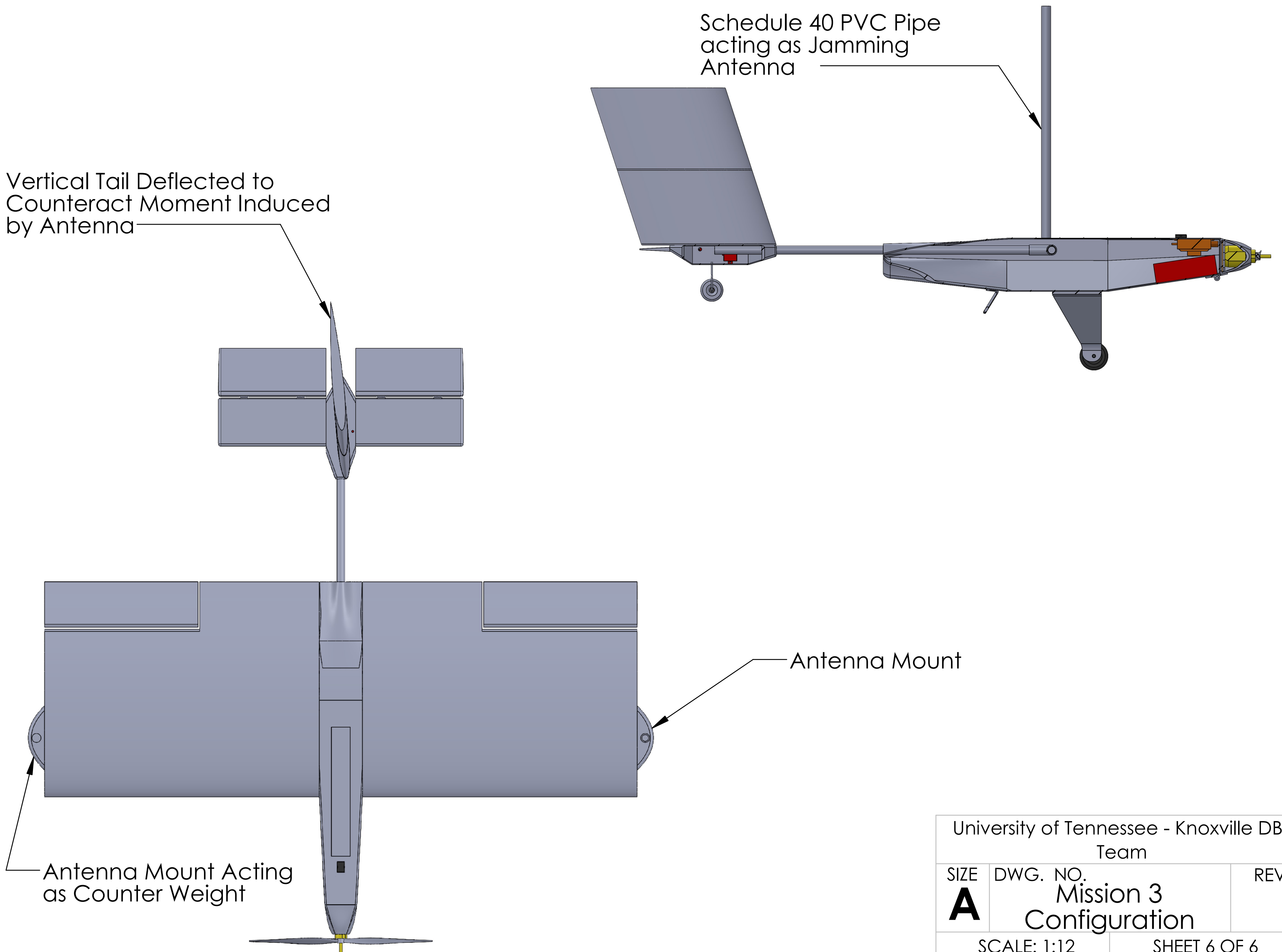
Empty Flight; No payload of any kind required

| University of Tennessee - Knoxville DBF Team | | |
|---|---|---|
| SIZE A | DWG. NO. Mission 1 Configuration | REV |
| SCALE: 1:12 | SHEET 4 OF 6 | |






| | | |
|---|---|---|
| University of Tennessee - Knoxville DBF Team | | |
| SIZE A | DWG. NO. Mission 2 Configuration | REV |
| SCALE: 1:12 | SHEET 5 OF 6 | |




| University of Tennessee - Knoxville DBF Team | | |
|---|---|---|
| SIZE A | DWG. NO. Mission 3 Configuration | REV |
| SCALE: 1:12 | SHEET 6 OF 6 | |

## 6 Manufacturing Plan

Manufacturing is a critical aspect of preparing a competition-grade aircraft for flight and is the stage in which all analytical work becomes reality. Common processes used in the construction of model aircraft were considered and ranked based on the complexity, cost, resources required, and knowledge of team members. This section serves to outline the possible manufacturing methods and a discussion of the final construction of the aircraft.

### 6.1 Materials and Processes Investigation

In order to fabricate a final aircraft that optimized production/assembly time, structural integrity, weight, and cost, a wide range of materials and processes were considered. The following subsections outline the materials and processes considered and detail the procedures chosen for the fabrication of the final aircraft.

#### 6.1.1 Laminated Expanded Polypropylene (EPP)

Laminated expanded polypropylene is a common material used to construct radio control (RC) plane wings. It was considered for use in the construction of the wings due to its low cost, compression strength, and excellent elastic properties. Even more, the laminated coating on the foam increases the tensile strength and smooths the surface which increases aerodynamic performance.

#### 6.1.2 Carbon Fiber and Polystyrene

The combination of carbon fiber and extruded polystyrene (XPS) was also considered for the prototype wing, fuselage, and vertical tail fabrications. XPS is similar to EPP in cost, but lacks its highly elastic properties. However, XPS makes a good base for a composite structure that improves the rigidity and strength of the wings while keeping weight as low as possible. Carbon fiber and epoxy can be applied in layers to coat the polystyrene cores. Thus, control of the weight and part strength, depending on the number of layers applied, could be achieved during fabrication.

#### 6.1.3 MonoKote and Balsa Structure

To minimize weight aft of the neutral point, extremely lightweight materials were considered for the construction of the vertical and horizontal tails. MonoKote and balsa wood were considered due to their low cost, low density, and adequate structural properties when assembled. A skeleton of balsa wood would be constructed with truss sections to distribute force loads to the respective vertical and horizontal tail spars. Then, to simultaneously maintain the lightweight structure and improve aerodynamic performance, the vertical and horizontal tails would be wrapped once with the MonoKote film.

#### 6.1.4 Balsa-Sheeted Polystyrene

A cheaper and simpler alternative to the carbon fiber and polystyrene fabrication method was considered with the use of balsa-sheeted polystyrene. To improve the tensile strength of the polystyrene, thin sheets of balsa wood would be wrapped around the polystyrene core in the chord-wise direction. These materials and processes are not as structurally sound as the parts coated with fiberglass but do have the advantages of being cheaper and significantly more lightweight.

#### 6.1.5 Laser Cut Plywood

Another type of wood that was considered was the use of $\frac{1}{16}$ in plywood. In contrast to balsa wood, plywood is much more dense, giving it the benefit of added strength but at the drawback of added weight. Thus, plywood was only considered where structural support was more crucial. The use of plywood made the manufacturing process quick and easy as pieces can be precisely laser cut from large, low cost sheets. The laser cut plywood could be used to create accurate guides used for hot wire cutting foam wings as well as creating a strong, flush connection point between the wings and fuselage.

#### 6.1.6 Composite Structure

Composites consist of the combination of two or more materials to create a different material with better qualities than the original. This allows us to combine the strengths and minimize the weaknesses of multiple different materials. A composite material of carbon fiber laminated with epoxy resin was considered for the manufacturing process. Carbon fiber has impressive tensile strength capabilities but can not support itself under compressive forces. Epoxy resin is extremely hard and strong in all directions, which allows it to absorb compressive forces well. However, because it is so hard, it is also brittle and breaks easily under tensile and shear forces. Using this composite stabilizes the fibers and decreases the brittleness of the epoxy resin creating a strong, hard, and tough material.

#### 6.1.7 Composite Landing Gear

When designing a landing gear, the primary design goal was to minimize unnecessary weight while having a balance between strength and stiffness to protect the aircraft and prevent prop strike. It was determined that a composite landing gear would be ideal over a metal or wood gear. Using a composite allows the gear to be shaped into the desired geometry while balancing strength and stiffness. Being too light will make the gear weak and the extra springiness can cause a prop strike, but being too strong will result in unnecessary weight. This can be aided through the addition of multiple layers until the ideal balance is found. Through this method, landing gear can be manufactured that is specific to the aircraft's needs.

#### 6.1.8 Additive Manufacturing (3D Printing)

Additive manufacturing was considered a viable manufacturing option due to the ability to rapidly prototype and create unique and specific parts. The application of 3D printing requires a balance between the weight and strength of the part that is intended to be made. Thus, additive manufacturing was only used when the part to be created could be lightweight and still maintain structural integrity, or the complexity of the part required the accuracy of additive manufacturing.

### 6.1.9 Investigation Results

Of the methods and materials detailed above, a carbon fiber composite was used for the fabrication of the fuselage, tail box, and landing gear. The wings were constructed out of XPS foam and covered in a single coat of carbon fiber composite. Plywood was used as a stronger connection point between the wings and fuselage for attaching alignment pins, retention screws, and spar holes. The wing spar is a manufactured ¾ in 3k plain weave carbon fiber tube. A truss-like balsa wood structure wrapped in MonoKote was used for the horizontal tail. The vertical tail was constructed using MonoKote around XPS foam inlaid with two laser cut plywood ribs, similar to the process in Section 6.1.1 but with more readily available material. The spars used for the tail section are 0.28 in carbon arrow shafts. Additive manufacturing was used in the fabrication of the piece that joins the wing and tail spars, as well as the hardpoint adapters used in Mission 3.

## 6.2 Manufacturing Processes Selected for Major Components

### 6.2.1 Fuselage

The fuselage is constructed via a multi-layer composite layup. This process starts with a model created from an XPS foam board then cut into 2 male plugs. An additional 1 in spacer with the same cross-section is added to the cut plane. On one of the male plugs, the spacer is sanded down slightly around all walls, creating a joggle connection between the halves after composite layup. During the layup process, a single ply will cover the entire fuselage plug with additional layers added in load bearing areas, then vacuum bagged to reduce excess epoxy and more closely conform to the shape of the plugs. The fuselage components will then be sanded and joined with epoxy and a carbon fiber strip. Jigs will be used to properly position the main spar holes as well as holes for alignment/retention pins and wires.

### 6.2.2 Wings

The wings are constructed from an XPS foam board that has been cut to shape using a hotwire bow. The wings are prepared for the layup process by filling gaps with glass microspheres and drilling a hole for the main spar. The wings are wrapped in a single ply of carbon fiber, and vacuum bagged to reduce excess resin and reduce surface wrinkles. After curing, an additional resin layer is added and wet sanded after trimming excess from the wings. Holes are cut in the root and tip of the wings for alignment pins, retention screws, spar, and Mission 3 hardpoints using a jig to ensure proper alignment. Control surfaces are cut from the wing and hinged with nylon hinges. Recesses are cut out of the wing's lower surface for electronics and servo arm clearance.

### 6.2.3 Empennage

The horizontal tail is constructed from 0.5 in square balsa dowels. Full-size plans based on CAD drawings are printed and used to guide construction. Each dowel is cut and sanded to shape before being glued in place by cyanoacrylate glue. Spar guides are 3D printed to secure the 0.28 in diameter carbon arrow shaft within the tail body. The parts are sanded smooth, covered with MonoKote, and hinged with nylon hinges.

The vertical tail has two laser-cut airfoil sections, one at the root and one at the midplane, placed interstitially in a block of XPS. A hotwire bow is guided along the airfoil sections to create a wing shape which is then sanded to shape at the leading and trailing edge. This foam body is wrapped in a layer of MonoKote to provide additional rigidity and a notch is removed from the root to allow servo horn attachment.

The tail section spars are mounted through the tail boom to provide significant stability. A jig is used to drill properly spaced and perpendicular holes. The spars also go through the tail box, constructed from a plug wrapped in a single ply of 3K plain weave carbon fiber, providing additional stability and mounting points for the vertical stabilizer control servo and tail wheel.

### 6.2.4 Landing Gear

A mold of the landing gear will be created from XPS foam sheets that have been glued together to reach the proper thickness. After shaping, unidirectional and 3K plain weave carbon fiber sheets will be applied in an alternating fashion, with epoxy resin between each layer, until the desired thickness is reached. The landing gear will be vacuum bagged to reduce excess resin and ensure layer adhesion. After debagging, the landing gear will be post-processed by sanding away any wrinkles for improved airflow, then marking and drilling mounting locations. Small dowels will be used for quick alignment of the landing gear, and a bolt will be used to secure it to the fuselage.

### 6.2.5 Jamming Antenna Mounting System

The antenna mount will be 3D printed using PLA with 6 perimeters and 25% cubic infill for added strength. Compensation for shrinkage is done after printing a sample part, but the interface between the mount and the antenna itself will be sanded to specifications. The model contains a small hole designed to allow space for a retention screw to be used on the jamming antenna if desired.

## 6.3 Manufacturing Milestones Chart

The manufacturing milestone chart is seen below in Figure 6.1. As the legend in the top left corner shows, gray bars mark the projected date ranges for work on each subsystem, and orange bars mark the actual date ranges required to complete each subsystem's tasks. The chart has been reduced to the Year-To-Date view for readability but has been used as a task distribution framework since the draft rules' release. Finally, note that each aircraft component was broken into two sections: preliminary construction and final construction.

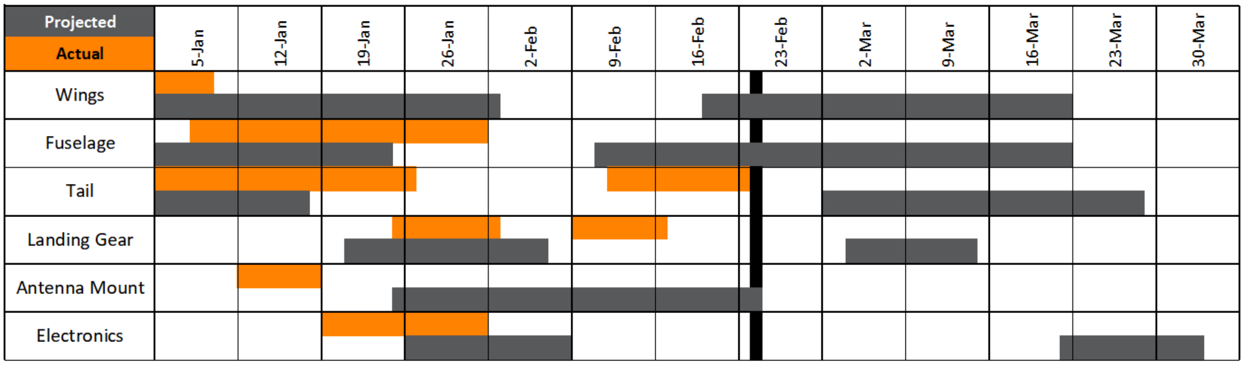



**Figure 6.1.** Manufacturing Timeline YTD

## 7 Testing Plan

Physical testing of the aircraft was of the utmost importance and vital to the success of this project. With the preliminary design based on analytical data, the prototype aircraft performed below expectations in crucial areas. Testing was completed following the schedule in the manufacturing milestone chart in Figure 6.1. Initially, extensive testing was performed on each uninstalled subsystem. With satisfactory results, subsystems were integrated to form the aircraft prototype. The aircraft then completed ground and flight testing. This testing provided real-world feedback that identified areas of improvement for future iterations. Testing subsystems and the entire assembly separately reduced the overall time of the build by finding failure points at the individual component level first. The strenuous testing also reduced the probability of failure at vital moments in flight and improved the overall chance of success. The significant tests conducted and their desired takeaways are listed below.

### 7.1 Tests

Static Thrust

- Verify the plane can meet takeoff and flight speed requirements.
- Acquire data on power consumption.

Jamming Antenna Mount Static Test

- Static loading is applied to the antenna while mounted and attached to a rigid body.
- Attach the antenna mount to wingtip hard points and perform a static loading test greater than the estimated drag force found during the sensitivity analysis.

Impulse/Stress Test

- Verify that additional weight can be securely stowed in the “electronics package” during additional weight tests.
- At various weights (up to or more than desired for Mission 2), perform a wingtip load test.

- (Drop Test) Perform a drop test at various weights (up to, or more than, desired weight for Mission 2) and heights (6 to 12 in) to ensure that the plane can survive hard landings.
- Attach the ground test stand to wingtip hard points and add weight following the ground mission described by the AIAA.

Mission Testing

- Verify that the plane can successfully takeoff and land at maximum takeoff weight.
- Beginning with a 6 in antenna, fly the required flight path and verify sufficient controllability and stability. Increase antenna length incrementally until the desired length of 22 in or sub-optimal flight characteristics occurs.

### 7.1.1 Static Thrust Test

The propulsion team conducted multiple tests to validate the power consumption and thrust that the propulsion system provides. These tests were completed with multiple propellers to choose the proper propeller based on test stand results. This data helped calculate expected takeoff performance, team score, and overall aircraft performance. Thrust data was gathered using an Arduino and a 10 kg load cell attached to a test stand that held the motor. Battery voltage, current, and power consumption was measured using a TENERGY watt meter and power analyzer connected between the primary propulsion battery and ESC. These components allowed the team to gather all the necessary data to make final decisions on the plane's motor and propeller. The testing checklist for this test is listed below.

- Propeller balance is verified on the propeller balancer.
- Arduino and load cell are calibrated to a known 200 g weight.
- Motor and propeller are securely attached, and the motor is secured to the test stands mounting bracket.
- Motor and ESC are connected along with motor rotational direction verified.
- All potential foreign object debris is secured or removed from the testing location.
- All team members are well behind the stand and wearing safety glasses.

### 7.1.2 Antenna Mounting Bracket

To verify that the 3D printed antenna mounting bracket and the hardpoint mounted in the wings would be strong enough to withstand the stresses induced during flight, the manufacturing and structures team performed a series of stress tests with the antenna mounted on and off the wing. These tests began by attaching the antenna bracket to a workbench as it would attach to the wingtip mounting point. Using a linear force scale, a simulated drag force is applied to the antenna 12 in above the mount. A distance of 12 in is used for ease of calculation as it produces an ft-lb of torque applied at the antenna mount. Once the antenna mount was repeatedly tested on the workbench, testing was replicated with the mount fixed to the wingtip hardpoint itself with force applied 12 in above the wing surface. This was repeated for each wing. These tests allowed the team to optimize the antenna mount for weight while ensuring the structural integrity of the 3D mount along with the wingtip mounting point. The requirements of these tests are as follows.

- Secure the antenna mount to a rigid structure and apply gradual loading to the attached antenna 12 inches above the antenna mount's top surface.
- Incrementally add load until system failure.
- Analyze and record the failure point of the system and modify the design until an acceptable failure load and the total weight of the sub-assembly.
- Attach improved antenna mount onto wingtip mounting point and apply gradual load up to 125% of expected forces at max Mission 3 velocity.
- Inspect for system integrity and repeat the process three times to check for fatigue points.

#### 7.1.3 Impulse/Stress Test

To verify the structural integrity, the structures and manufacturing team, and the aerodynamics team performed a combination of analytical and practical tests. The aerodynamics team analyzed wing loading using the max vehicle weight during Mission 2. The wing loading data provided insight into if the desired weight is realistic depending on estimated g-loading based on optimal aircraft velocity while banking during flight. Additionally, using the data from the aerodynamics team, the structures and manufacturing team performed wingtip lift and aircraft drop tests. The wingtip and drop tests verified the plane’s wings and landing gear’s performance and verified that all internal components and additional weight were secure. Once all previous tests were completed, the aircraft was affixed to the ground test stand at the wingtips, and a simulated ground mission was performed. The checklist for this test is below.

- Ensure all internal components are secure.
- Insert wing spar through fuselage and tail boom interface mount, slide wings onto spar, and fasten $C_r$ to fuselage mounting points. Insert the tail boom into the fuselage and attach it to the tail boom interface mount.
- Lift fully assembled aircraft, including electronics package, by the wing tips while visually looking for issues. If there are no issues, perform a drop test starting at 6 in from the ground. Repeat visual check for structural damage and functionality. If visual and functionality checks pass, repeat the test at 12 in and perform post-drop inspections.
- Inspect internal components for movement and check the plane's structure for cracks, bends, or tears.
- Attach ground test stand to wingtip mounting fixture while at Mission 2 configuration weight; add additional weight to electronics package in 4 oz increments while checking for structural deformation and damage.

### 7.1.4 Mission Testing and Planning

Flight testing was split into multiple stages to best address design modifications and optimize time. The first testing stage included tests to gauge basic vehicle performance, stability, and maneuverability. Flight testing began with an unloaded, unmodified prototype simulating Mission 1 of the DBF competition. The data collected from the first testing stage was analyzed and interpreted to revise the initial aircraft prototype for increased performance.

The second stage of flight testing incorporates knowledge and modifications from the initial prototype airframe to better understand the aircraft's capabilities. Stage two began similarly to stage one with the aircraft in Mission 1 configuration. Beginning in Mission 1 configuration aimed to compare if the modifications made after the first stage had the desired impact on flight characteristics. With corrected flight characteristics confirmed, more strenuous flight testing could be started. This testing included increased flight speed stability, along with maneuverability checks. Additionally, flight tests were performed with the addition of varying length antennas to simulate Mission 3 performance and varying internal weights to simulate Mission 2 flight performance and takeoff distances. The findings from this testing stage will be implemented during the final aircraft's construction.

The third and final stage of flight testing will integrate all knowledge attained from previous flight testing to fine-tune aircraft performance. In the third stage, the aircraft will be flown to mirror the DBF competition environment for each mission. The data obtained from these tests will be used to make final adjustments to the aircraft and ensure it is fit for competitive flight. Stage three flight tests will be repeated multiple times leading up to the DBF competition in April to ensure successful performance. A breakdown of the completed flight testing as of this report and expected future flight testing is found below in Table 7.1a - 7.1c. Additionally, the team used a checklist to ensure proper data collection during all flight testing. This checklist can be seen in Table 7.2a- 7.2b and will also be used during the 2023 DBF competition in Tucson, Arizona.

**Table 7.1a.** Flight Test Plan

| Flight | Date | What was tested | Changes Made/Data Collected |
|---|---|---|---|
| **Stage 1** | | | |
| 1 | 02/05/23 | Initial aircraft "shakedown", Can the aircraft fly in Mission 1 configuration. | Sensitive in pitch. Pilot reports inadequate up-elevator. |
| 2 | 02/05/23 | What elevator trim is required for stable flight. | 10° nose-up trim to elevators improved flight characteristics. Aircraft still very pitch sensitive. |
| 3 | 02/05/23 | How does adding a 4oz weight 3 in aft of the firewall affect CG and subsequent flight dynamics. | CG moved forward an inch to improve the static margin, and flight stability increased substantially with questionable directional stability attributed to nonrigid vertical tail. |

**Table 7.1b.** Flight Test Plan

| Flight | Date | What was tested | Changes Made/Data Collected |
|---|---|---|---|
| **Stage 2** | | | |
| 4 | 02/18/23 | How do updated aircraft components perform in Mission 1 configuration? | Installed a more rigid vertical stabilizer and changed incidence angle for the horizontal stabilizer. Takeoff and steady level flight stability was significantly improved without trimming the horizontal tail. |
| 5 | 02/18/23 | How does aircraft perform under increased flight speed and maneuvers? | Marginal direction stability, problem traced back to play in vertical tail servo interface, (Issue persisted for all subsequent Stage 2 flight tests) |
| 6 | 02/18/23 | Expand flight speed envelope. | A max speed of 70 ft/s was obtained, reduced from the expected speed due to direction stability concerns. |
| 7 | 02/18/23 | Observe flight characteristics with 6 in antenna. | Slight yawing moment was observed which was successfully counteracted with vertical tail |
| 8 | 02/18/23 | Observe flight characteristics with 12 in antenna. | Increased yawing moment successfully counteracted with vertical tail, slight wing drop during takeoff due to antenna weight. |
| 9 | 02/18/23 | Observe flight characteristics with 18 in antenna. | Increased yawing moment successfully counteracted with vertical tail, increased wing drop during takeoff due to antenna weight. |
| 10 | 02/18/23 | Observe flight characteristics with 22 in antenna. | Increased yawing moment successfully counteracted with vertical tail, significant wing drop during takeoff due to antenna weight. |
| 11 | 02/18/23 | What is takeoff distance and flight characteristics with 5 lb internal load placed at CG, check for damage to landing gear and fuselage interface. | Successful takeoff in 30 ft, similar flight characteristics as flight 1, successful landing, no damage to any components found. |
| 12 | 02/18/23 | What is takeoff distance and flight characteristics with 11 lb internal load placed at CG. | Successful takeoff in 59 ft, observed reduced but satisfactory flight performance, failed landing due to running off the end of runway. |

**Table 7.1c.** Flight Test Plan

| Flight | Date | Configuration | Desired Data | Status |
|---|---|---|---|---|
| **Stage 3** | | | | |
| 13 | 03/11/23 | Mission 2 | Simulate Mission 2 with a conservative payload weight | Incomplete |
| 14 | 03/18/23 | Mission 3 | Simulate Mission 3 with a conservative antenna length | Incomplete |
| 15 | 03/25/23 | Mission 2 | Simulate of Mission 2 at max payload weight | Incomplete |
| 16 | 04/1/23 | Mission 3 | Simulate of Mission 3 with maximum antenna length | Incomplete |

## 7.2 Pre-Flight Checklist

The pre-flight checklist used to record pertinent testing information is shown in Table 7.2a - 7.2b. This checklist is intended to prevent negligence to aircraft setup and ensure that valuable test data is collected before the start of each flight. In case of a vehicle crash or system malfunction the corresponding checklist can be referenced to help determine the cause of the accident or malfunction.

**Table 7.2a.** Pre-Flight Checklist

| **Date** | | **Time** | | | |
|---|---|---|---|---|---|
| **Aircraft Name** | | **Flight Number** | | | |
| **Structure** | | | | | |
| **No Tears, Cracks, or Rips** | ☐ | **Control Surface Connections** | ☐ | **Secure Pushrod Connections** | ☐ |
| **Servos Installed** | ☐ | **Wings and Tail Secure** | ☐ | **All Loaded Objects Secure** | ☐ |
| **Wheels Turn Freely** | ☐ | **Tail Gear aligned and Tight** | ☐ | **Motor Securely Mounted** | ☐ |

Table 7.2b. Pre-Flight Checklist

| Electronics and Propulsion | | | | | |
|---|---|---|---|---|---|
| Propeller Used | | Aircraft Battery Voltage | | Controller Battery Voltage | |
| Insert and Secure All Batteries | ☐ | All Wires Secure | ☐ | MicoSD Card Inserted | ☐ |
| Turned On Transmitter | ☐ | Propeller Tightened | ☐ | Throttle Test | ☐ |
| **Controls** | | | | | |
| Rear Steering | ☐ | Ailerons | ☐ | Elevators | ☐ |
| Vertical Tail | ☐ | Rudder | ☐ | Control Surfaces Move Freely | ☐ |
| **Weight Distribution** | | | | | |
| Empty Weight | | Total Weight | | | |
| CG Location | | | | | |
| **Weather** | | | | | |
| Temperature | | Pressure / Altitude | | Wing Speed / Heading | |
| Runway Heading | | Crosswind Component | | Weather Souce | |
| **Post Flight** | | | | | |
| Aircraft Battery Voltage | | | | | |
| Structural/Electrical Damages | | | | | |

# 8 Performance Results

## 8.1 Stability Performances

Stability of the aircraft is rigorously tested and monitored during stage one of flight testing. During the first test flight, it was apparent that the tail assembly (horizontal tail, vertical tail, and tail box) required considerable changes. These changes consisted of reducing the total weight of the tail assembly, adjusting the angle of incidence of the horizontal tail section, implementing a stronger spar for the vertical tail, and reducing the backlash between the vertical tail/servo interface. The tail assembly's weight was reduced to improve the aircraft's static margin during the initial flight. This over-responsiveness was exacerbated by the 3.36° angle of incident of the horizontal tail relative to the top of the fuselage, which required adding a 4 oz weight 3 in behind the firewall for the vehicle to be safely flown. The vertical tail spar used during flight 1 allowed for substantial bending, and the backlash between the servo and vertical tail interface resulted in a vertical tail incidence change during flight.

To correct the weight issue, a new tail box was constructed with a reduced height profile, and an internal 3D-printed brace was removed, reducing the total tail section weight by approximately 100 g. With a new tail box constructed, the horizontal tail spar holes were re-drilled to have a 0° angle of incidence, a change from the previous nose-up angle. Furthermore, the connector fixtures used for the vertical tail servo push rod were changed from a metal clevis to a metal collar that was press fit into the servo horns preventing any backlash within the actuating system. Finally, the vertical tail spar which was originally a 450-spine fiberglass arrow shaft was replaced with a stiffer 300-spine aluminum sheathed carbon fiber arrow shaft which reduced bending to a negligible amount. During Stage 2 flight testing (February 18, 2023), the improvements proved to work as pitch control was now easily managed and directional stability was improved. These improvements allowed for a total of 9 flight tests during stage 2 flight testing. These tests included jamming antenna tests up to a maximum length of 22 inches and takeoff distance tests while loaded with 11 lbs of additional weight to simulate Mission 2.

### 8.2 Aerodynamics

Flight tests provided valuable insight into how the plane would perform with respect to aerodynamics, notably, in terms of stability and takeoff distance. Because Mission 3 requires a very stable and controllable aircraft, this was one of the main focuses of the later flight tests, followed by the 60 ft takeoff distance at various takeoff weights. Takeoff distances for all flights were under 60 ft. Thus, no significant changes were needed to increase lift. The vertical tail was found to be a weak point in the system and proved to be marginally stable during stage 1 test flights, and a low static margin meant maintaining pitch control was a difficulty for the pilot. To remedy these issues, multiple steps were taken. To increase directional stability, XPS foam was hot-wire cut into the shape of a NACA 0009 and bisected horizontally by a ⅛ in plywood brace to provide more torsional support in the vertical tail and finally wrapped in MonoKote. This method was selected instead of the original design of a MonoKote wrapped balsa structure. The added rigidity and strength should help to increase control from the vertical tail and thus improve the overall stability. To increase the longitudinal stability, the CG was moved further forward to increase the longitudinal stability, thus increasing the static margin.

### 8.3 Propulsion

The performance of the propulsion system was tested using a motor mount with a 10 kg load cell connected to an Arduino for recording and a battery that satisfied the subsystem requirements and also met the overall competition requirements. The 2 motors selected for testing were the E-flite Power 60 and the Scorpion SII-4025-330 kV; these 2 motors were tested with the same propeller, battery, and ESC configuration. The goal of these tests was to find a motor that would provide the most thrust at maximum power output rating. This maximum thrust value was imperative for the aircraft design to fly at a certain weight and be able to meet the takeoff requirements. The results of this test were previously shown in Figures 4.4 and 4.5 These results are broken down and shown in Table 8.1 below.

**Table 8.1.** Motor Max Power Output vs. Thrust Comparison

| Motor | Max Power Output | Maximum Static Thrust |
|---|---|---|
| **E-flite Power 60** | 1800 W | 13.01 lb |
| **Scorpion SII-4025-330 kV** | 2000 W | 12.79 lb |

From Table 8.1 it is evident that the E-flite Power 60 Produced more thrust than the SII-4025-330 kV motor. However it required overloading the motor by 194 W, which could result in the damage or failure. To prevent failure of the E-flite Power 60, a smaller propeller would be needed reducing the max thrust from the E-flite Power 60. For that reason, the Scorpion SII-4025-330 kV motor was chosen. From here, the propulsion team's next goal was to find the most efficient propeller for the motor. The goal of choosing a propeller was to achieve thrust required for cruise at the lowest possible electrical power output. The cruise power required was estimated to be around 70% throttle. The Scorpion SII-4025-330 kV was tested with three different propeller sizes, the results of these tests are summarized in Table 8.2 below. These results show that while the 16X10E 3-blade propeller gave the most thrust, the 17x10E would be the more efficient propeller in real world flight conditions while still satisfying system requirements.

**Table 8.2.** Propeller Performance

| Propeller Size | Static Thrust at Cruise Power (1400 W) |
|---|---|
| **16X8** | 5.31 lb |
| **16X10E** | 6.02 lb |
| **16X10E 3-Blade** | 8.51 lb |
| **17x10E** | 6.97 lb |
| **18x12E** | 6.42 lb |

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