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Subscale Mars Colonization Mission

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LMU|LA
University Honors Program

Subscale Mars Colonization Mission

A thesis submitted in partial satisfaction

of the requirements of the University Honors Program

of Loyola Marymount University

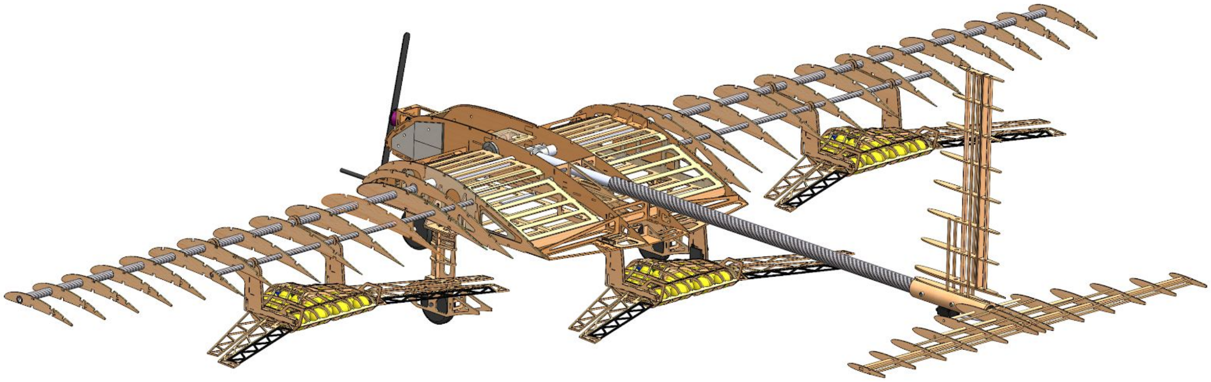
by

Cameron LaMack, Ali AlTamimi, Riley Evers, Anthony Keba, James Lumsden, Anthony Modica, Sean Nevin, Alexandra Poulakos, Donner Schoeffler, Skyler Tan, Siraj Zaman

Advisor: Dr. Emin Issakhanian

May 3, 2019

Subscale Mars Colonization Mission
SAE Aero Design West 2019 - Advanced Class



Loyola Marymount University
AirLions
Team 213

Project Team: Cameron LaMack, Ali AlTamimi, Riley Evers, Anthony Keba, James Lumsden, Anthony Modica, Sean Nevin, Alexandra Poulakos, Donner Schoeffler, Skyler Tan, Siraj Zaman
Advisor: Dr. Emin Issakhanian

HONORS PROGRAM ADDENDUM: Please note the Honors Student involved in this project is Cameron LaMack, specifically responsible for part of the design of the Colonist Delivery

Aircraft, as well as flow analysis of inter-aircraft attachment and the manufacturing of the Primary Aircraft.

List of Figures and Tables

Figures:

Tables:

List of Acronyms

a = Acceleration
b = Wing Span
AR = Aspect Ratio
C_d = Coefficient of Drag
C_{di} = Coefficient of Induced Drag
C_L = Coefficient of Lift
CDA = Colonist Delivery Aircraft
d = Propeller Diameter
D = Drag
e = Oswald Efficiency Factor
F_c = Coefficient of Rolling Friction
$FF_{"x"}$ = Form Factor of "x"
g = Gravity
GUI = Graphical User Interface
h = Distance from the Leading Edge to the Center of Gravity
h_n = Distance Between the Leading Edge to ¼ of the Chord Length
I = Moment of Inertia
I = Current
k = Gust Alleviation Factor for Subsonic Travel
Kv =Velocity Constant
K' = Inviscid Factor
K'' = Wing Viscous Drag-Due-to-Lift Factor
L = Length
L_a = Airfoil Thickness Location Parameter
MAC = Mean Aerodynamic Chord
M.S = Margin of Safety
μ = Coefficient of Friction
n = Load Factor
η = Ratio of 2D Lift Curve Slope to Theoretical Slope
σ = Stress
ρ = Density
PA = Primary Aircraft
Re = Reynold's Number
RPM = Rotations per Minute
S_{ref} = Total Wing Platform Area
S_{wetted} = Wetted Area
$S_{whole\ plane}$ = Surface Area of Whole Plane
T = Thrust
τ = Torque
T/C = Thickness Ratio
U = Velocity

v_0 = Propeller Forward Airspeed
V = Velocity
V_{TO} = Takeoff Velocity
W = Weight

Table of Contents

§1.0 Executive Summary:

The Society of Automotive Engineers (SAE) Aero Design West competition for the Advanced Class has the objective of optimizing a radio controlled aircraft to perform a series of tasks. The competition allows students to research, design, manufacture, test, and fly their creations. The competition also allows students to develop other skills as well; including cost analysis and budgeting, material selection and optimization, and time management for long term projects. This report details the design process and calculations made to develop the completed aircraft design.

§1.1. System Overview:

The objectives of the competition include designing, manufacturing, and flying a radio controlled aircraft, which drops supplies and autonomously guided unpowered aircraft to deliver colonists to a target. The competition rules state that three different dynamic payloads onto a designated target, to use downlink telemetry to ground station specifically Data Acquisition System (DAS), to limit available power to 750 Watts, and to limit total aircraft weight to 55 pounds. Teams that carry the most static and dynamic payload, while successfully delivering colonists and resources to the drop zone, are awarded the most points. The overall goal is to receive the most points by flying successfully and dropping payloads consistently.

§1.2. Competition Projections/Conclusions:

We project to fly consistently while always dropping the designated payloads within the target. Aircraft performance is critical for this competition, which is why the design is focused on reliability and durability while also being lightweight to maximize points received based on payload carried.

§2.0 Schedule Summary:

Table 2.0 Schedule Summary			
Task	Start Date	Duration	End Date
Initial Research/Concept Generation	27-Aug	28	24-Sep
System Requirements Review (SRR)	3-Sep	7	10-Sep
Isolate Mission Architecture	19-Sep	11	30-Sep
Preliminary Design Review (PDR)	24-Sep	7	1-Oct
Primary Aircraft Design (Aerodynamics, Powertrain, Structures Lift/Drag/Thrust Testing)	19-Sep	54	12-Nov
Stress Calculations/FEA	15-Oct	21	5-Nov
Electronics/Telemetry/DAS (Planning/Development)	1-Oct	35	5-Nov
Colonist Delivery Aircraft Design (Aerodynamics, Payload, Autonomy)	19-Sep	54	12-Nov
Critical Design Review (CDR)	5-Nov	7	12-Nov
Subsystem Optimization	5-Nov	28	3-Dec
Control System Modelling	5-Nov	78	22-Jan
Electronics Preliminary Testing	5-Nov	35	10-Dec
Final Critical Design Review (dCDR)	2-Dec	1	3-Dec
CAD Generation (Fuselage, Wings, Tail, CDAs + Integration)	10-Oct	54	3-Dec
Order All Materials	13-Nov	10	23-Nov
Report Drafting	5-Nov	111	24-Feb
Building	8-Jan	53	2-Mar

Subassembly Testing (Controller/Electronics Integration/Testing)	8-Jan	53	2-Mar
Test Flights 1, 2 and 3	20-Feb	37	29-Mar
Modifications 1, 2 and 3	21-Feb	43	4-Apr
Competition	5-Apr	3	8-Apr

§3.0 Cost Analysis:

The total estimated budget is $13,137.14. However, due to receiving a static thrust test stand from RC Benchmark, the electrical engineers having their own small budget for their components, and not crashing the team was able do have a total costs of $9,169.63. The budget was mostly comprised of material and parts, while some of it was dedicated to tooling. This project will not need outside labor costs because the scope of the project building is within the team's abilities. Overall, the objective was to use the most cost efficient materials. Each was chosen as it was the highest quality material at a reasonable price point. This lead to the main aircraft being made primarily out of wood with a few carbon fiber parts. This allowed for the most durable design while still being cost effective. To see the complete Bill of Materials see *Appendix C,* which is the cost to build the aircraft. This does not include hotel and registration fees.

§4.0 Table of Referenced Documents, References, and Specifications:

Table 4.0 Referenced Documents and Specifications	
Reference Number	Citation
[1]	Simons, Martin. *Model Aircraft Aerodynamics*. Special Interest Model Books, 2015.
[2]	Raymer, Daniel P. *Aircraft Design: a Conceptual Approach*. American Institute of Aeronautics and Astronautics, Inc., 2018.
[3]	Phillips, Warren F. *Mechanics of Flight*. John Wiley & Sons, 2010.
[4]	Torenbeek, E., and H. Wittenberg. *Synthesis of Subsonic Airplane Design: an Introduction to the Preliminary Design of Subsonic General Aviation and Transport Aircraft, with Emphasis on Layout, Aerodynamic Design, Propulsion and Performance*. Delft University Press, 1982.

§5.0 Design Layout & Trades:

§5.1 Overall Design Layout and Size:

The guiding principle behind the design of the Primary Aircraft was the minimization of drag and weight. Severely underpowered at 750 W of propulsive power, the aircraft had to be as aerodynamically efficient as possible and generate as much lift possible given the power constraints.

In order to aid in takeoff performance, a tricycle landing gear configuration was chosen. With this configuration the wings would sit and a neutral angle of attack on the runway, allowing for less drag during takeoff. Therefore, the aircraft will be able to take off in a short amount of time. The nose gear and rear gears chosen for the design were metal struts, which come stock with simple mounting brackets for ease of implementation. The struts also allowed for some give in the event of a harsh landing.

Wind tunnel tests were performed on the Nerf habitat modules to determine whether they could be mounted on the exterior of the aircraft. It was determined that each generated 0.39 lbs of drag, which would be detrimental, given the design goal of 8 habitat modules. In order to mitigate the large amount of induced drag of a traditional fuselage and to accommodate the volume of 8 habitat modules and 67.6 ounces of water, the team designed the blended wing body. This design in beneficial for two primary reasons: it minimizes drag given the required volume and utilizes the center body as a source of lift opposed to just creating parasitic drag.

Following the decision to fit the payload inside of the aircraft, a payload box was designed to relieve any complications of loading the payload through the bottom of the body, piece by piece. Designed to be a removable cartridge, all necessary structure, electronics and payloads are self contained. The payload box is simply plugged into the primary aircraft's (PA) electronics and secured with quick release fasteners.

The empennage design is based off the conventional layout and consists of a vertical stabilizer-rudder assembly with a horizontal stabilator. Although the stabilator would be comparatively more difficult to manufacture than the traditional assembly, the reduced drag and weight of the all-moving tail is ideal. The NACA 0009 airfoil was selected for both tail surfaces because of its low drag characteristics and is commonly used in low speed flight. To securely fix the tail stabilizers at the calculated moment arm of five feet aft of the MAC of the wing, a tubular carbon fiber tail boom was utilized as the structural connecting member.

The Colonist Delivery Aircraft uses a flying wing aircraft type to achieve high structural efficiency and reduced parasite drag. Flying wings eliminate the empennage and have no definite fuselage. The wing airframe structure is used for both packaging of the colonists, avionics, and shock sensors, but also for all required structure and lift generation. The CDA flying wing is divided into two sections: a main colonist cabin, and two additional wings.

The CDA colonist cabin uses a balsa rib structure, where the ribs use the vacant space between the colonists. The thickness of the cabin is limited by the colonists and the vertical shock sensor, and so the cabin ribs fit within these constraints to achieve a cabin as thin as possible, reducing otherwise significant parasite drag.

The wings use a flat plate geometry to increase aircraft aspect ratio and lifting area, without introducing significant cost to weight or drag budgets. Although a 2% camber was introduced for the final wing design, the flat plate allows the aircraft to achieve lift since the

CDA glides with a positively trimmed pitch angle, giving the wing a positive angle of attack. The wings used balsa wood to reduce weight by a factor of four over an alternative foam design.

§5.2 Overall Electrical Design Layout

A robust telemetry system provided the pilot and ground station vital information for precise payload expulsion. A Pixhawk 4 flight controller provides accurate motion measurements, transmits real-time altitude, and includes its own battery management system. A laptop at the grounding station displays a Graphical User Interface (GUI) to present the data to the judges and payload specialist. In addition, the GUI exports flight information onto a CSV file for the judges viewing for playback functionality. The telemetry system utilizes a pair of SiK radios for reliable connection between the ground station and PA.

The team allocated weight restrictions for the different CDA components and subsystems to meet the 9 oz weight limit for the CDAs. In total, the electronics and servos were allocated a maximum weight of 2 oz to allow for a light, compliant, yet sturdy aircraft structure. An Arduino Nano microcontroller, programmed using C++, guides the CDA to the desired target by reading GPS and Inertial Measuring Unit (IMU) recordings and actuating the servos to align the CDA with the relative vector.

§5.2.1 Primary Aircraft Electronics

Careful consideration and research into telemetry systems was placed during the design phase of the DAS since competition rules stated that DAS failures are considered a missed flight attempt. The Pixhawk 4 flight controller was selected due to its features and capabilities in assisting the payload specialist and pilot. The Pixhawk transmits real-time altitude, distance traveled, and distance from the landing zone to assist the payload specialist at the grounding station. The GUI is written in Python and is used by the payload specialist to determine when to drop the payload by pressing a button specified for each payload. Additionally, the Pixhawk 4 includes a 3-axis accelerometer, a 3-axis gyroscope, and a designated magnetometer/barometer to provide accurate motion measurements on the serial output port. It also has its own battery management system on its power management board that measures the voltage and current of the battery. The SiK radios operate at 955 MHz with a line of sight range of 1 kilometer which provides strong communication since the PA flies within a radial distance of less than 500 feet. Figure 5.2.1 below depicts the complete diagram showing the electrical and mechanical components of the PA.

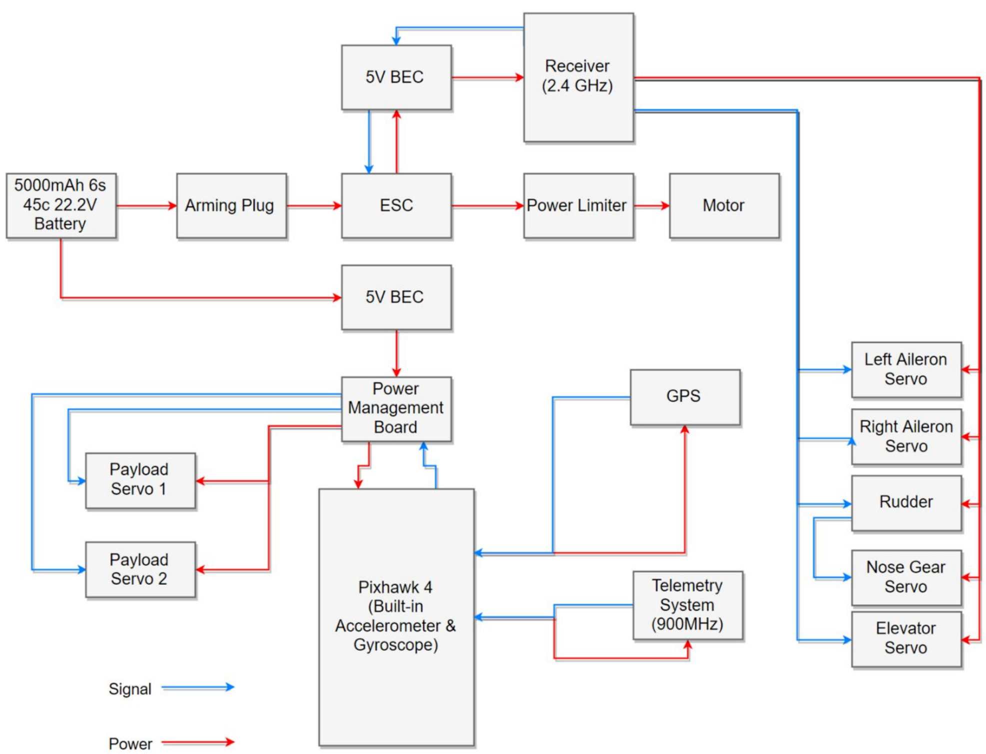


Figure 5.2.1: PA Block Diagram

The battery for the PA was sized by evaluating mandatory flight time and relating that to necessary battery capacity. The maximum safe flight time can then be calculated by dividing the battery capacity in milliamp hours by the total current draw. From Eq (1), it was determined that a 3000 mAh battery at 25c drawing roughly 45 Amps (taking into account the servos in its idle state), would fly the aircraft roughly 3 minutes and 10 seconds. A safety factor was implemented to prevent the battery capacity from draining below 20%. Since the desired flight time was estimated to be at least five minutes, a larger battery capacity was chosen according to this time. Using Eq (1), a 45c, 5000 mAh battery was chosen as the power source for the motors, electronics, and all the servos.

$$flight\ time = \frac{battery\ capacity}{current\ draw} \times 60 \times 80\% \tag{1}$$

§5.2.2 Colonist Delivery Aircraft Electronics

Several trade studies were conducted with autonomous flight system complexity and power source capacity as the primary components during the CDA design phase. After conducting extensive research, a relatively simple mechanism was chosen. The resultant system does not include extensive processing power, which utilizes a smaller power unit and results in a light and effective system.

The autonomous flight path is controlled by an Arduino Nano microcontroller which guides each of the CDAs to land within the landing zone. Flight control is achieved via a pair of servos that control the ailerons. The software is written in C++, and features two software loops. The first loop is utilized during standard operation of the CDA, and takes advantage of both a GPS receiver and an IMU sensors package onboard the aircraft. These are used to determine the CDA's relative velocity, altitude, heading, and global coordinates. These values are compared with target zone coordinates and the software calculates a relative vector that the CDA must follow in order to land successfully without activating the shock sensors. Once this relative vector has been calculated, the microcontroller will actuate the ailerons in order to correct itself and remain on course to the target zone. The second software loop is the emergency halt system, which employs an active low flag on the Arduino. If the timeout period is expired onboard the CDA, and no signal is received, then the emergency halt system will be employed to safely bring the CDA to the ground. Additionally, the emergency halt system can be manually triggered via a button in the pit, which will interrupt the main loop.

The system continuously requires 1.21 Amps and 5 Volts to stay powered. Given that weight needed to be kept at a minimum, a 250 mAh 1s 30c lithium-polymer battery was chosen. But as mentioned previously, the electronic components operated at higher voltage, and thus the battery would need to be connected to 5 Volt step-up DC-to-DC converter. Using Eq (1), the flight time was calculated to be 9 minutes and 55 seconds which is sufficient for the CDAs to reach the landing zone. An XBee Pro S1 receiver on the CDA provides the rules compliant manual override by interrupting the autonomous flight system and actuating full up pitch if deemed necessary by judges. The electronic system schematic can be seen in Figure 5.2.2.

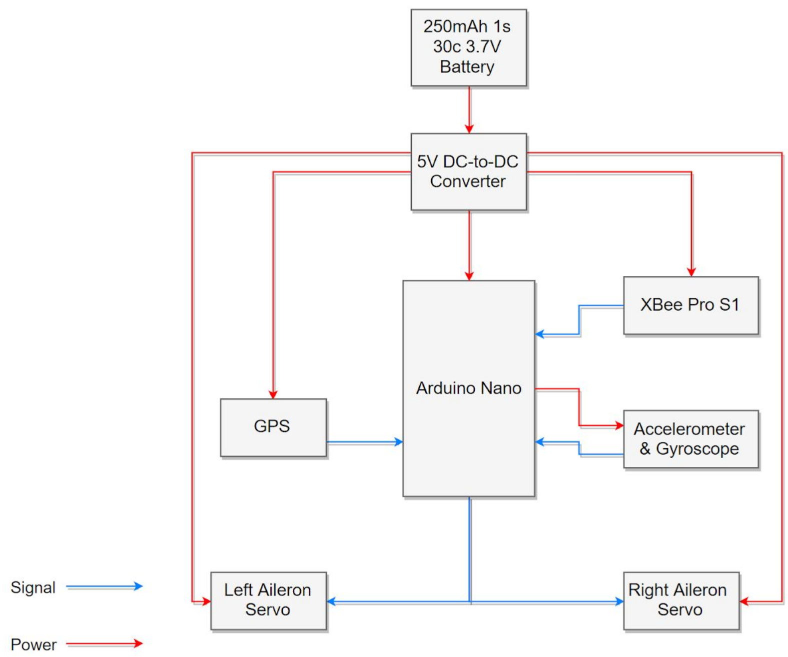


Figure 5.2.2: CDA Block Diagram

§5.3 Optimization

The electric motor used to power the PA is a Hacker A40-10s V4 14 pole. This specific model was chosen due to its maximum power rating and Kv (RPM/Volt ratio) value. Rated at 900 Watts, it exceeds the 750 Watt limit which ensures the motor is not overworked by constantly running it at its maximum power. This motor also has a relatively low Kv value at 355 Kv. This is preferable because as the Kv value decreases, the torque of the motor increases, as seen in Eq (2). With thrust optimization in mind, this motor was paired with a 16x4 propeller. This larger diameter, low pitch propeller gave the highest static and dynamic thrust numbers.

$$\tau = \frac{I}{Kv} \tag{2}$$

§5.3.1 Competitive Scoring and Strategy Analysis:

The inception of our scoring and design strategy was an analysis of the scoring equation, shown below in Eq (3).

$$FFS = \frac{N_c * D}{15N} + \frac{2S_p}{N} \tag{3}$$

D is given by Eq (4):

$$D = 25(2^{1-Maximum(\frac{N_c}{8N_H}, \frac{N_c}{N_W})}) \tag{4}$$

The variable for water, N_W, can only increase in increments of 16.9, so it can be said that for every minimum increment of water, there should be 2 habitat modules. Calling this new equivalent resource variable N_R, Eq. (4) can be substituted into Eq. (3), resulting in Eq (5):

$$FFS = \frac{N_c * 5(2^{1-(\frac{N_c}{16N_R})})}{3N} + \frac{2S_p}{N} \tag{5}$$

Finding the maximum of this equation with respect to the number of colonists (setting the partial derivative with respect to N_C equal to zero) yields the following, Eq (6):

$$\frac{\partial FFS}{\partial N_C} = \frac{5}{3N}\left(2^{1-\frac{N_C}{16N_R}}\right)\left[1 - \frac{\ln 2}{16}\frac{N_C}{N_R}\right] = 0 \tag{6}$$

Solving this results in the following ratio, Eq. (7):

$$N_c = \frac{16}{ln(2)} N_R \approx 23 N_R \tag{7}$$

This means that the optimal number of colonists is 23 for every 16.9 oz of water and every 2 habitat modules. This optimal number informed our design goal, which is to carry 90 colonists, 8 habitat modules, and 67.6 ounces of water.

§5.3.2 Optimization and Sensitivity Analysis:

The first iteration of payload transport involved external underwing mounting. To determine the drag of the Nerf footballs, their drag was measured using wind tunnel testing, shown in Figure 5.3. It was found that each football generated 0.39 pounds of drag at 55 ft/s. Given our goal of 8 housing modules, it was decided that the payload could not be mounted externally. This further dictated the design, forcing the creation a blended wing body.

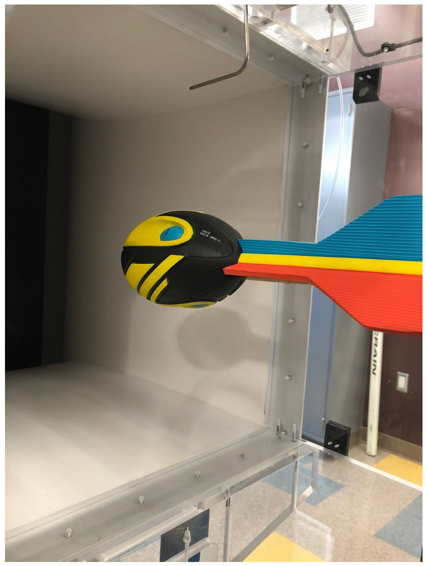


Figure 5.3: Wind Tunnel Testing on a Nerf Football

§5.4 Design Features and Details:

The sizing of the payload box was determined based on the previous scoring analysis. From this it was determined that 2 one litre water bottles and 8 nerf footballs should be released to maximize score. Packing these as efficiently as possible, a payload box size of 25.88 x 18.25 inches was needed.

§5.5 Interfaces and Attachments:

In order to maximize structural efficiency and minimize weight, the team decided to create a core structural member, known as the "T-bar" because of its shape. All major loads on the aircraft would be transferred to this assembly, making it the backbone of the aircraft. It is the primary attachment point for the wings, tail, and carries the weight of the center body. Due to the tubular shapes the T-bar, spars and tail boom, these attachments are as easy as slipping one tube inside the other and pinning in place. Specifically, to step down the diameter of the tail boom to that of the T-bar, a hard fiber tube was used. It uses cotton fabric as the reinforcing material and was primarily chosen due to its high strength to weight ratio, impact resistance and machinability.

The mounting mechanism for the release of the Colonist Delivery Aircraft (CDA) was inspired by work done by previous hobbyists who release gliders from remote control aircraft. The structure was designed with the intent of minimizing drag as well as the least amount of interference with the airflow over the wings. Moreover, the middle CDA could not hit the tail of the PA upon release, so the structure had to provide sufficient elevation. The flight mechanics of bi-planes and bi-plane theory were also taken into consideration, as before release the system has some flight mechanics similar those of a biplane. The release mechanism was designed such that it only used one servo for actuation, and therefore only had one point of release failure.

§6.0 Loads and Environments, Assumptions:

§6.1 Design Loads Derivations:

The loading on the wing will come from two primary sources, lift and drag. The lift distribution for the designed planform was calculated using a Schrenk's approximation. This method assumes the average lift on a non-elliptical wing is the average of an elliptical wing and a trapezoidal shape. The lift distribution across the span of the wings was used for the calculation of stresses and sizing of the spars.

§6.2 Environmental Considerations:

Wind speeds and ambient conditions were taken into account during the design process. Previous experience and analysis of weather patterns around Van Nuys during the month of April dictated that high-torque servos be used to counteract possible high wind pressure. In addition, possible gust instability was taken into high consideration when designing the CDA. One of the benefits of the flying wing design is its aerodynamic profile, both in flight direction as well as against gusts. This gives it more resistance to instability to crosswinds than a rectangular fuselage.

§7.0 Analysis:

§7.1 Analysis Techniques:

§7.1.1 Analytical Tools:

SolidWorks was used for 3D modeling as well as the primary method of performing FEA to find stresses. Abaqus was used as a preliminary FEA tool for finding the stresses and deflections in the T-bar.

XFLR5 is a free computational fluid dynamics tool with an emphasis on airfoils and other aircraft. It was used throughout the design process for the analysis of aerodynamics and flight kinematics of both the PA and CDA.

MATLAB was used for the development of charts which show aircraft flight performance in turning as well as the power required to overcome drag. These figures are shown in Figures 7.1.2 and 7.2.1, respectively.

§7.1.2 Developed Models (Take-Off, Turning Flight, etc.):

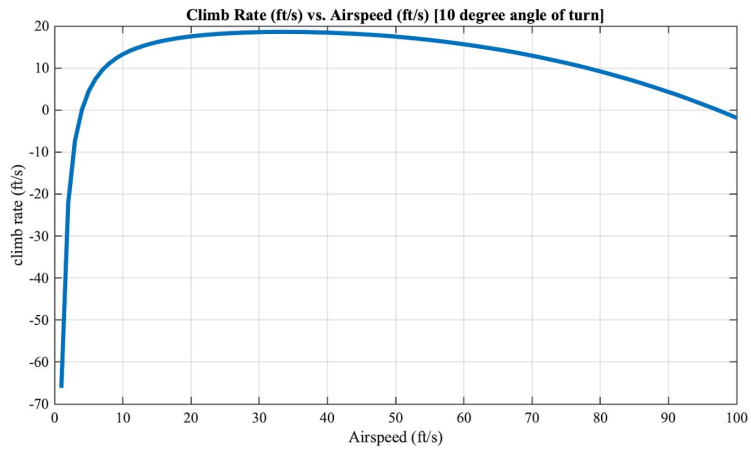


Figure 7.1.2: Climb Rate vs. Airspeed Graph

Figure 7.1.2, shown above, illustrates how at a turn angle of 10 degrees and at a realistic airspeed, the PA still generates sufficient lift such that it will not sink.

§7.2 Performance Analysis:

§7.2.1 Runway/Launch/Landing Performance:

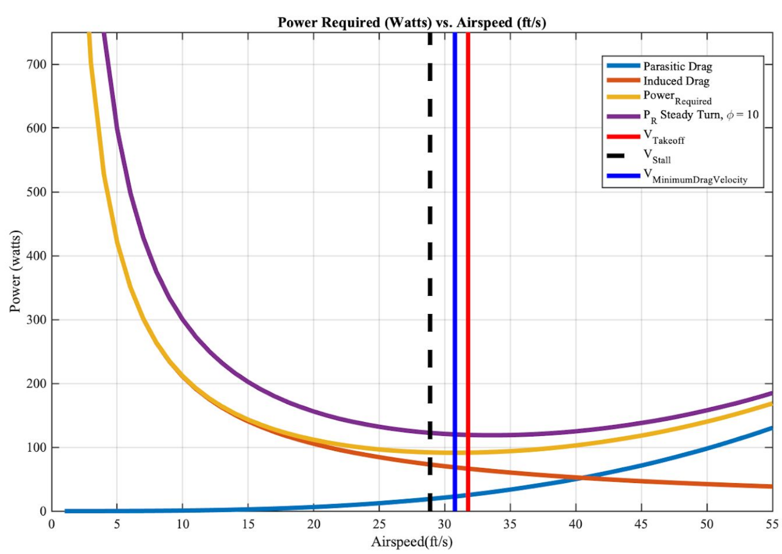


Figure 7.2.1: Power Required vs. Airspeed Graph

Figure 7.2.1, shown above, illustrates the recursive power balance of propulsive power required and the drag that such power would give the aircraft and achieve a certain airspeed. The important implications of this figure is that our take-off velocity occurs at 31.7 ft/s and our velocity of minimum drag is at 30.7 ft/s.

§7.2.2 Flight and Maneuver Performance/Dynamic & Static Stability

To counteract the effects of adverse yaw when banking a large turn using ailerons, we oversized our rudder slightly from the standard specifications for RC applications to give more effective control. Additionally, the design of the horizontal stabilator allows for effective trimming to longitudinally stabilize the plane for steady flight with only a small amount of deflection due to its increased size versus a standard elevator setup. Also, the ailerons were sized using standard RC application recommendations and placed at an outboard location for lateral stability. Lastly, the CG of main aircraft is below the lifting wing, contributing to static stability.

§7.2.3 Aeroelasticity:

The primary concern with aeroelasticity is flutter, commonly associated with a Strouhal number. While it is less of a concern for low speed aircraft, considerations were still made to mitigate the possibility of flutter. The weight of the wings was designed to be concentrated near the fuselage attachment, which decreases the eigenfrequency and shifts the flutter speed up. Moreover, servo motors were carefully placed and sized to ensure minimal control surface slop, another cause of flutter.

§7.2.4 Lifting Performance and Payload Prediction:

To determine the optimal lifting capacity of our design for steady flight based off our effective thrust numbers, we conducted a drag to thrust equivalence study while varying the airspeed. Starting with the static thrust, we summed the forces in the x-direction to find the acceleration of the plane for a given mass and multiplied it by a time step to obtain the change in velocity. Continuing on with these time steps, dynamic thrust was implemented along with the corresponding parasitic and pressure drag from an increased lift for the higher airspeed. Eventually the thrust and drag equalized deciding our maximum weight capacity of 25 lbs based on the lifting performance at this theoretical maximum airspeed.

§7.3 Structural Analysis

§7.3.1 Critical Stress and Deflection Calculations

For the main and secondary spars, carbon fiber was chosen because of its high strength to weight ratio. Calculations showed that a fracture failure due to bending stress is not realistic. Therefore, the limiting factor of the spar design became the amount deflection. With the Schrenk's approximation discussed earlier, the sum of moments was used to determine an equivalent tip load (6.7 lbs) to ease calculations. The chosen design resulted in a wing tip deflection of 2.1 inches.

Each center body component was subjected to FEA in order to determine the stresses each would experience. Due to the anisotropic nature of plywood, the main material of the center body, the methodology of FEA was more useful and beneficial than hand calculations. The maximum stress occurs at the connection of the primary spars and tail boom such that only strong materials such as aluminum and carbon fiber could be used.

The primary concern for the tail boom was deflection as determined from a stress analysis. Modelling the tail boom as a cantilever beam, the deflection was the driving factor of the sizing of the tube, as the maximum stresses were well under the yield stress of the carbon fiber. The selected sizing of 1 ¼" x 1 ⅜" resulted in a maximum deflection of 0.03 in during worst case loading situations. This low deflection design constraint was chosen to avoid unwanted vibrational modes that could result in a failure at the connection joints of the tail boom that would certainly ensure a crash when the tail breaks off.

§7.3.2 Mass Properties & Balance:

Due to the performance requirement of releasing payload that makes up a large percentage of planes loaded weight, the center of gravity considerations were crucial to the stability of the plane during flight. Thus, the loaded and unloaded CG's were designed to be within a small margin of each other at 0.2 in. The weight distribution of the aircraft is displayed below in Table 7.3. The corresponding contributions to the CG for each component of the aircraft can be found below in Appendix A.

Table 7.3: Weight Distribution

Group	Weight (lb.)	% T.O.W.
T-Bar Spar Assembly	3.1785	14
Blended Wing	3.2347	14
Tail Assembly	1.6800	7
Gear and Motor	2.0588	9
Electronics	2.2261	10
Dynamic Payload	8.4756	37
Misc.	1.8706	8
Total	22.7243	

§8.0 Assembly and Subassembly, Test and Integration:

§8.1 Testing/Trade Studies:

A trade study was performed comparing the traditional tail, t-tail, v-tail, and h-tail assembly. The trade study placed an emphasis on weight, manufacturability, drag, and stability. Although the t-tail reduced drag, the increased weight and difficulty of manufacturability is not ideal. Research determined that a v-tail required the same amount of effective control surface as a traditional tail which results in minimal weight savings. The h-tail provided more stability compared to the traditional tail but the increased weight and difficulty of manufacturability is not ideal. Another trade study was performed comparing the stabilator and the traditional stabilizer-elevator assembly with an emphasis on weight, manufacturability, drag, servo layout, and innovation. Interference drag is reduced because the hinge line found in a traditional design is removed. Weight is reduced because hinge connectors and an extra servo are no longer necessary. Weight is also reduced since the tail area necessary for pitch control is smaller because the entire surface now acts as an elevator.

Weight and deflection were the primary design considerations for the tail boom because the long moment arm results in a potentially large deflections and contributions to the CG. Any weight savings in the tail boom can significantly shift the CG of the aircraft forward to help stabilize the plane without the need for a heavier ballast. For these reasons carbon fiber and aluminum were compared in a trade study due to their lightweight and stiff characteristics. Carbon fiber was chosen in the end due to its superior stiffness to weight ratio characteristics. Specifically, a multi-layered unidirectional ultra high modulus carbon fiber tube of 1 ¼" inner diameter by 1 ⅜" outer diameter was chosen.

The motor and propeller selection was initially analyzed based on Eq (8). This allowed calculations to be made and showed theoretical values that lead to the conclusion of either a single or double motor would be the best option. For a 14" x 5" propeller spun at 8000 rpm, a static thrust of 6.2 lbf was calculated. For a 12" x 4" propeller spun at the same rpm, the static thrust calculated was 3.2 lbf. These values simulate expected thrust values for a single motor, and dual motor configuration respectively. Since the smaller propeller would be used on the twin motor set up, the value must be multiplied by a factor of two, thus giving 6.4 lbf. This is similar to the thrust produced from the single motor with a larger propeller. These numbers lead to the testing phase for the powertrain components.

$$T = 1.225\frac{\pi(.0254*d)^2}{4}[(RPM * .0254*pitch*\frac{1\,min}{60\,sec})^2 - (RPM * .0254*pitch*\frac{1\,min}{60\,sec})^2 v_o](\frac{d}{3.29546*pitch})^{1.5} \quad (8)$$

§8.2 Prop Configuration and Validation Testing Procedure:

Once the best propeller size was found by theoretical calculations using an estimated RPM value, the propellers were tested using the large motor on a RC Benchmark 1580 thrust stand. The thrust stand was first calibrated and then the Hacker A40-14s motor was attached along with the propellers that would be tested. A multitude of propellers were tested including gas propellers 12.25x3.75 and 14x6, narrow propeller 14x5, and many electric propellers 15x4, 15x6, 16x4, 16x8, 17x6, and 17x8. These propellers were chosen because they were within the range of the theoretical calculations, but also allowed to see the effect of the different type, pitch, and diameter had on the selected motor with limited power. These tests showed that the 16x4 would provide the most thrust at 7.365 lbf of thrust with power at 744.472 W, as seen in Figure 8.2.1. This propeller was then tested multiple times to ensure consistent results, which were obtained. This data was then extrapolated using Eq (8) to provide dynamic thrust estimations, as seen in Figure 8.2.2.

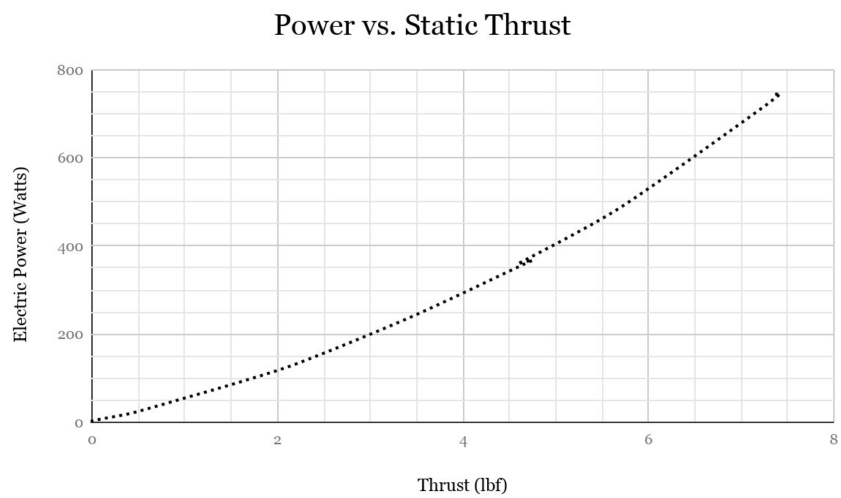


Figure 8.2.1: Power vs. Static Thrust Graph

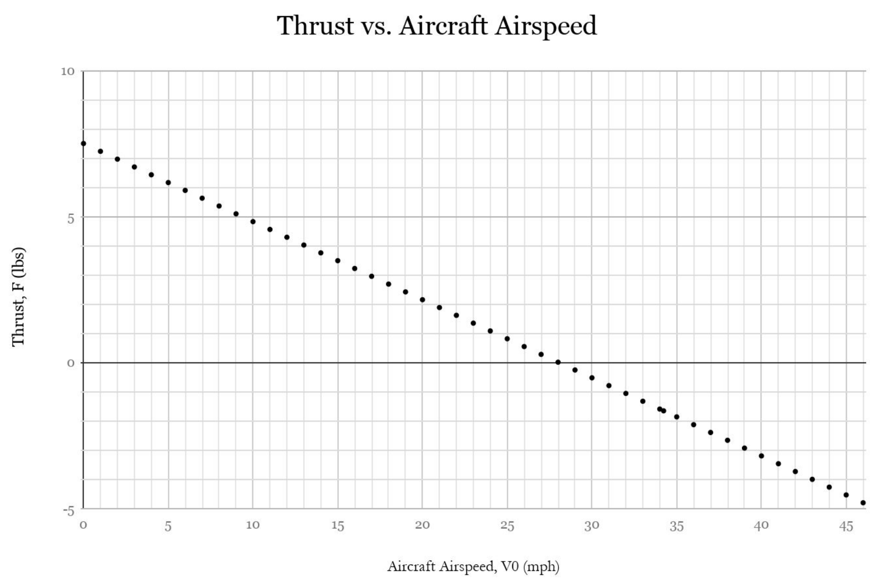


Figure 8.2.2: Dynamic Thrust vs. Airspeed Graph

§8.3 CDA Validation Testing Procedure:

§8.3.1 CDA Hardware Validation Testing Procedure:

Another scope of the design that needed to be tested was the gliding of the CDAs to ensure the configuration would allow for a gentle enough landing to not trip the 50G shock impact devices. The CDA design was tested by attaching a small Turnigy 2730 motor, esc, receiver, and an 8x4 prop to the prototype. These elements allowed for the CDA to be tested without the main aircraft built and also simulated the weight of the electronics and ping pong balls the CDA will be carrying for competition flight. To test the CDA, the aircraft was powered and thrown into the air allowing the CDA to reach appropriate height and speed to simulate the gliding it will need to perform for competition. Once the CDA reach that point of height and velocity the motor was shut off and it glided to the ground. The original design had a low glide ratio to allow for the CDAs to be released and hit the target within a relative short time span. After testing, it was established that design needed to be slightly altered because the glide ratio was too low which would trigger the 50G shock impact device. The changes made to the design included adding a cambered airfoil to the wing profile in order to add lift, and reshaping the center body to be thinner in attempt to reduce parasitic drag.

§8.3.2 CDA Software Validation Testing Procedure:

CDA Software was tested and validated through a combination of software-driven tests, and real-world ‘test like you fly’ trials. The Autonomous flight software driving the CDA features two modes of operation: Manual and Autonomous flight. In Manual flight, the CDA will anticipate input from a standard OTS RC Transmitter, and flown like any standard aircraft. The CDA will employ a standard OTS RC Motor to reach a suitable altitude, where testing can be performed. Autonomous mode will utilize a combination of GPS and IMU sensor data to determine the current heading, speed, and altitude of the CDA. This data is compared with a desired GPS coordinate, and an expected path for reaching that desired destination to determine the CDA's deviance from that path. This deviance is translated into a set of motions that the flaps will perform in order to return to the desired path.

§9.0 Manufacturing:

Due to the modular design of the aircraft and its subassemblies, the primary tool used for manufacturing was an Epilog Zing 40W Laser Cutter. This method of manufacturing allowed us to rapidly prototype and create parts, provided they were a planar extrusion. This allowed the majority of parts to be cut and assembled in a matter of hours. All spar, stringer, wire and hollowing holes for the airfoil ribs were pre-cut by the laser cutter.

In terms of control surface manufacturing, two main servo configurations were used with careful considerations from previous hobbyist recommendations from last year's competition. A pull-pull configuration was set up for the rudder using strengthened nylon cable and tensioners. Standard pushrod and control horn attachments were implemented on all other control surfaces. Z-bends and rubber stoppers were added to prevent any loosening or separation of the pushrods during flight.

§10.0 Conclusion:

A combination of effective and continuous communication as well as the ability to respond to the challenges intrinsic to being the first of teams to compete given a new mission requirement were the primary sources of this team's success. The largest obstacle was creating requirements beyond those given in the rules, as there has been no past work done for such a mission problem statement.

The team rose to the challenge and created not only one, but two aircrafts designed to achieve maximum success in a subscale mars colonization landing mission. The PA is an efficient lifting body, despite the severely underpowered propulsive power by which it is constrained. It minimizes parasitic weight and drag while still achieving the necessary volume and lifting force that is required of it. The CDA follow the same design philosophy of the PA, minimizing structure while maximizing volume. However, they have the added challenge of autonomous, unpowered flight across a distance of 200 feet. The final flying wing design met the constraints of aerodynamic and structural efficiency perfectly.

§11.0 Areas of Design Improvement

Competition performance

The team's design performed well at the SAE Aero Design West, achieving 5th place in flight among the 20 teams in the Advanced Class competition. The team also came in 2nd place among the North American teams. Overall, the team came in 8th place with a score of 76.5352, and receiving 6th place for the technical presentation and 11th place for the technical report.

A lack of full understanding of the rules and their enforcement during the competition was a major point of failure for the team. It was not understood that the payload specialist was fully responsible for guiding the pilot towards the target in order to drop the dynamic payload, and as a result the interface was subpar. This led to the team's inability to successfully drop dynamic payload on target, instead scoring only through static payload.

System Design

The PA and CDA system was designed to deliver an optimal ratio of resources and colonists to the target. This ratio failed to recognize two significant aspects of the scoring analysis: the greater scoring potential of increased resource delivery and sensitivity to changes in delivered colonists or resources. The analysis performed and documented above looked at the optimal number of colonists to be delivered for a given number of resources. There is a clear maximum in the scoring equation, however increasing resources delivered always increases score - it is a constantly increasing function. Our system was designed considering a maximum number of colonists that can be delivered, not the maximum number of resources. We were not ignorant of these factors in making decisions, but instead we used the wrong factors as system drivers. Focus should have been on delivering increased number of resources and not colonists. Delivering one more resource unit (2 habitats and 16.9 fl oz of water) produces a stark increase in scoring potential, i.e. the increase in score from increasing resources delivered is far more significant than the impact of increasing colonists delivered. These factors are important to include in the trade studies involved in system and aircraft designs.

BWB Trade Study

The decision to choose a blended-wing body design for the Primary Aircraft was fundamentally a consequence of drag calculations and estimates. Estimates used to make these calculations ultimately used a cruising airspeed significantly higher than what was later calculated and measured in flight. For example, drag on the Nerf howlers used a cruise airspeed of 55 ft/s, versus the actual 40 ft/s achieved by the aircraft, resulting in a drag calculation inflated by a factor of 2. This should be considered for future designs, since conclusions based on it were used to dictate the entire PA system design.

Manufacturability and operation should also be considered in the blended-wing body design trade. Both of these factors introduced unnecessary complication in the PA design. For example, the contours of the BWB required careful construction with balsa stringers, followed by time-expensive monokoting. The complexity of the BWB's center structure could be simplified to aid ease of manufacturability. For example; the outer tip blending section of the BWB could be simplified so as to greatly speed up the time taken to assemble the center blended wing body's airframe. Additionally, in order to preserve the contours on the aircraft's top side, all access to avionics and payload was from the bottom. Therefore, when the subsystems in the PA were not functioning properly, the BWB presented an obstacle for troubleshooting and fixing the subsystems.

CDA Design

Since the Colonist Delivery Aircraft could not be adequately flight tested due to schedule overruns and the failure of the flight control system, it is difficult to draw any conclusions about the CDA's performance.

Drag considerations for the CDA, since it is a gliding aircraft, are imperative in its design. In designing the wings, aspect ratio should be considered a system driver, and camber should be avoided, since lift-induced drag increases with the square of the lift coefficient. The 2% camber introduced into the final CDA design was likely an error, negatively impacting performance, although this was not rigorously evaluated. Wings with high aspect ratio allow lift generation without significant cost to lift-induced drag.

Flight loads on the CDA are nearly negligible due to its small span loading (13x less than for the PA), however this is only during the CDA's own gliding flight, and increased flight loads from PA flight should be considered in CDA wing design. The left balsa wing of the CDA folded during PA take off due to the increased flight loads.

Due to unknown final weights of avionics and glue, weight was conservatively budgeted throughout airframe design, producing a final aircraft 1.3 oz under the competition limit. This 1.3 oz could have been used for strengthening the wings.

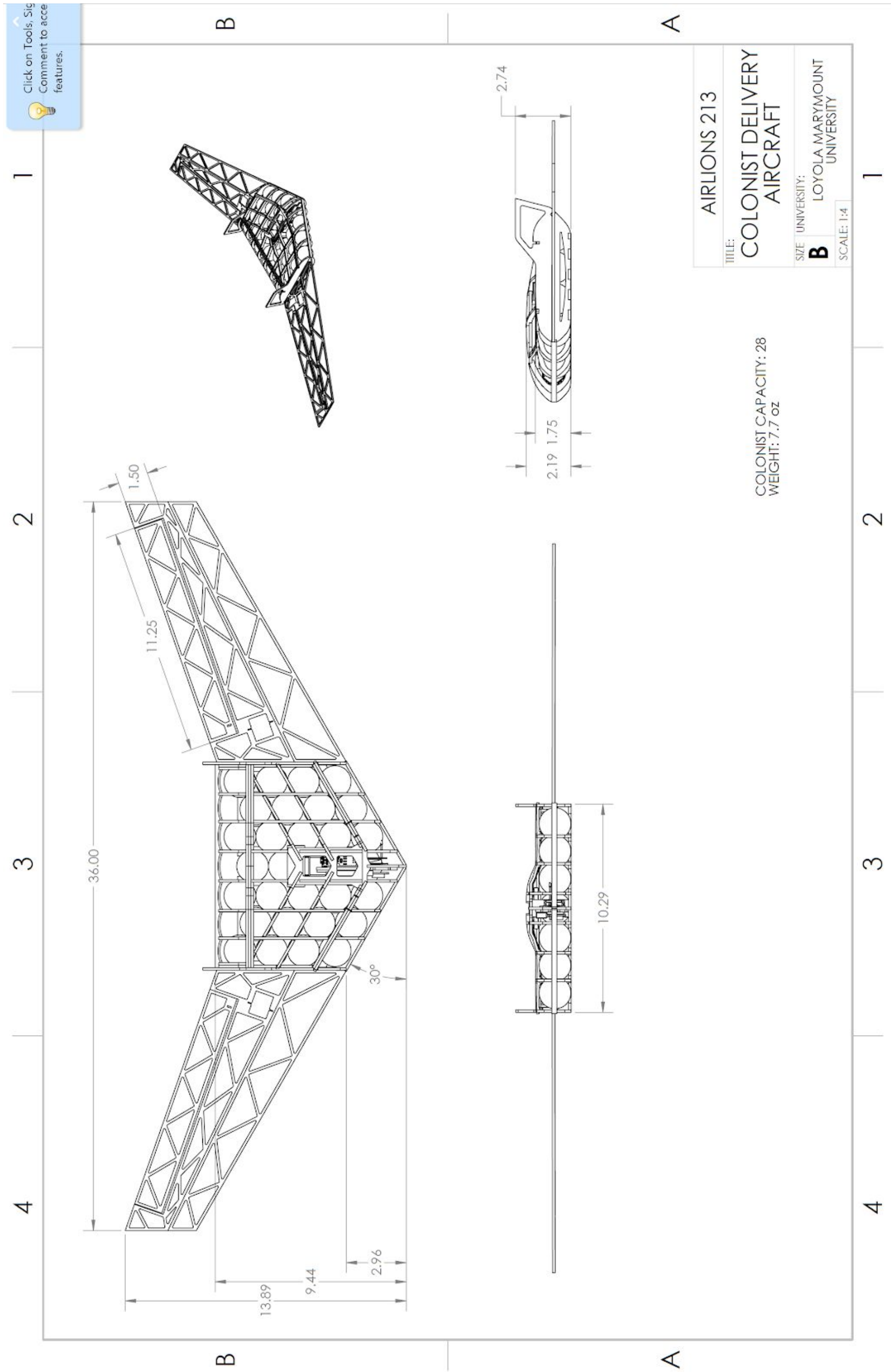
Tail Housing

Several design changes were made to the tail housing due to a lack of appropriate equipment to manufacture the original design which required drilling a hole through a solid basswood block. The drill press had difficulties making concentric holes with the spade bit and it struggled to go through the wood block which generated a lot of heat. The new design utilized laser cut basswood ribs glued directly to the tail boom for a permanent attachment. Basswood plates with spar and servo wire holes were glued to these ribs and balsa stringers were attached to assist in a smooth covering of the housing in ultrakote. The vertical stabilizer was attached to the housing by glueing the spar into the top plate cutout as well as glueing the bottom rib to the top plate. A high torque servo capable of actuating the horizontal stabilator was glued underneath the housing. A carbon fiber pushrod connects the servo arm to a custom servo horn glued to a rod running through the length of the horizontal tail. In the rear of the housing a pinning hole is used as the pivot point for the horizontal stabilator. This new lightweight design was very similar in shape to the original design and it simplified manufacturing.

Appendix A – Supporting Documentation and Backup Calculation

Table A: Center of Gravity Ledger								
	Take-Off (Loaded)				Landing (Unloaded)			
Category	Item	Weight (lb.)	Dist. Datum (in)	Moment (lbin)	Item	Weight (lb.)	Dist. Datum (in)	Moment (lbin)
Airframe	Center Body	0.9847	13.8303	13.6187	Center Body	0.9847	13.8303	13.6187
	Payload Box (Empty)	1.0500	19.3152	20.2810	Payload Box (Empty)	1.0500	19.3152	20.2810
	T-Bar Assembly	1.1640	20.8285	24.2448	T-Bar Assembly	1.1640	20.8285	24.2448
	Main Spar	1.6061	16.6252	26.7019	Main Spar	1.6061	16.6252	26.7019
	Secondary Spar	0.4083	21.8552	8.9241	Secondary Spar	0.4083	21.8552	8.9241
	Lifting Wing (x2)	1.0000	18.8852	18.8852	Lifting Wing (x2)	1.0000	18.8852	18.8852
	Blended Wing (x2)	0.2000	18.8852	3.7770	Blended Wing (x2)	0.2000	18.8852	3.7770
	Tail Assembly (Boom+Tail)	1.6800	56.0852	94.2231	Tail Assembly	1.6800	56.0852	94.2231
	Motor	0.5276	0.5300	0.2796	Motor	0.5276	0.5300	0.2796
	Nose Gear	0.4063	4.5702	1.8566	Nose Gear	0.4063	4.5702	1.8566
	Rear Gear	1.1250	19.1402	21.5327	Rear Gear	1.1250	19.1402	21.5327
	Wheels	0.5423			Wheels	0.5423		
Electronics	Main Battery	2.0966	8.3127	17.4284	Main Battery	2.0966	8.3127	17.4284
	ESC	0.0947	4.5702	0.4328	ESC	0.0947	4.5702	0.4328
	Pixhawk 4	0.0348	8.3127	0.2895	Pixhawk 4	0.0348	8.3127	0.2895
Dynamic Payload	1L, Water Bottles (x2)	4.6033	17.0000	78.2553	1L, Water Bottles (x2)	0.0000	17.0000	0.0000
	Nerf Howler - Front (x4)	1.0924	15.0000	16.3860	Nerf Howler - Front (x4)	0.0000	15.0000	0.0000
	Nerf Howler - Back (x4)	1.0924	19.0000	20.7556	Nerf Howler - Back (x4)	0.0000	19.0000	0.0000
	CDA (x3)	1.6875	19.3552	32.6619	CDA (x3)	0.0000	19.3552	0.0000
Misc.	Servos (6 @ 0.1323 lb. ea.)	0.7937	0.0000	0.0000	Servos @	0.7937	0.0000	0.0000
	Monokote (@9.4g/sq ft)	0.7300	0.0000	0.0000	Monokote (@9.4g/sq ft)	0.7300	0.0000	0.0000
	Ballast	0.0000	0.0000	0.0000	Ballast	0.0000	5.1252	0.0000
	Glue and Discep.	0.3469	0.0000	0.0000	Glue and Discep.	0.3469	0.0000	0.0000
Total		23.2666		400.5343638	Total	14.7911		252.4756
Center of Gravity (in)		17.2150			Center of Gravity (in)	17.0695		

Appendix B – Technical Data Sheet



Appendix C – Bill of Materials

Item	Qty	Unit Price	Shipping +Tax	Base Cost	Total Cost
TD50R 50G TELADROP / DROP N TELL RESETTABLE	15	$4.15	$4.82	$62.25	$67.07
Advanced Class Limiter SAE 2019 limiters 2019 V3 version of SAE Limiter	2	$75.00	$11.63	$150.00	$161.63
18x6W Propeller	1	$20.99	$1.63	$20.99	$22.62
12x6 Propeller	1	$4.75	$0.37	$4.75	$5.12
12x6E Propeller	1	$4.30	$0.33	$4.30	$4.63
A30-16 M V4 Similar to glow .15, more aggressive than Power 15 Elite motor.	1	$69.49	$5.39	$69.49	$74.88
A40-10S V4 14 pole	1	$110.49	$8.56	$110.49	$119.05
ZIPPY Flightmax 5000mAh 6S1P 45C w/ XT90	2	$83.08	$12.88	$166.16	$179.04
16.7 oz. Super 77 Multi-Purpose Spray Adhesive	1	$9.99	$0.77	$9.99	$10.76
FOAMULAR 1 in. x 2 ft. x 2 ft. R-5 Small Projects Rigid Pink Foam Board Insulation Sheathing	6	$5.98	$2.78	$35.88	$38.66
17x6E Propeller	1	$9.95	$0.77	$9.95	$10.72
16x4E Propeller	1	$8.42	$0.65	$8.42	$9.07
5x4E Propeller	1	$7.10	$0.55	$7.10	$7.65
1/8”x12”x24” basswood sheets	6	$13.00	$6.05	$78.00	$84.05
1/4”x12”x24” basswood sheets	4	$19.90	$6.17	$79.60	$85.77
1/4”x1/4”x48” balsa sticks	8	$0.99	$0.61	$7.92	$8.53
1/16" Thickness Half Sheet Finnish Birch Aircraft Plywood	5	$19.32	$7.49	$96.60	$104.09
1/8" Thickness Half Sheet Finnish Birch Aircraft Plywood	3	$33.88	$7.88	$101.64	$109.52
#680 5/8" dia Straight RoboStrut	2	$83.45	$12.93	$166.90	$179.83
#159F Steerable Fixed NoseGear w/Fork Strut	1	$191.95	$14.88	$191.95	$206.83
1/4" x 3/8" x 24" Basswood Stick	4	$0.70	$0.22	$2.80	$3.02
1/8" x 12" x 24" Balsa Sheet	22	$11.53	$19.66	$253.66	$273.32
1/2" x 1/4" x 48" Basswood Stick	2	$1.10	$0.17	$2.20	$2.37
1/4" x 1/8" x 48" Balsa Stick	10	$0.53	$0.41	$5.30	$5.71
1/4" x 3/8" x 48" Balsa Stick	20	$1.01	$1.57	$20.20	$21.77
1/4" x 8" x 24" Balsa Sheet	8	$9.88	$6.13	$79.04	$85.17
1/8" x " x 24" Basswood Sheet	4	$13.00	$4.03	$52.00	$56.03
12" x 2" x 2" Basswood Block	2	$2.77	$0.43	$5.54	$5.97
1/4" x 1" x 48" Balsa Trailing Edge	4	$0.99	$0.31	$3.96	$4.27

1/4”x1/4”x48” Basswood Sticks	4	$0.83	$0.26	$3.32	$3.58
1" x 1" x 24" Balsa Plank	3	$1.97	$0.46	$5.91	$6.37
1 1/4″ X 1 3/8″ Ultra High Modulus Carbon Fiber Tube 72″ Length	1	$239.00	$18.52	$239.00	$257.52
1/2″ X 3/4″ X 72" Carbon Fiber Tube	2	$129.98	$20.15	$259.96	$280.11
TREADED LIGHTWEIGHT WHEEL 4.0"	3	$16.99	$3.95	$50.97	$54.92
Bob Smith Industries BSI-157H Maxi Cure/Insta-Set Combo Pack (3 oz. Combined)	1	$11.14	$0.86	$11.14	$12.00
Bob Smith 103 Insta-Cure 2oz Super Thin	6	$9.57	$4.45	$57.42	$61.87
Bob Smith Industries BSI-135H Maxi-Cure Extra Thick Super Glue, 1 oz.	1	$6.67	$0.52	$6.67	$7.19
Gorilla 2 Part Epoxy, 5 Minute Set, .85 ounce Syringe, Clear, (Pack of 2)	2	$9.49	$1.47	$18.98	$20.45
16x4E	6	$8.42	$3.92	$50.52	$54.44
Turnigy TGY-813 Slim Wing DS/MG Servo 25T 9.0kg / 0.09sec / 30g	3	$31.93	$7.42	$95.79	$103.21
Turnigy TGY-811 Slim Wing DS/MG Servo 25T 8.2kg / 0.12sec / 30g	2	$22.92	$3.55	$45.84	$49.39
5/16″ X 0.557″ Carbon Fiber Tube 72″ Length	2	$105.00	$16.28	$210.00	$226.28
HS-5585MH Servo	1	$64.99	$5.04	$64.99	$70.03
HS-5565MH Servo	1	$64.99	$12.03	$64.99	$77.02
1/64 THICKNESS HALF SHEET - FINNISH BIRCH AIRCRAFT PLYWOOD (METRIC)	3	$29.38	$29.58	$88.14	$117.72
Nerf Vortex Aero Howler Foam Battle Toy, Blue	12	$11.99	$11.15	$143.88	$155.03
Aluminum Slip-on Framing (Length 4ft)	2	$16.54	$2.56	$33.08	$35.64
Aluminum Slip-on Rail Fitting	1	$10.82	$0.84	$10.82	$11.66
Zinc-Plated Steel Tee Nut Inserts	1	$11.43	$0.89	$11.43	$12.32
Button Head Hex Drive Screw	1	$10.95	$0.85	$10.95	$11.80
Blue Transparent UltraCote Covering, 78" Roll	6	$15.99	$49.84	$95.94	$145.78
Red Transparent UltraCote Covering, 78" Roll	4	$15.99	$4.96	$63.96	$68.92
Battery Arming Switch	1	$14.99	$1.16	$14.99	$16.15
50.0' Standard Futaba Servo Wire	1	$12.95	$1.00	$12.95	$13.95
Hitec Standard-Duty Extensions - 6" Wire Length	8	$3.45	$9.13	$27.60	$36.73
Premium Silicone Wire (by foot) / BLACK / 12AWG	5	$1.65	$0.64	$8.25	$8.89
Premium Silicone Wire (by foot) / RED / 12AWG	5	$1.65	$0.64	$8.25	$8.89
6976 Arming Switch, with XT60 connectors, HD Wire	2	$12.95	$9.96	$25.90	$35.86
Pushrod Assembly Kit Carbon Fiber 330 x 5mm	2	$15.00	$2.33	$30.00	$32.33
Pull-Pull Deluxe System Kevlar	1	$15.00	$1.16	$15.00	$16.16

Pull-Pull Wire Couplers (2)	1	$13.00	$15.41	$13.00	$28.41
Great Planes Nylon Clevis 2-56" with 12" Rod (Set of 12)	2	$10.47	$1.62	$20.94	$22.56
Hobbypark 10 Sets Nylon Standard Control Horns W13xL18xH25mm 4 Holes with Screw for RC Airplane Parts KT Model Replacement	2	$7.98	$1.24	$15.96	$17.20
1/4" x 1/4" x 36" Balsawood Sticks	30	$0.95	$9.63	$28.50	$38.13
ABS Tube 1-1/4" OD x 1" ID – Length, 1 ft.	1	$6.13	$0.48	$6.13	$6.61
Structural Fiberglass Round Tube 5 Feet Long, 1-1/4" OD, 1" ID	1	$22.07	$1.71	$22.07	$23.78
Hard Fiber Tube 40" Long, 1-1/4" OD, 1" ID	1	$47.61	$3.69	$47.61	$51.30
Impact-Resistant Polycarbonate Round Tube 1-1/2" OD, 1-3/8" ID, Clear, 8' Long	1	$24.00	$1.86	$24.00	$25.86
Clear PETG Tube 1-5/8" OD x 1-3/8" ID – Length 1 ft	2	$6.25	$0.97	$12.50	$13.47
Ring-Grip Quick-Release Pin Aluminum, 1/4" Diameter, 1-1/2" Usable Length	6	$2.85	$1.33	$17.10	$18.43
Aluminum Clevis Pin 1/4" Diameter, 1-1/2" Usable Length	2	$12.02	$1.86	$24.04	$25.90
Hook and Loop with Adhesive Backing, 1/2" Wide x 5 Feet Long - Black	1	$6.22	$0.48	$6.22	$6.70
Screw-In Hook and Loop Cable Tie Mount with Adhesive Back, for 1/2" Maximum Cable Tie Width	1	$12.94	$1.00	$12.94	$13.94
Press-Fit Drill Bushing 0.25" ID, 3/8" OD, 1/4" Long	2	$7.48	$1.16	$14.96	$16.12
Nylon Tube 1/2" OD, 1/4" ID, 5 Feet Long	2	$12.20	$1.89	$24.40	$26.29
Washdown Set Screw Shaft Collar for 1/2" Diameter	1	$5.50	$0.43	$5.50	$5.93
Thrust Ball Bearing for 1/2" Shaft Diameter, 15/16" OD, 0.249" Thick	2	$2.80	$0.43	$5.60	$6.03
Set Screw Shaft Collar for 1/8" Diameter, Zinc-Plated 1215 Carbon Steel	4	$1.03	$0.32	$4.12	$4.44
Nylon Unthreaded Spacers 1/2" OD, 5/8" Long, Black	1	$2.93	$0.23	$2.93	$3.16
Alloy Steel Shoulder Screw 1/4" Shoulder Diameter, 2-1/2" Shoulder Length, 10-24 Thread	3	$2.06	$0.48	$6.18	$6.66
Aluminum Nylon-Insert Locknut 10-24 Thread Size	1	$4.04	$0.31	$4.04	$4.35
Alloy Steel Shoulder Screw 1/4" Shoulder Diameter, 2-3/4" Shoulder Length, 10-24 Thread	3	$3.16	$0.73	$9.48	$10.21
Thrust Ball Bearing for 1/4" Shaft Diameter, 9/16" OD, 0.193" Thick	6	$2.21	$1.03	$13.26	$14.29

KEVENZ 50-Pack 3-Star Plus 40mm Orange Table Tennis Balls,Advanced Training Ping Pong Balls	2	$11.95	$18.85	$23.90	$42.75
1/8 x 4 x 24 Balsa	40	$2.58	$8.00	$103.20	$111.20
1/4 x 1/4 x 48 Balsa Stick	40	$1.16	$3.60	$46.40	$50.00
1/8 x 4 x 24 Basswood Sheet	20	$2.47	$3.83	$49.40	$53.23
KEVENZ 50-Pack 3-Star Plus 40mm Orange Table Tennis Balls,Advanced Training Ping Pong Balls	2	$11.95	$1.85	$23.90	$25.75
Du-Bro 916 Electric Flyer Hinge Tape (1 roll, 15 ft)	2	$5.99	$0.93	$11.98	$12.91
1/4”x1/4”x48” Basswood Sticks	40	$0.99	$3.07	$39.60	$42.67
1/8" x 12" x 24" Balsa Sheet	22	$11.53	$19.66	$253.66	$273.32
1/8" x 12" x 24" Basswood Sheet	5	$13.00	$46.53	$65.00	$111.53
1/4" x 1" x 48" Balsa Trailing Edge	8	$0.95	$0.59	$7.60	$8.19
1/16 THICKNESS HALF SHEET - FINNISH BIRCH AIRCRAFT PLYWOOD (METRIC)	2	$19.32	$2.99	$38.64	$41.63
1/8 THICKNESS HALF SHEET - FINNISH BIRCH AIRCRAFT PLYWOOD (METRIC)	2	$33.88	$5.25	$67.76	$73.01
2 oz. Bottle BSI INSTA-CURE SUPER THIN CYANOACRYLATE	4	$8.65	$2.68	$34.60	$37.28
Refill - 8 Fl. oz. BSI INSTA-SET CYANOACRYLATES ACCELERATOR	2	$10.60	$1.64	$21.20	$22.84
Pump Spray - 2 Fl. oz BSI INSTA-SET CYANOACRYLATES ACCELERATOR	4	$5.35	$1.66	$21.40	$23.06
2 oz. Bottle BSI INSTA-CURE GAP FILLING CYANOACRYLATE	2	$8.65	$1.34	$17.30	$18.64
Turnigy TGY-811 Slim Wing DS/MG Servo 25T 8.2kg / 0.12sec / 30g	4	$21.00	$26.92	$84.00	$110.92
Red Transparent UltraCote Covering, 78" Roll	8	$15.99	$52.48	$127.92	$180.40
NUTSET-M6	1	$12.95	$8.88	$12.95	$21.83
ALLENLIFE Water Bottle Carrier Bag Pouch Cover, Insulated Neoprene Water Bottle Holder - Great for Stainless Steel, Glass, or Plastic Bottles	2	$10.99	$1.70	$21.98	$23.68
Low-Carbon Steel Bar 1/4" Thick, 5" Wide 1 ft Long	7	$24.08	$13.06	$168.56	$181.62
1/4”x1/4”x48” Balsa Sticks	40	$0.99	$58.54	$39.60	$98.14
Mat Board Center, Pack of 10 1/8" White Foam Core Backing Boards (20x24, White)	1	$37.99	$2.94	$37.99	$40.93
Spectra Braided Fishing Line 15Lb 150 Yd Moss Green	1	$12.84	$1.00	$12.84	$13.84

Black Vinyl Numbers Stickers - 4 Inch Self Adhesive - 2 Sets - Premium Decal Die Cut and Pre-Spaced for Mailbox, Signs, Window, Door, Cars, Trucks, Home, Business, Address Number, Indoor or Outdoor	4	$16.95	$5.25	$67.80	$73.05
Seamuing 6Pcs MG90S Micro Servo 9G Servo Motor Metal Geared Micro Servo Motor 9G Smart Robot Car Helicopter Plane Boat	2	$23.79	$3.69	$47.58	$51.27
Washdown Set Screw Shaft Collar for 1/2" Diameter	5	$5.50	$2.13	$27.50	$29.63
Thrust Ball Bearing for 1/2" Shaft Diameter, 15/16" OD, 0.249" Thick	2	$2.80	$0.43	$5.60	$6.03
Aluminum Nylon-Insert Locknut 10-24 Thread Size	1	$4.04	$0.31	$4.04	$4.35
Thrust Ball Bearing for 1/4" Shaft Diameter, 9/16" OD, 0.193" Thick	8	$2.21	$1.37	$17.68	$19.05
Alloy Steel Shoulder Screw 1/4" Shoulder Diameter, 1-3/4" Shoulder Length, 10-24 Thread	2	$1.68	$0.26	$3.36	$3.62
Alloy Steel Shoulder Screw 1/4" Shoulder Diameter, 2" Shoulder Length, 10-24 Thread	2	$1.77	$0.27	$3.54	$3.81
Plastic Ball Bearing with 316 Stainless Steel Ball, Trade No. R8, for 1/2" Shaft Diameter	3	$6.56	$1.53	$19.68	$21.21
316 Stainless Steel Washer Oversized, Number 12 Screw Size, 0.25" ID, 0.562" OD	1	$7.29	$0.56	$7.29	$7.85
				Total Cost	$6,188.35