Project Final Report
BUBO BUBO

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Acronyms

APM	ArduPilot MEGA
AR	Aspect Ratio
AVL	Athena Vortex Lattice
BAS	Boulder Aeromodeling Society
BEC	Battery Eliminator Circuit
BUBO BUBO	Big Unmanned Boxwing Operation & Bigger Unmanned Boxwing Operation
CAD	Computer Aided Design
CDD	Conceptual Design Document
CDR	Critical Design Review
CFD	Computational Fluid Dynamics
CG	Center of Gravity
ConOps	Concept of Operations
COTS	Commercial Off-the-Shelf
CPE	Critical Project Element
DR	Design Requirement
DBF	Design Build Fly
EPP	Expanded PolyPropylene
ESC	Electronic Speed Controller
FAA	Federal Aviation Administration
FADS	Flush Air Data Sensing
FBD	Functional Block Diagram
	Free Body Diagram
FEM	Finite Element Method
FFR	Fall Final Review
FMU	Flight Management Unit
FOS	Factor of Safety
FR	Functional Requirement
GPS	Global Positioning System
IMU	Inertial Measurement Unit
IRISS	Integrated Remote and In-Situ Sensing
LiPo	Lithium Polymer
LVC	Low Voltage Cutoff
MHP	Multi-Hole Probe
MSR	Manufacturing Status Review
NiCad	Nickel Cadmium
NiMH	Nickel-Metal Hydride
PAAS	Pressure - Angle of Attack - Sideslip
PAB	Project Advisory Board
PCB	Printed Circuit Board
PD	Proportional Derivative
PDD	Preliminary Design Document
PDR	Preliminary Design Review
PFR	Project Final Report
PID	Proportional Integral Derivative
PMB	Power Management Board
PVC	PolyVinyl Chloride
PWM	Pulse Width Modulation
PX2	Pixhawk 2

RC	Radio Control
RECUV	Research and Engineering Center for Unmanned Vehicles
RPM	Revolutions Per Minute
RTSB	Rectangular Top Swept Bottom
SCL	Serial Clock
SDA	Serial Data
SFR	Spring Final Review
SLF	Steady Level Flight
TBD	To Be Determined
TRR	Test Readiness Review
UAS	Unmanned Aircraft System
V&V	Verification and Validation
WBS	Work Breakdown Structure

Nomenclature

$\dot{h}$	Rate of Climb
$\dot{m}$	Mass Flow Rate
ν	Poisson's Ratio
ϕ, θ, ψ	State Variables Describing Aircraft's Attitude
$\vec{u}$	Control Surface Deflection Vector
$\vec{x}$	State Vector
A	Aerodynamic Stability Matrix
	Cross Sectional Area
a	Acceleration
	Airfoil Lift Slope
AR	Aspect Ratio
B	Control Derivative Matrix
b	Span
C_D	Coefficient of Drag
C_L	Coefficient of Lift
$C_{D,0}$	Coefficient of Skin Friction Drag
$C_{D,i}$	Coefficient of Induced Drag
D	Drag
d	Propeller Diameter
	Gap (Vertical Distance Between Wings)
E	Modulus of Elasticity
F	Force
f	Force of Friction
g	Acceleration Due to Gravity
K	Control Gains Matrix
k	Spring Constant of Bungees
L	Lift
L/D	Lift-to-Drag Ratio
M	Moment
m	Mass of Aircraft
N	Normal Force
n	Load Factor
P	Power
	Pressure
p, q, r	State Variables Describing Aircraft's Angular Velocity
q	Dynamic Pressure
R	Turn Radius
	Specific Gas Constant
S	Planform Area
s	Stagger (Horizontal Distance Between Wings)
T	Thrust
	Temperature
	Tension on Bungees
t	Time (s)
u, v, w	State Variables Describing Aircraft's Velocity
V	Velocity
	Voltage
W	Weight
x, y, z	State Variables Describing Aircraft's Position
α	Angle of Attack
β	Sideslip Angle
Δ	Prefix Indicating Change
δ	Control Surface Deflection Angle
ϵ, e	Span Efficiency Factor

γ	Glide Angle
	Maximum Climb Angle
∞	Subscript Indicating Free Stream
λ	Eigenvalue
μ	Dynamic Coefficient of Friction
ω	Imaginary Eigenvalue Component
	Angular Rate
ρ	Density
σ	Real Eigenvalue Component
τ	Shear Stress
	Torque

1. Project Purpose

Author: Kaitlyn Olson

1.1. Mission Statement

The goal of BUBO BUBO is to design, build, and test an unmanned, radio-controlled (RC), box-wing aircraft. The aircraft will be a scalable data collection platform for a Flush Air Data Sensing (FADS) system, which will collect pressure data to aid in the study of turbulence by Dr. Brian Argrow of the University of Colorado Boulder.

1.2. Description

Unmanned Aircraft Systems (UAS) are becoming increasingly popular in research due to their low cost, relative ease of use, and ability to reach and survive harsh environments that are inaccessible and even hazardous for humans. While UAS have the potential to expand research, aid efforts, and contribute to countless other pursuits, their use is currently limited by the understanding of how these small aircraft fly and interact with the surrounding atmosphere. The current wind models available are great for large aircraft at high altitudes and Reynolds numbers, however they do not model small aircraft at low Reynolds numbers and altitudes as well. This shortcoming must be overcome to enable the safe operation and optimized design of small UAS as their potential continues to be realized and expanded. The development of these models requires extensive research of airflow and turbulence experienced by UAS. While seemingly counter-intuitive, one of the best ways to conduct this needed research is with UAS themselves. One way UAS enable this research is to directly measure turbulence. To collect this novel data, one could take the same aircraft, scale it by wingspan, and collect relative wind velocity and other air data with each size. While this can be done in various ways, BUBO BUBO will implement a flush air data sensing (FADS) system into a balsa-monokote airframe that can be easily scaled both up and down in size. The BUBO BUBO team could find no evidence to suggest a scalability effort such as the one being undertaken has previously occurred to study turbulence, nor evidence to suggest a FADS system has previously been integrated into a balsa-monokote construction.

The FADS system was selected due to the fact that it is one of the most cost-efficient and aerodynamically beneficial ways to collect the relevant data needed, the relative wind vector. FADS systems have the massive benefit of requiring no externally mounted hardware. Unlike more conventional sensor configurations such as air data booms and multi-hole probe solutions, this protects expensive sensors and instrumentation from damage.[2] This setup saves time and money by preventing the need to replace such instrumentation. Additionally, the flush nature of a FADS system can significantly reduce the drag the aircraft experiences.[4] This advantage can dramatically improve the aerodynamic performance of small, lightweight aircraft.[3]

The purpose of this project is to design, assemble, and test an unmanned, radio-controlled (RC), box-wing aircraft with an integrated FADS system. The unique box-wing configuration reduces the disturbance of the airflow through the two wings and allows for optimal sensor configuration according to the research of Dr. Roger Laurence. The FADS system will collect pressure data to be used to calculate the aircraft's relative wind vector. The aircraft will have an endurance of one hour and an integrated autopilot to be used during the data collection phase of the flight profile. The aircraft will also be reusable, being capable of completing at least ten takeoff and landing cycles without undergoing any major repairs. The direct scalability of the aircraft by wingspan will also be investigated through a feasibility analysis of the design. This feasibility study will focus on how the performance of the aircraft will change as the wingspan is altered, with the hope that the customer can apply the team's design to different sized airframes in the future. A fleet of various box-wing aircraft would be able to collect data at various altitudes in varied conditions.

2. Project Objectives and Functional Requirements

Author: Andrew Fendel, Kaitlyn Olson

2.1. Objectives

The objectives for the BUBO BUBO project have been broken up into three levels of success for the five main elements of the project. These objectives can be seen in Table 1. The five categories for which levels of success were established are navigation and control, sensor data, survivability, flight, and airframe scalability. The navigation and control category encompasses the full control scheme of the aircraft and takes into account both manual control from a human pilot and autonomous control. The sensor data category includes the development and integration of the FADS system, considering the type, amount, and accuracy of data desired. The survivability category considers the reusable aspect of the design, ensuring the structural components of the airframe are robust enough to survive the conditions imposed on the aircraft by flight cycle requirements. The flight category focuses on the ability of the aircraft to fly in a stable manner, as well as its endurance. The airframe scalability category covers the ability of the aircraft to be scaled according to a desired wingspan as requested by the customer. Together, these five categories paint a holistic picture of success for BUBO BUBO.

Level 1 success demonstrates theoretical feasibility of the aircraft, along with successful subsystem ground testing. For Level 1 success to be realized, the flight category requires a demonstration through modeling of the validity of the proposed design. This modeling must demonstrate the aircraft will be capable of steady, level flight. The navigation and control category also requires modeling to show the feasibility of the proposed autonomous control the aircraft will use in its loiter phase. A successful model of the autonomous control will show actuation of control surfaces to maintain a pre-determined flight path. The sensor data category requires the FADS system to demonstrate a successful data collection as well as the ability to store both the FADS and GPS data the aircraft will be collecting. The airframe scalability category requires a 1-meter span airframe be contructed. This prototype will demonstrate that the team has the manufacturing skills required to make a full aircraft with integrated subsystems. Finally, the survivability category requires the constructed airframe be subjected to and withstand load testing simulating the maximum expected aerodynamic force the aircraft will experience in flight. This assessment will demonstrate the aircraft's ability to withstand the forces of flight. All the Level 1 objectives will be verified without flight testing through ground-based testing and simulation. This decision ensures that even if flight is not achieved the project will not be considered a complete failure.

Level 2 successes demonstrates the aircraft is capable of successfully completing one full flight cycle. For Level 2 success to be realized, the flight category requires the aircraft to achieve stable, powered flight. This achievement will demonstrate the validity of both the theoretical design and the physical manufacturing of the aircraft. The navigation and control category requires the entire flight to be manually controlled. This allows a human pilot to give feedback before autonomous control is implemented. The survivability category also requires this flight to land without major damage to the aircraft. This prerequisite entails the aircraft being able to be repaired within 15 minutes to a standard that would allow it to complete another flight, demonstrating the practical re-usability of the aircraft. The sensor data category requires the ability of the sensors and GPS to collect and store one hour of data, the amount of data to be collected in one full flight. Finally, the airframe scalability category holds the same standard as its Level 1 objective, the construction of a 1-meter airframe. Level 2 success demonstrates that the mechanical components of the project are functional and prepared for integration.

Level 3 successes are a reflection of the ultimate project success across all elements of the BUBO BUBO project. In order to meet these objectives, the aircraft must demonstrate sustained powered flight for the desired endurance of 1 hour while showing full autonomous control during the steady loiter portion of flight. These two demonstrations ensure success for the flight and navigation and control objectives, and demonstrate the aircraft operates as desired. For the survivability category, the aircraft must survive 10 takeoff and landing cycles, realizing the full customer desire for re-usability. The sensor data category requires the sensors to be integrated into the airframe such that the accuracy of the measured pressure is not degraded by more than 5% of the known value. Finally, in order to meet the Level 3 success for airframe scalability, a feasibility study for a 2-meter wingspan, scaled airframe will be completed and delivered to the customer. These criteria reflect the completion of the full scope of the project.

Table 1. Success levels for BUBO BUBO mission objectives.

	Navigation and Control	**Sensor Data**	**Survivability**	**Flight**	**Airframe Scalability**
Level 1	Simulated autonomous control of pre-made flight path	Able to collect and store FADS pressure data and GPS data	Airframe withstands maximum expected aerodynamic forces during structural testing	Models demonstrate aircraft achieves steady level flight	Build 1 meter span box-wing airframe
Level 2	Flight with manual control	Able to collect and store data for one full flight	Lands with minimal field repairs (max. 15 minutes with field materials)	Aircraft achieves stable powered flight	Same as Level 1
Level 3	Autonomous control during loiter in-flight	Integration of sensors does not degrade accuracy by more than 5%	Survives 10 takeoff and landing cycles	Aircraft can sustain flight for a minimum of 1 hour	Feasibility study for scaled airframe

During the course of this project, the BUBO BUBO team has completed a Preliminary Design Document (PDD), Conceptual Design Document (CDD), Preliminary Design Review (PDR), Critical Design Review (CDR), Fall Final Report (FFR), Manufacturing Status Review (MSR), Test Teadiness Review (TRR), Final Oral Review (FOR), and this document, the Project Final Report (PFR). Each of these documents and presentations were delivered to both the course's Project Advisory Board (PAB) and the client. The results of this project were also intended to be delivered in a comprehensive package to the client, to include the fully functioning 1-meter span aircraft, as well as a full scalibility study of the 2-meter span aircraft. This scalability study would have included aerodynamic force modeling, stability modeling, control requirements modeling and potential resizing, and a weight change estimate in addition to performance metrics of the 2-meter span aircraft including power requirements, stall speed, and control responses (yaw rate, bank angle, etc.). Due to the shortened timeline of the project, the scalability study was unable to be completed, however, the 1-meter span aircraft manufactured and flown by the BUBO BUBO team, as well as all modeling and analysis required to construct that aircraft, will be delivered.

2.2. Functional Requirements

The functional requirements (FR's) the BUBO BUBO team shall adhere to are listed in the following section. These outline the main goals of the project and provide a baseline for the flow down of design requirements presented in Section 3.2. Each of these functional requirements was derived from the customer's requests for this project.

FR 1: The aircraft shall be a box-wing configuration with a scalable span.

FR 2: The aircraft shall integrate a Flush Air Data Sensing (FADS) system that can collect pressure data for the purpose of deriving the relative wind vector.

FR 3: The aircraft shall be able to complete 10 flight cycles without major damage.

FR 4: The aircraft shall be capable of sustained powered flight with an endurance of 1 hour.

FR 5: The aircraft shall be piloted by an autopilot during the loiter phase of the mission profile.

FR 1 expresses the customer's desire for a scalable box-wing aircraft. The box-wing design allows for unique sensor configurations the customer would like to explore. FR 2 provides framework necessary to collect the desired data, the relative wind vector. The specification of the Flush Air Data Sensing system as the method for this data collect is to utilize the method researched by the customer and his associates. FR 3 is a direct result of the customer's request for each aircraft to be reusable for a minimum of 10 flight cycles. This factor of re-usability helps to keep costs down and makes this aircraft a viable and affordable method for continuous research and data collections. FR 4 gives sufficient flight time for the desired data collection. A full hour of flight will allow the measurement of the relative wind vector over a timescale accounting for the possibility of changing wind and weather conditions, while allowing the turbulence and uncertainty associated with takeoff and landing to be excluded from the analyzed data. Finally, FR 5 allows the flight of the aircraft to be autonomous for the majority of the aircraft's flight pattern, minimizing the workload of the research team who must operate the aircraft in the field.

2.3. Concept of Operations

Figure 1 shows the concept of operations of the BUBO BUBO project.

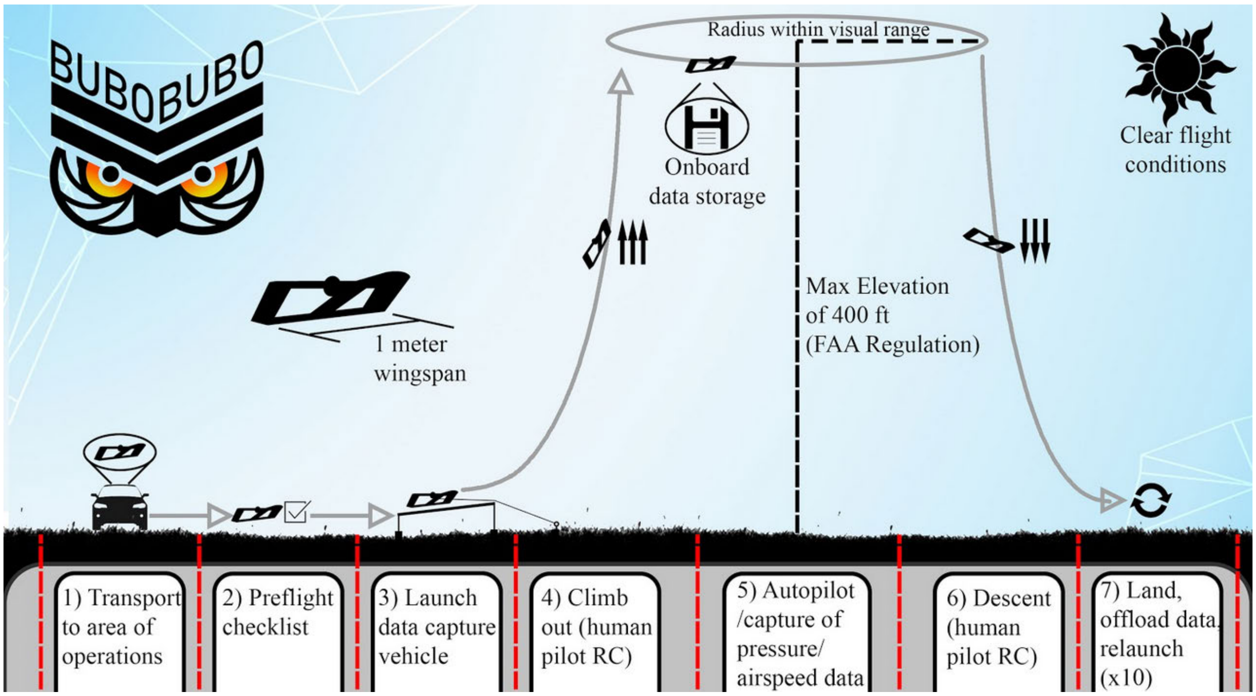

Figure 1. Concept of Operations for BUBO BUBO.

The concept of operations is a brief visual representation of the functional objectives of the mission. For this project, the concept of operations is divided into seven segments; these seven segments span the entire length of the mission and include the primary stages of the mission from the transportation of the aircraft to the recovery of data after landing. The first stage is the transportation of the aircraft to the area of operations. This stage highlights the ability of the aircraft to be transported by reasonable means (i.e. in a truck or car) to a location where the user is interested in capturing data. Immediately following transportation, a pre-flight checklist is completed to ensure all on-board systems are fully powered and functioning, and all control surfaces are unobstructed and responsive to commands. Next comes the launch phase of the mission, performed using the table and bungee method developed by the Integrated Remote and In-Situ Sensing (IRISS) program at CU Boulder. After takeoff, the aircraft will climb to data capture altitude through pilot commands sent through an RC transmitter/receiver pair. Once it reaches the appropriate altitude, the aircraft will begin its circular loiter stage, capturing data and storing it on-board while being controlled by an autopilot. For a full flight cycle, the aircraft will remain in this loiter for approximately one hour. Following data collection, the aircraft will descend via pilot control to land. After landing, the ground team will offload data, inspect the aircraft for damages, make any necessary repairs, and relaunch if so desired.

2.4. Functional Block Diagram

Figure 2 shows the functional block diagram of the BUBO BUBO project.

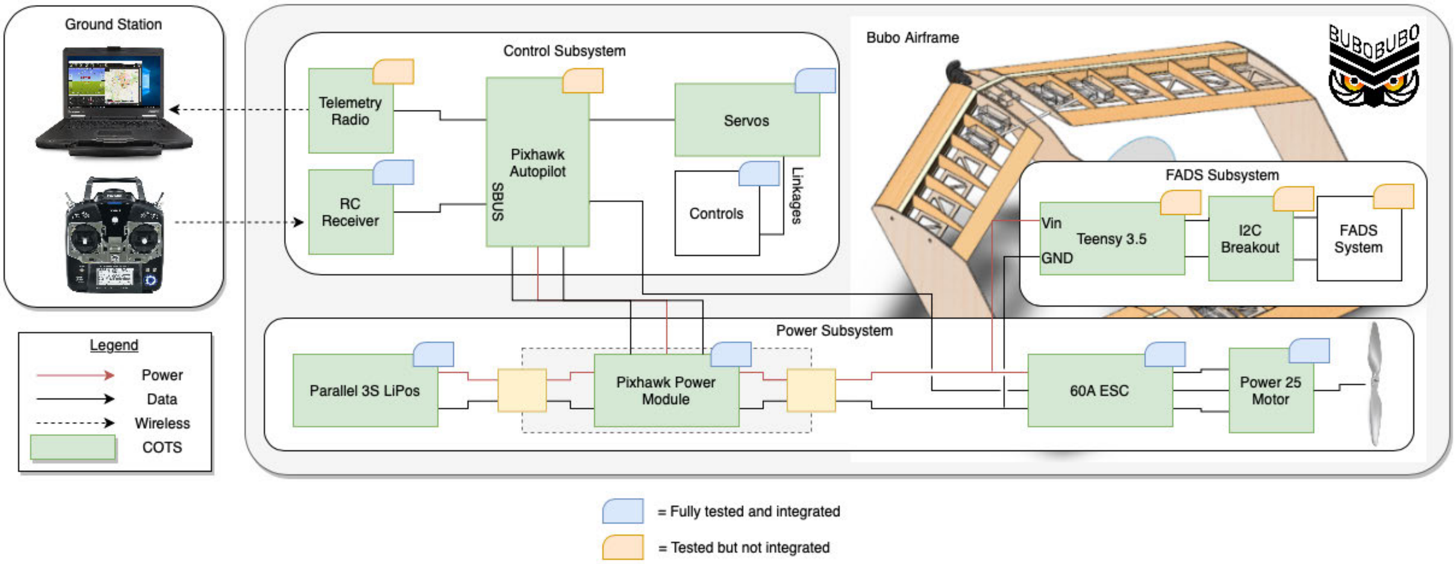

Figure 2. Functional block diagram of BUBO BUBO with integration status at cutoff

The BUBO box-wing aircraft can be broken into a few main subsystems: the airframe houses the control subsystem, the power subsystem, and the sensor subsystem, with a required ground station consisting of a laptop for telemetry and an RC controller. The control subsystem is built around the integrated Commercial-Off-The-Shelf (COTS) autopilot, the PixHawk 2. This takes in pilot commands from the RC Receiver and sends the required control commands to the servos and controls system. The RC Transmitter is all that is required to control the BUBO, with the laptop augmenting the user experience to allow tweaking and verification of the autopilot in flight. The radio accepts pilot commands and, with the flip of a switch, can engage the autopilot into Cruise / Loiter Mode. The Sensor Subsystem consists of the FADS system, the autopilot's required sensors, and an on-board data-storage microcontroller. The FADS system is an array of pressure transducers arranged symmetrically across the airframe in locations of high angle of attack or side slip angle gradient. The autopilot will require GPS and IMU sensors to calculate position and attitude, and the FADS is used to calculate the relative wind vector. All the sensor data is input to an Arduino Teensy microcontroller to be stored on-board the aircraft and offloaded post-flight. The BUBO is powered by the Power Subsystem, consisting of the power source (lithium polymer batteries), the propulsion system, and a power distribution circuit.

3. Design Process and Outcome

Author: All team members; individual contributions listed in Section 9.

3.1. Trade Studies

3.1.1. Rationale

At the beginning of the design process, several trade studies were conducted in the following manner to inform important design decisions. First, the subject of the trade study was identified, with the focus of the more important trades being on overarching architecture of particular subsystems, or even the project and aircraft as a whole. Once the subject of the trade study was identified, the various options for that design element were identified and researched, and the pros and cons of each option were tabulated. Once each option was thoroughly explored, the criteria by which the options would be evaluated was formally established and defined. Each criterion was then assigned an individual weight in the form of a percentage based on the importance of each criterion to the overall success of the project, as it relates to that element. The larger the weight, the more important the criteria was determined to be, with the summation of the weights of all the criteria for each trade study being unity. Once the criteria had been identified and weighted, each design option was scored in each category on a scale from one to five, with five being the best. Each criterion score was multiplied by its respective weight for every design option. These multiplied figures were then summed for each design option, with the largest total signifying the best design choice. A full list of the trades conducted and their outcomes can be found in the following Section 3.1.2.

3.1.2. Trades Conducted and Results

A list of each trade study conducted, organized by subsystem, is shown here. The design options considered are listed for each trade study, with the ultimate design choice indicated in bold. The full trades studies which yielded these results can be found in Appendix A: Trade Studies.

Aerodynamics
Wing Configuration: Delta Wing, Straight Wing, Reflected Sweep, **Single Sweep**, Symmetric Sweep
Boom Configuration: **One Centered Boom**, Two Booms Attached to Side Walls

Controls
Autopilot Controller: Pixhawk 4, **Pixhawk 2**, BetaFlight F4, ArduPilot Mega, iNAV Matek F405

FADS
FADS Configuration: **Traditional** (Pneumatic Tubes), Simplified (Direct Trandsucer Exposure)

Power
Battery Type: **LiPo**, Li-Ion, NiCd, NiMH, SLA
Microcontroller Architecture: **Arduino**, FPGA, Raspberry Pi
Power Configuration: One Circuit One Battery, **One Circuit Parallel**, Two Circuits, Three Circuits

Propulsion
Propulsion Configuration: Two Pushers, One Puller, **One Pusher Centered**, Two Pusher Centered, Multiple

Structures
Wing Span: **One Meter**, Two Meter
Landing Method: **Skid/Hard Landing**, Landing Gear, Net, Moving Landing, Parachute
Launch Method: **IRISS Table Bungee**, IRISS Hand Bungee, RECUV Rail Bungee, Pneumatic System, Car Roof System

3.2. Design Requirements Flowdown

The Design Requirements are derived from the top-level Functional Requirements outlined in Section 2.2. Design Requirements delve further into the specifics of each Functional Requirement and are meant to define the design of the system on a more detailed level. Each of these requirements is listed in the flow down that follows, with both a motivation of why the requirement must exist as well as a planned method of verification that can be used to show the requirement has been met. An explaination of the rational behind the flow down of the Design Requirements from their parent Functional Requirement is also provided for each of the Functional Requirements.

FR 1: The aircraft shall be a box-wing configuration with a scalable span.
Motivation: The customer desires a box-wing configuration to study the effect of turbulence on aircraft of different wing spans.
Verification: Design space will be limited to ensure a box-wing configuration is used. Scalability will be determined by investigating multiple wingspans and documenting the impact of span change.

- **DR 1.1: The aircraft shall have two vertically separated lifting surfaces connected by struts and outer walls.**
  Motivation: The customer desires a box-wing configuration to allow for airflow between the two lifting surfaces to be analyzed.
  Verification: Airframe design space will be limited to ensure that this requirement is met by the final configuration of the aircraft.
- **DR 1.2: A one-meter and two-meter wingspan design shall be investigated.**
  Motivation: The desire for scalability requires multiple wingspans to work. The specific spans of one meter and two-meter were provided by the customer.
  Verification: The design space will be limited by the parameter of wing span such that the requirement is met. The span of the constructed prototype will be measured upon completion, and the scaled model will be constrained to the secondary span value.
  - **DR 1.2.1: Either a one-meter or two-meter span aircraft shall be constructed and flight tested. The size of the aircraft being constructed will be determined by trade study.**
    Motivation: Proves the design satisfies the customer's desire for flight test.
    Verification: Prototype of aircraft will be constructed and flown, and the span measured.
  - **DR 1.2.2: The span which is not built shall have a feasibility study conducted.**
    Motivation: This allows for an analysis of the second wingspan without physically constructing a second aircraft, saving money and resources.
    Verification: A full report on the capabilities of the scaled aircraft, as well as blueprints for construction, will be provided to the customer.
    - **DR 1.2.2.1: The feasibility study shall include physical alterations that must be made to change the span.**
      Motivation: The end goal of the feasibility study is to provide the customer with information necessary to manufacture a scaled aircraft.
      Verification: Calculations of changed parameters will be delivered in a physical report.
    - **DR 1.2.2.2: The feasibility study shall include analysis showing the scaled aircraft is capable of flight.**
      Motivation: This analysis will show that the scaled aircraft is capable of completing the same mission profile as the aircraft that is manufactured.
      Verification: Calculation of thrust required vs. thrust produced, lift required vs. lift produced for steady level flight, and load verification for a maximum 2.5 G's maneuver will be provided.

The driving Functional Requirement 1 states that the team must design a box-wing aircraft with a scalable span. Design Requirement 1.1 is in place in order to ensure that the desire for a box-wing configuration is met, and gives a formal definition of such an airframe configuration, directly from the customer. Requirement 1.2 was derived in order to address the customer's desire for a scalable design, driven by the ultimate goal to use box-wing aircraft of different sizes to study turbulent airflow. This is further explained with Design Requirements 1.2.1 and 1.2.2, which state that one airframe shall be built, while another scaled version shall be thoroughly investigated by way of a feasability study. Design Requirements 1.2.2.1 and 1.2.2.2 go on to further define the scope of such a study, and what characteristics shall be reported as deliverables following the conclusion of the feasability investigation.

FR 2: The aircraft shall integrate a Flush Air Data Sensing (FADS) system that can collect pressure data for the purpose of deriving the relative wind vector.
Motivation: Customer requires relative wind vector for aerodynamic research.
Verification: Data collected from the FADS system during a ground test will be used to compute relative wind vector and compared to pitot static probe reference.

- **DR 2.1: The FADS system shall be integrated into the wing of the aircraft such that the sensors are flush with the wing surface.**
  Motivation: Flushness reduces the impact on the airflow over the wings and the risk of damage.
  Verification: Visual validation that sensors do not protrude above aircraft's mold line.
- **DR 2.2: An array of pressure transducers shall be integrated into the airframe at locations of high coefficient of pressure (C_p) gradient.**
  Motivation: High C_p gradient allows for high sensitivity to relative wind vector orientation.
  Verification: Either analytical model or CFD model of C_p differential will be used to verify the locations selected have a high C_p gradient.
- **DR 2.3: An on-board processor shall be integrated with the sensors to capture data.**
  Motivation: Data must be stored so it can be accessed for post-flight analysis.
  Verification: Verify that test data was collected by uploading it to a computer.
  - **DR 2.3.1: The on-board processor shall be capable of recording sensor data at a rate of at least 6 Hz.**
    Motivation: Prior research done by the customer indicates this is an acceptable rate to record data.
    Verification: Timestamps on data agree with the required sampling rate.
  - **DR 2.3.2: The on-board processor shall be capable of storing at least a one-hour flight's worth of data.**
    Motivation: The customer desires one hour of data collection in flight.
    Verification: One hour's worth of flight data does not completely fill up the data storage.

Functional Requirement 2 states that the aircraft designed by team BUBO BUBO shall feature an integrated FADS system in order to recover the relative wind vector. Design Requirement 2.1 states that the sensors shall be flush to the aircraft's surfaces, i.e. not protruding over the outer mold line of the wings or sidewalls. This flush nature not only allows for less airflow interruption (and thereby a reduction in drag), but also greatly reduces the risk of damage upon landing by eliminating the need for any protruding sensors or probes. Design Requirement 2.2 dictates the location of the FADS sensors themselves, constraining them to locations of high pressure gradient in order to more accurately capture useful insight into the changing relative wind vector through the capture of pressure data alone. Design Requirement 2.3 and its subsequent flow down requirements state that the FADS system shall be integrated with an on-board processor that can collect data at a high enough sampling rate of 6 Hz, while storing enough data to encompass a full hour of collection.

FR 3: The aircraft shall be able to complete 10 flight cycles without major damage.
Motivation: The customer has requested the aircraft be capable of being reused for a minimum of 10 flight cycles.
Verification: Flight test will show the capability of 10 flight cycles without major damage. The customer has defined "major damage" as damage requiring a repair exceeding 15 minutes of work in the field.

- **DR 3.1: The aircraft shall demonstrate a pilot-controlled takeoff.**
  Motivation: Risk associated with automated takeoff is much higher than that associated with a manual takeoff.
  Verification: Flight test will show the capability of 10 flight cycles without major damage. The customer has defined "major damage" as damage requiring a repair exceeding 15 minutes of work in the field.
  - **DR 3.1.1: The launch system shall be deployable in the field in less than 15 minutes.**
    Motivation: Customer requests aircraft can be launched within 15 minutes of recovery.
    Verification: Stopwatch will be used to ensure the launch is set up and deployed in less than 15 minutes.
  - **DR 3.1.2: The launch system shall integrate with the airframe such that no major damage is imparted to the aircraft.**
    Motivation: The aircraft must survive the launch phase of the mission profile in order to complete a flight cycle.
    Verification: Flight test shows no major damage.

- **DR 3.2: The aircraft shall demonstrate stable flight in a loiter pattern within visual range.**
  Motivation: The mission profile calls for a data collection segment over a singular area, and FAA requirements state that unmanned aircraft operators must maintain visual contact with the aircraft during flight.
  Verification: GPS data confirms acceptable loiter path, variant based on flight condition.
  - **DR 3.2.1: The aircraft shall have dynamically stable flight characteristics upon small perturbations (less than 10°) to the aircraft's pitch, yaw, and roll.**
    Motivation: Stable flight characteristics are necessary to remain in loiter pattern for data collection.
    Verification: Computed stability derivatives shall show dynamic stability.
- **DR 3.3: The aircraft shall land and be able to fly again within 15 minutes.**
  Motivation: The customer intends to use the aircraft for multiple flights, and may need to collect several data sets at the same location with limited repair time and materials available.
  Verification: Any repairs needed after each flight cycle will be timed with a stopwatch to confirm that they take 15 minutes or less.
  - **DR 3.3.1: The power source shall be interchangeable.**
    Motivation: The in-between flight setup shall take an average time of 15 minutes.
    Verification: A stopwatch shall be used to measure turnaround time for battery replacement.
  - **DR 3.3.2: The aircraft shall be able to land in a field.**
    Motivation: Landing location will be, at best, minimally prepared. Aircraft should be able to land over small stones and bumps without catastrophic damage.
    Verification: Inspect frame for landing-related major damage after each flight cycle.

Functional Requirement 3 is concerned with the aircraft's ability to perform 10 successive flight tests without the need for any major repairs. The flow down requirements from this are thereby concerned with the three main phases of a typical flight profile; takeoff, loiter, and landing. Design Requirement 3.1 discusses the necessity for the craft to complete a takeoff while under the control of a human pilot. DR 3.1.1 further specifies that whatever method is used to launch the aircraft is quickly deployable in no more than fifteen minutes, while 3.1.2 specifies that the launch method shall integrate with the airframe such that there is no lasting damage imparted during the launch process. These two requirements ensure that launch does not hinder the success of the project as far as meeting the functional requirements. Design Requirement 3.2 then specifies that the aircraft shall be stable and fly in a loiter pattern within visual range. The stability requirement is to ensure that the pilot does not lose control of the aircraft during flights. This is further described in requirement 3.2.1, which states that the aircraft shall be able to demonstrate dynamic stability when subjected to small perturbations. The third driving Design Requirement in this series, 3.3, has to do with the landing and subsequent repairs of the aircraft between flights, constraining these to no more than fifteen minutes. The flow down requirements, 3.3.1 and 3.3.2, go on to define that the power source shall be easily interchangeable, and that the aircraft shall be able to land in an open field. These two requirements are in place to clearly define how the aircraft shall achieve its fifteen minute turn around time.

FR 4: The aircraft shall be capable of sustained powered flight with an endurance of 1 hour.
Motivation: The customer requested a minimum flight time of 1 hour.
Verification: Ground tests shall demonstrate the operational capability of all systems for the total flight time.

- **DR 4.1: The aircraft shall possess an internal power system.**
  Motivation: The aircraft shall be capable of autonomous powered flight. It shall be able to operate in this way for a minimum of 1 hour.
  Verification: Ground-based testing for the full flight duration with all systems active, including propulsion (at 1.3x trim throttle) and control mechanisms.
  - **DR 4.1.1: Power shall be distributed to each subsystem that requires it such that the needs of each powered system are met.**
    Motivation: In order for the system to function as a whole, the power requirements of each subsystem need to be met.
    Verification: A voltmeter shall be used to determine if the voltage across each internal component is in accordance with the manufacturer's specifications. A full electrical systems test prior to the installation shall be used as a final verification.

- **DR 4.2: The propulsion system shall support sustained flight for a minimum of one hour at standard operating loads.**
  Motivation: In order to meet the endurance goals set by the customer, the propulsion system must be correctly sized so as to provide adequate thrust for the aircraft.
  Verification: Flight testing shall verify propulsive sufficiency by maintaining a consistent flight speed for an extended time.

  - **DR 4.2.1: The propulsion system shall generate sufficient thrust to overcome the expected drag forces on the aircraft.**
    Motivation: For sustained flight, the propulsion system must be able to overcome the drag forces acting on the airframe during flight.
    Verification: Thrust performance shall be determined on the ground via static thrust testing.
  - **DR 4.2.2: The propulsion system shall be positioned to prevent damage to the motors.**
    Motivation: In the interest of rapid turn around and ease of repair, the propulsion system should be protected from undue damage on landing. Propeller damage is admissible due to the availability of replacement propellers.
    Verification: Motor units shall not be damaged during flight testing.

Functional Requirement 4 specifies the aircraft's powered endurance goal of one hour, per customer request. Design Requirement 4.1 goes on to further specify that the aircraft shall achieve this endurance using an internal, integrated power system. This internal system shall be able to meet the power needs of all on-board components, as specified by the flow down requirement 4.1.1. Design Requirement 4.2 deals with the propulsion system needed to support sustained flight for the full hour of required endurance. The derivative requirement 4.2.1 goes on to define this support as producing enough thrust to overcome the drag forces that arise from steady flight at the expected cruise velocity. Requirement 4.2.2 concerns the positioning of the propulsion system within the airframe itself, ensuring that the motor is not damaged upon landing or any other phases of flight testing.

FR 5: The aircraft shall be piloted by an autopilot during the loiter phase of the mission profile.
Motivation: Autopilot will remove human error from the loiter stage of flight, enabling a more consistent method of data collection.
Verification: The autopilot's response to inputs from typical flight conditions will be tested to ensure the desired response is achieved.

- **DR 5.1: The flight controller shall receive manual commands from the RC pilot.**
  Motivation: The customer requires that takeoff, landing, and general maneuverability be manually controllable. These phases of the flight profile are generally very difficult to control via autopilot.
  Verification: Pilot commands transmitted by the aircraft controller are executed by the flight controller on the servos during ground testing.

- **DR 5.2: The autopilot system shall contain the sensors necessary to implement feedback control for a steady flight.**
  Motivation: In order for the feedback system to adjust the aircraft, onboard state determination shall be required to calculate the necessary control outputs.
  Verification: Flight information fed from the flight controller to ground control matches the conditions set for the test such as pressure, rotation, and changes in altitude.

  - **DR 5.2.1: The flight controller shall have the ability to ensure path deviations in loitering are under 15 meters.**
    Motivation: The aircraft will be collecting data through the FADS system, and thus must not deviate over time from the location of interest.
    Verification: The aircraft does not deviate away from the designated flight path more than the specified deviation range of $\pm$15 meters.

- **DR 5.3: The RC pilot shall be able to switch from manual control to autopilot control for loitering flight.**
  Motivation: Due to the expected time of flight which will be approximately 1 hour, the customer requires that an autopilot be used for steady flight as it will be the major portion of the flight.
  Verification: The flight controller switches from manual control to autopilot control when the RC controller switch is activated.

Functional Requirement 5 defines the need for an autopilot aboard the airframe, and the implementation of this autopilot during the loiter portion of the flight profile. Design Requirement 5.1 first states that the aircraft shall be able to receive manual commands from an RC pilot on the ground. This is in place so that should an error occur with the autopilot during loiter, the aircraft can still be recovered and flown. It also allows for human control during the takeoff and landing portions of flight, stages of the flight profile which pose much higher risk than the loiter period due to changing flight conditions and close proximity to the ground. Requirement 5.2 then goes on to define the necessary features of the autopilot, and specifically, the inclusion of sensors that allow for closed loop feedback control to be implemented. The flow down requirement, 5.2.1, then defines the maximum deviation deemed acceptable from the planned loiter flight path while the autopilot is running. This value of fifteen meters was selected to ensure that the aircraft does not leave visual range at any point during flight, and also continues to collect data at desired locations and altitudes. Design Requirement 5.3 reconciles the two methods of control by stating that the switch from manual to automated control take place in flight. This requirement is in place to ensure that the autopilot can be switched on and off as necessary during flight testing.

3.3. Final Design

3.3.1. Control System

Controls was one of the few subsystems that had not had any significant progress in testing at the time the project was stopped. However, the aircraft itself proved to be highly stable during the flight test as predicted by the stability models. The iteration of the BUBO used for the flight test did not feature fully autonomous flight capabilities, as the PixHawk2 (PX2) had not yet been configured for the unconventional airframe that is a box-wing. Instead, this iteration had a manual-only control system that consisted of an RC receiver, an RC transmitter, and two servos attached to the elevons on the back wing. Servo tuning was accomplished using the RC transmitter, while control authority was achieved using elevons that combine the functionalities of an aileron and an elevator for direct control of pitch and roll. The aircraft does not contain a rudder of any sort, as yaw is indirectly controlled using lateral coupling to establish relationships between roll angle and induced yaw rates.

The final aircraft iteration would have contained a fully autonomous-capable control system setup with the PixHawk2, GPS module, servos, radio telemetry, and elevons, as well as an RC receiver and transmitter to still allow for manual control during takeoff and landing. For this final design, the PX2 and its internal ArduPilot software required slight reconfiguration to account for the unconventional design of the aircraft. Though it was adjusted to interface with the elevons using the default option available in the firmware, the selection of the gains for PD control was not complete. Further tests were needed for PD control setup, including a ground test with the full setup of the control system to compare with the developed dynamics model of the aircraft. In addition, flight modes required signal setup (PWM signals) on the RC transmitter to ensure that the pilot can switch between autonomous loiter flight and manual flight without any issues. Further necessary alterations included setting up a fail-safe mechanism in the case of any RC control loss. In such a scenario, the aircraft would automatically lock into RTL (Return To Launch) mode and return to the site of its launch using GPS data. A ground station was to be used as well to send commands to the aircraft during flight as well as receive flight data pertaining to the roll, pitch, and yaw for further comparison with the models. This also required a ground test where the telemetry capability would have been tested with a radio attached to the PixHawk in the full control system setup and radio attached to a computer to act as the ground station.

3.3.2. Airframe

The iteration of the BUBO that was used in the flight test was a 1-meter span box-wing aircraft with a straight bottom wing and a 30° swept top wing. The bottom wing had a 5° decalage, or fixed angle of attack, while the top wing was level. The top wing had a cambered NACA6412 airfoil and the bottom wing had a reflexed NACA23112 airfoil. The combination produced a positive pitching moment designed to counteract the negative pitch induced by the ballast. The airframe had solid panels on both outboard ends connecting the two wings as well as a center strut that joined the wings and served as the mounting location for the motor mount, launch hook, and autopilot bay.

The airframe itself was built using a modular approach. It can disassemble into seven main components: two top wing sections, two bottom wing sections, two end panels, and one center pylon. These components are connected in several ways. The wing sections are secured to the center pylon with three separate methods. First, four aluminum rods run spanwise through the center pylon to connect the left and right wing sections, with two rods for the top wing and two for the bottom. These rods are intended to transfer shear and bending loads in the airframe. Second, a singe screw and nut fastened in tension connects each wing section to the center pylon. These secure the wing sections and prevent them from separating in the spanwise direction from the center pylon. Lastly, strapping tape is used along the outside of the connecting junctions in order to cover any gaps and improve aerodynamic performance. The outer panels are connected to the outboard ends of the wing sections via four screws each (two for each wing section). Nut plates were built into the wing sections in order to reduce the complexity of assembly. The screws attaching the lower wing section to the outer panels also serve as the mounting location for the landing skids. This was done to reduce the amount of fasteners required, therefore lowering part count, cost, and weight.

All seven main components of the airframe were constructed using various woods and adhesives as described in previous reports. A mixture of balsa for its low weight and ease of manufacturing, plywood for its strength and versatility, and basswood for its ideal tensile and flexural properties were utilized. The landing skids and the autopilot bay were made using 3D-printed PLA in order to support rapid prototyping of these relatively complex shapes. In addition, these parts serve as some of the main landing protection for the aircraft and therefore have a high likelihood of breaking. By 3D-printing these components, we were able to have multiple spare parts on hand in the field should a landing skid need replacing. Additional bracing for landing was provided by the ballasted boom protruding from the front of the aircraft, made by attaching mass to a beech wood dowel. Originally intended just to move the center of gravity forward for stability reasons, this boom proved to be a valuable asset in landing due to its tendency to strike the ground before the leading edge of the top wing, thereby absorbing a great deal of kinetic energy. Similar to the landing skids, the boom was designed to be easy and inexpensive to replace should it break upon landing, and in fact, it was preferred to break so as to protect the rest of the airframe.

All wetted surfaces on the airframe (surfaces that are exposed to the airflow during flight) except for the center panel were covered in Monokote, a thin, transparent, and easily repairable plastic sheeting commonly used in hobbyist RC aircraft as a skin material. Not only does it provide a smooth aerodynamic surface, but it is significantly strong in tension and therefore makes an airframe much stronger when applied. When lightening holes were added to the outer panels to help improve performance, monokote was used to cover the holes in order to prevent large amounts of turbulence drag coming from these open areas.

Because there is no fuselage in a box-wing aircraft to house the avionics, the airframe had to be designed such that all onboard electronics were housed within the wing sections. To accomplish this, a bay-floor made of plywood was added to each wing section along with pass-through holes in every rib section for wiring. Certain components such as the FADS sensors and the numerous batteries were to be located in the wing sections, while more critical flight components like the telemetry radio, ESC, and the autopilot were made to live inside the structure of the center pylon. Not only do some of these avionics components require being on the centerline of the aircraft, but by being in the innermost structure they are also theoretically the most protected from damage upon impact. This was a priority for some of our more expensive components, such as the autopilot controller. A 3D-printed component, known as the autopilot bay, was designed and fabricated that acts as the floor of the lower wing section of the center pylon. It attaches to the center panel with two screws in shear and helps transfer some compressive loads spanwise through the lower wing. It has screw holes made specifically for our PixHawk autopilot controller so that the PixHawk's exact orientation within the aircraft is known and so the PixHawk does not come loose during flight. The orientation of the autopilot is important for accurate autopilot feedback and controls.

3.3.3. Electrical Circuit

The final circuit design schematic for the aircraft is shown in Figure 3. The electrical system design of the BUBO fills multiple functions. Primarily, it ensures that power is properly distributed through the aircraft to all components that require it. Second, it makes sure that data collected on the aircraft is saved and able to be processed after the flight, and that control commands from the pilot or autopilot are properly executed by the aircraft. Finally, the power system must be able to handle a sustained flight load for an endurance of one hour, as defined by the requirements laid out previously. The key design requirements that dictate the electronics design are shown previously. These requirements motivated the modeling and testing done to create the electrical system design for the aircraft.

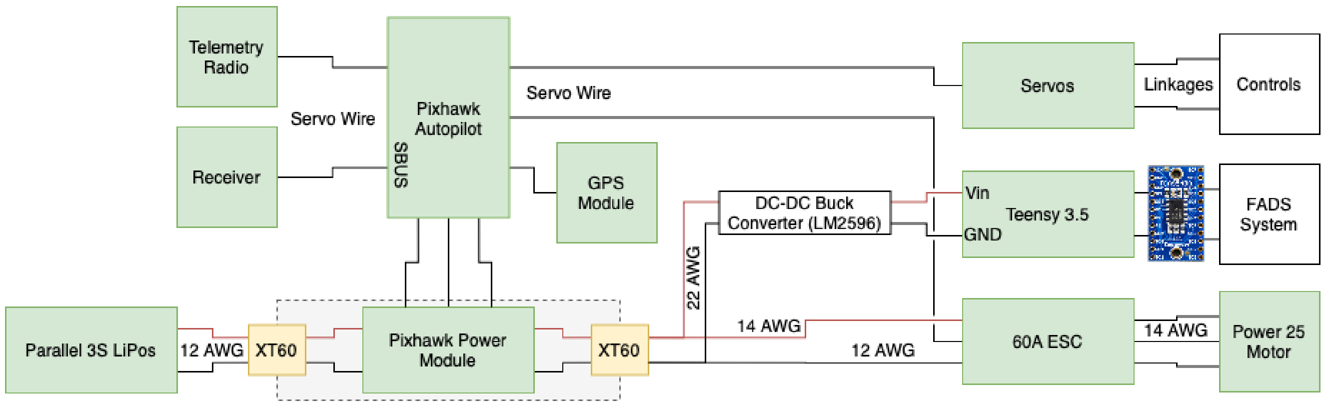

Figure 3. Overall Electronics Circuit Diagram

The power subsystem consists of the batteries, Pixhawk Power Module, and the propulsion system, the speed controller (ESC) and motor. Design Requirement 4.1 states that the aircraft must have an internal power system, and therefore an internal power source. In the conceptual design phase, trade studies were conducted on different battery types and configurations to power the aircraft in an efficient and manageable way. Lithium Polymer (LiPo) batteries were chosen for their reliability, energy density, and ease of acquisition. Additionally, many small batteries in parallel was the chosen configuration, as it works very well with the structural design, which has many bays in the wings able to hold many small batteries easily. This allows the user to move batteries between the two wings to adjust the center of gravity of the aircraft in the field. Ideally, to maximize power efficiency, a high cell count battery would be chosen, as higher cell counts store the energy at higher voltage. However, as cell counts increase, the thickness of batteries increase as well, making high cell count batteries impossible to fit in the wing of the aircraft. Ultimately, three cell LiPos were chosen, specifically Thunderpower Prolite 25C 3S 910mAh packs. These are small enough to fit two batteries in any wing bay, yet provide enough capacity to limit the total number of batteries required in the aircraft. The group has experience with Thunderpower, where they have proven to produce quality batteries for a respectable price and availability. The amount of parallel batteries required for our aircraft is driven by Design Requirement 4.2, which states our aircraft must achieve an endurance of one hour. This drove the development of the endurance model, which allows us to predict our battery count requirements, and will be discussed later.

The control subsystem consists of the Pixhawk autopilot, GPS and radios, and servo actuated controls. The Pixhawk autopilot is further discussed in the control system design section. The RC receiver communicates with the pilot's transmitter to get pilot commands to the control subsystem. The choice of transmitter, which is a Futaba T8J, drives the choice of receiver as it defines the communication protocol. The transmitter was chosen as it is a very capable computer radio that the team's test pilot has used for years. A radio is a significant investment, and as a capable one was already on hand, it was decided to go forward using it. The Futaba T8J uses the S-FHSS communication protocol, so a matching receiver needed to be selected. To keep the receiver as light as possible, an SBUS receiver was chosen, which lets the receiver connect to the autopilot, send data, and receive power by just a single wire, eliminating the need for multiple channels of wires for each channel of pilot control. This aircraft does not need a long range receiver, as it is designed to complete circular loiter pattern missions within visual range. Given these requirements, the Superior Hobby RSFSB 8 receiver was chosen.

Finally, the sensor subsystem consists of the FADS circuit, shown in Figure 4, and it's accompanying data storage microcontroller. The Flush Air Data Sensing (FADS) system, as required by Design Requirements 2.1 and 2.3, consists of the data storage microcontroller and the bays of I2C breakout and pressure transducer boards.

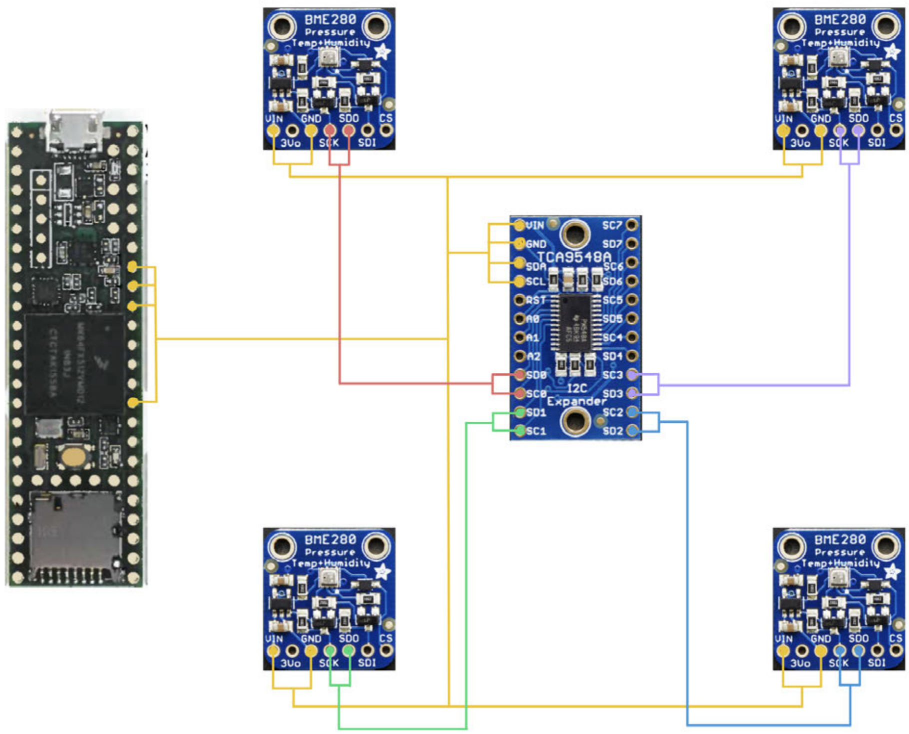

Figure 4. FADS Bay Circuit Diagram

In the conceptual design phase, an Arduino-architectured microcontroller was settled on for its ease of use and prior group experience. A Teensy 3.5 was selected for its small profile, integrated SD card, and three I2C rails. This setup allows the user to connect up to three bays of pressure transducers and store data from them in a way that is easily and quickly switched out between flights. The Teensy operates at 3-6V, making it the only component on the aircraft that is powered directly by the aircraft batteries that can not accept the battery voltage of 10-12V. A solution was designed using a resistor to dissipate enough power to drop the voltage to the required level. This was the simplest solution but not the most robust, and will be discussed in the next section. Assuming the Teensy is successfully powered, it will be the hub of the FADS system, connecting directly to the sensor bays spread throughout the aircraft and saving the data to be analyzed post-flight. Arduino's are programmed using a modified C++ derived programming environment. The environment comes with many useful libraries, including the Inter-integrated Circuit (I2C) transmission library that includes very useful scripts for dealing with the I2C communication that the digital pressure transducers use. This makes programming data storage from the pressure transducers extremely simple.

The pressure transducers selected for the FADS system are digital BME280s that send digital pressure data over I2C communication. To simplify the FADS bay circuit, a version integrated into an Adafruit breakout board was chosen, allowing four-strand ribbon wire to be used to easily connect the pressure transducers to an I2C breakout board. This is required as the pressure transducers are fixed address, so multiple transducer boards cannot be connected to the same I2C bus using addressed I2C. The Adafruit I2C breakout allows multiple transducers to be connected and addressed into one I2C bus that can be connected to the Teensy's I2C busses, as shown in Figure 4. This allows up to eight pressure transducers to be connected to each of the three I2C ports on the Teensy, letting the airframe house up to 24 flush FADS pressure ports. These groupings of FADS transducers and a breakout board make up the individual FADS bays, which is discussed more in the FADS section.

4. Manufacturing

Author:

4.1. Mechanical Manufacturing Scope

The scope of the mechanical manufacturing tasks for team BUBO BUBO can be described by the components given in Figure 5. The components here include all of the necessary hardware items to construct a fully functioning BUBO aircraft, most of which were successfully manufactured and placed into the aircraft for the first flight test. Components that did not make it into the aircraft are assigned a red status indicator. It is worth noting that the only components that did not achieve full implementation (from a hardware standpoint) were the hardware components of the FADS system. These components were planned to be implemented in the second test flight. More information on the planned FADS integration will be given in the Section 4.2. In terms of subsystems, the large majority of the mechanical manufacturing scope belonged to the structures subsystem where most of those components were easily manufactured via the laser cutter in the SMEAD aerospace building.

Quantity	Part	Did it make it in the plane? (red or green)	Manufactured or COTS?	Material (if applicable)	Manufacturing/Purchase Location	Manufacturing Process (if applicable)	Subsystem (if applicable)
x4	Leading Edge Stock		Manufactured	Balsa wood	SMEAD Aerospace	Band Saw/Dreme	Structures
x8	Spar		Manufactured	Basswood	SMEAD Aerospace	Band Saw/Dreme	Structures
x24	Shear web		Manufactured	Balsa wood	SMEAD Aerospace	Band Saw/Dreme	Structures
x20	Airfoil (Balsa)		Manufactured	Balsa wood	SMEAD Aerospace	Laser Cutter	Structures
x8	Airfoil (Plywood)		Manufactured	Plywood	SMEAD Aerospace	Laser Cutter	Structures
x2	Side Wall		Manufactured	Plywood	SMEAD Aerospace	Laser Cutter	Structures
x4	Bay Floor		Manufactured	Plywood	SMEAD Aerospace	Laser Cutter	Structures
x4	Connection Rod		COTS	Aluminum	https://www.hobbylobby.com		Structures
x12	Connection Tube		Manufactured	Carbon Fiber	SMEAD Aerospace	Band Saw/Dreme	Structures
x2	Hose Clamp		COTS	Aluminum	https://www.mcguckin.com/		Structures
x1	Center Strut		Manufactured	Plywood	SMEAD Aerospace	Laser Cutter	Structures
x2	Landing Skid		Manufactured	PLA	SMEAD Aerospace	3D Printer	Structures
x1	Pylon Floor		Manufactured	PLA	SMEAD Aerospace	3D Printer	Structures
x1	Boom Rod		Manufactured	Basswood	SMEAD Aerospace	Band Saw/Dreme	Structures
x8	Connection bolts (wing to pylon/wi		COTS	Zinc/Stainless Steel	https://www.mcguckin.com/		Structures
x1	Motor Mount		Manufactured	Plywood	SMEAD Aerospace	Laser Cutter	Structures
x1	Launch Hook		Manufactured	Plywood	SMEAD Aerospace	Laser Cutter	Structures
x1	Pogo		Manufactured	Plywood	SMEAD Aerospace	Laser Cutter	Structures
x8	LE Sheeting		Manufactured	Balsa wood	SMEAD Aerospace	Hand Cut	Structures
x8	TE Sheeting		Manufactured	Balsa wood	SMEAD Aerospace	Hand Cut	Structures
x10	Elevon Rib		Manufactured	Balsa wood	SMEAD Aerospace	Laser Cutter	Structures
x4	Elevon Sheeting		Manufactured	Balsa wood	SMEAD Aerospace	Hand Cut	Structures
x2	Elevon Back Wall		Manufactured	Plywood	SMEAD Aerospace	Laser Cutter	Structures
x2	Servo Arm		Manufactured	ABS	SMEAD Aerospace	3D Printer	Structures
x2	Control Rod		Manufactured	Music Wire	SMEAD Aerospace	Hand Bent	Structures
x2	Control Horn		Manufactured	Plywood	SMEAD Aerospace	Laser Cutter	Structures
x8	Nut plate		Manufactured	Balsa wood	SMEAD Aerospace	Laser Cutter	Structures
x2	Elevon Alignment Plate		Manufactured	Plywood	SMEAD Aerospace	Laser Cutter	Structures
x2	FADS Sensor Bays		Manufactured	PLA	SMEAD Aerospace	3D Printer	FADS
x12	1/8" Rubber tubing		COTS	Urithane	https://www.mcguckin.com/		FADS
x24	Rubber gromets		COTS	Rubber	https://www.mcguckin.com/		FADS

Figure 5. Mechanical Manufacturing Component List

Part of the scope of the mechanical manufacturing for team BUBO BUBO was the decision to purchase certain components rather than manufacture them in house. Commercial off-the-shelf (COTS) components will be defined as any part of the aircraft which is purchased and not physically modified in any way before being integrated into the fully constructed aircraft. The following Figure 6 gives a visual representation of which components were COTS (shown in green) and which were manufactured (shown in white) by the BUBO BUBO team. Note that many of the COTS components are electrical, where the top wing houses batteries, GPS and RC receiver and the bottom wing houses more batteries, the FADS system, servos and the autopilot. This gives a reference for the sheer quantity of components that were required to construct a single BUBO aircraft and the general placement of the electrical components inside of the airframe.

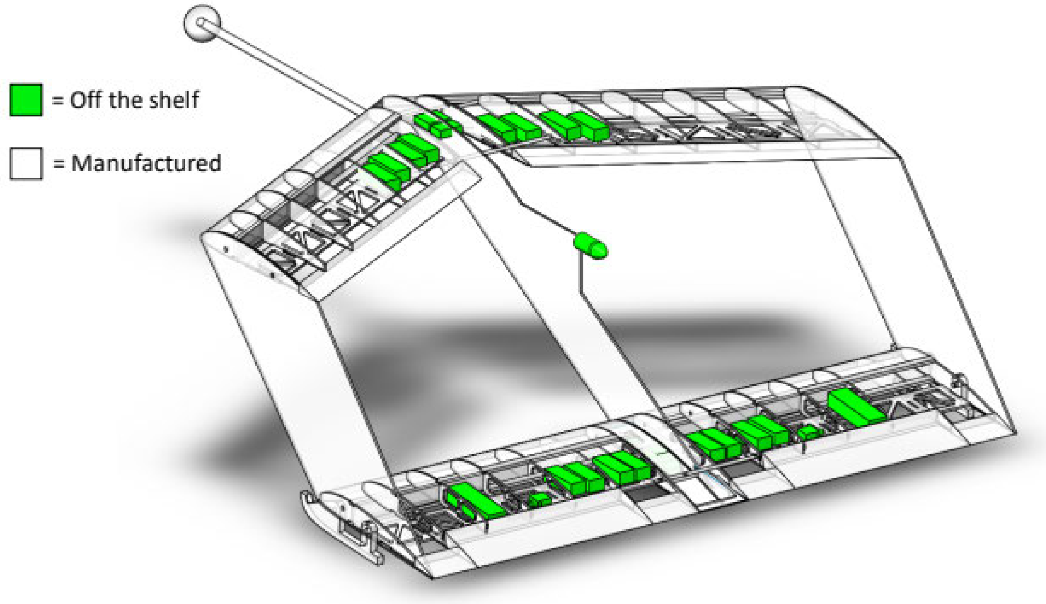

Figure 6. Manufactured and Off the Shelf Components

4.2. Electrical Manufacturing Scope

The electrical manufacturing scope of the BUBO was defined by the circuit design created in the fall semester, as shown in Figure 3. Excepting the FADS system, the aircraft circuit is designed as an integration of many COTS, hobby-grade aircraft components including standard servos, motor/ESC, etc. The FADS system can be regarded as a closed sensor system that is only powered by the rest of the aircraft circuit, with the circuit previously shown in Figure 4. The overall aircraft circuit manufacturing/integration design is shown in the following Figure 7. The wire gauges chosen were guided by the American Wire Gauge (AWG) standard for the calculated maximum current running through them.

The largest section of manufacturing work for electronics was completely constructing the aircraft circuit outside of the actual airframe for testing and verification. This included the power, propulsion, control, and sensor subsystems all tied together and working as commanded and intended. Power distribution and quality was checked and validated for all components, the autopilot commanded the servos in response to IMU perturbations in stabilized mode, the motor was throttled up through the RC radio, and the FADS microcontroller was verified to store data on an SD card. As shown in Figure 7, all systems were designed with physical connectors between components to allow wing-sections to be entirely swappable in the field with no soldering required.

The next step in the manufacturing and integration process was to prepare the BUBO airframe for the initial flight test. In order to ensure the highest chance of success with only one shot to fly the aircraft before the COVID-19 cutoff, the electrical setup in the aircraft was simplified and lightened as much as possible. Due to C ratings, the minimum number of batteries required to fly the aircraft safely, without overheating, is four; this limited the initial flight test endurance to just around five minutes. The FADS system was entirely removed from the circuit, along with the autopilot and all of it's components. This made the aircraft circuit just four LiPo batteries, the RC receiver, ESC, motor, and two servos. The overall integration layout of components in the aircraft was very similar to the design in Figure 7, however the ESC and receiver were moved to the center section of the top wing, leaving the servos the only electrical components in the bottom wing (all four batteries were placed in the top wing bays only).

The rest of the electrical manufacturing scope for the BUBO was left incomplete due to the suddenly-imposed time restraints. The first of these incompleted tasks was to integrate the Pixhawk autopilot system into the tested airframe. This would include integrating the Pixhawk IMU, power module, telemetry radio, and GPS module into the aircraft. This integration would allow the BUBO to complete the autopilot loiter section of the mission profile, completing the autopilot-controlled one-hour endurance goal (which would require a full battery suite, predicted to be around sixteen 910 mAh LiPo batteries). It would also allow the team to start onboard FADS testing. The autopilot system was fully tested outside of the airframe and would have been an easy stepping stone along the path to full electrical integration.

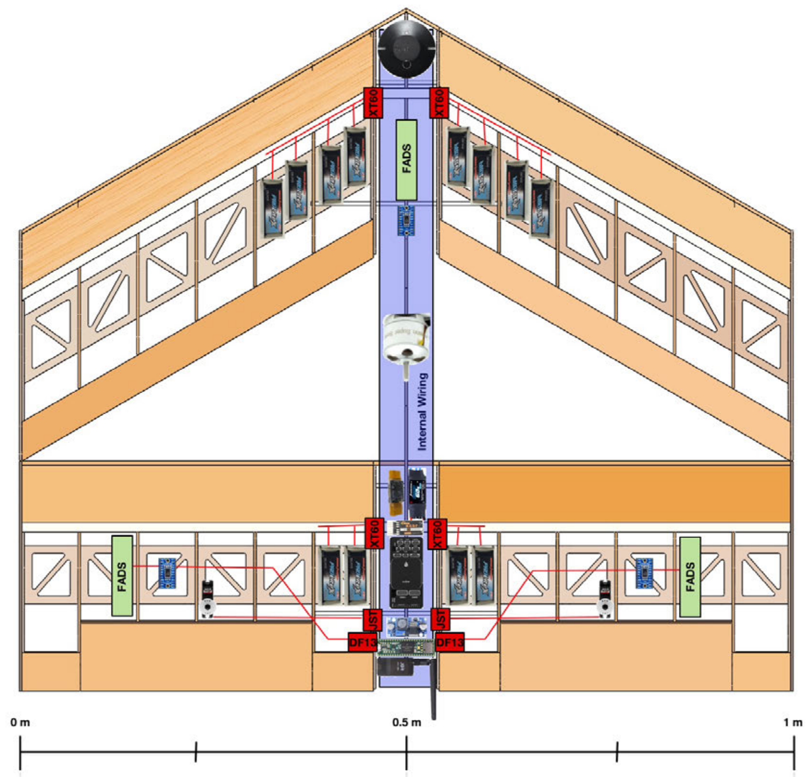

Figure 7. Aircraft Circuit Integration Layout

Once the autopilot system had been fully integrated, tested, and validated, the FADS system would be integrated into the BUBO for flight testing. This would start with the full manufacturing and testing of three FADS bays of four sensors each connected to the data-storage microcontroller. Each bay would be tested for sensor isolation and data integrity outside of the aircraft, and then the FADS bays would be secured in the wing bays with velcro, and tubing would be piped from the leading edge and side panels to the sensors. The system would then be flight tested through an autopilot loiter phase at multiple attitudes. Ideally, a calibration system would have been developed and the goal was to deliver a full data set at multiple altitudes for future processing and interpretation.

4.3. Software Manufacturing Scope

The software selected to configure the autopilot was ArduPlane, a free off-the-shelf software that was designed to be compatible with a range of flight controllers, including the PixHawk 2. This software contains a graphical user interface that allows the user to change parameters and configure firmwares that could be uploaded on to the flight controller. For the initial successful phases of the autopilot setup, the flight controller was being configured to communicate with the GPS Module, servos, motor, and the telemetry radios. The next phase was to adjust certain parameters for flight such as the type of control surfaces to be used by the flight controller, the gains on pitch, roll, yaw, the fail-safe mechanism, the flight modes, and data capture of flight behavior. These parameters were not adjusted in time for the flight test and, thus, the flight controller was not used. However, for the final iteration the PixHawk would have been fully ready for use in flight and capable of autonomous loiter flight had testing not been cutoff.

4.4. Outcome of Manufacturing Tasks

The outcome of the manufacturing tasks in this project was a fully constructed airframe as well as functioning power, RC control and propulsion systems with the capability of supplying additional systems (such as the FADS system) with ample amounts of power. Each of these successful manufacturing tasks can be grouped into three major subsystems of the manufacturing process, these being mechanical, electrical, and software oriented manufacturing tasks.

4.4.1. Outcome of Mechanical Manufacturing

The mechanical subsystem of the manufacturing process included all of the hardware components on the aircraft that do not require electrical power to serve their primary purpose. The outcome of the mechanical manufacturing was one successful airframe, which was comprised of approximately 150 components cohesively working to distribute aerodynamic loads across the airframe during flight. These 150 components put together created large assemblies which included: four wing sections, a center strut, side panels, landing skids, pylon floor, weighted boom, boom attachment mechanism, motor mount, launch hook, and bay door access hatches. Each of these larger assemblies could then be connected via screws and guide rods for an extremely modular design which is both easy to assemble and extremely impact resistant. An intermediate step in this modular construction is shown in the following Figure 8. In addition to the airframe, the mechanical subsystem of the manufacturing process also yielded a pogo style nose wheel (depicted in Figure 10) which was designed to detach from the aircraft upon takeoff. This pogo mechanism was simple as it was comprised of five components: a wheel, two triangular braces, an axle, and a rectangular spacer between each of the triangular braces. This pogo was essential in the success of the test flight as it kept the aircraft at a nose-up attitude during launch.

Figure 8. Intermediate Mechanical Manufacturing Step

4.4.2. Outcome of Electrical Manufacturing

The outcome of the electrical manufacturing, integration, and testing, was limited to the initial flight test model described in Section 4.2. All further tasks, including autopilot integration and FADS integration into the airframe, were left incomplete due to the time cutoff put in place due to COVID-19. Despite the amount of work left to do, the aircraft performed well in the testing that was conducted, and if time was left to complete, further successes were expected throughout the remaining work.

4.4.3. Outcome of Software Manufacturing

There was no major software outcome as the software that was used to configure the PixHawk was off-the-shelf, and, thus, required no development. The only major task was to understand how the GUI of the software operated to allow for configuration and firmware setup in the PixHawk.

4.5. Manufacturing Challenges

Team BUBO BUBO experienced many project related challenges throughout the semester; this section will specifically dive into the manufacturing challenges associated with building a small scale UAS in a collegiate, non-industry setting. The three primary challenges faced with the manufacturing of the BUBO aircraft were materials procurement, delegation of personnel for manufacturing tasks, and build quality tolerance issues. In addition to identifying these challenges, this section will also explain the primary causes of each of these challenges and how these challenges were overcome by the project management, systems engineer and manufacturing lead.

The first major challenge that the team experienced during the development of the BUBO aircraft was materials procurement. Since the BUBO was constructed of a multitude of hobbyist wood types, most of the procurement of materials had to occur via hobby stores local to the University of Colorado. Local procurement was an issue for the team because there was no way of knowing if the hobby stores had the exact types of wood that were needed in stock. As such, many of the stores did not have the materials required for the project which caused the schedule to be pushed back further and further. In addition to scheduling issues, there were also issues with the quality of the wood procured from each of the local stores. Much of the wood was far too warped to be used on the aircraft and, as such, had to be scrapped for fear of building stress into the airframe during construction by bending the wood back into alignment. Although these issues were frustrating, they were easily remedied by purchasing select wood materials online and pressing the warped wood back into alignment. Certain wood types could be ordered online for low cost and fast shipping times so that the project could continue manufacturing without a major delay in the project schedule. On top of this, warped wood procured by the financial team could be soaked in water and pressed using 45 lb plates to eventually straighten it for manufacturing use.

The second major challenge that the team experienced during the development of the BUBO was the delegation of personnel for manufacturing tasks when the project was in the height of its manufacturing phase. As this project had more than 150 parts to fabricate to come together into a full aircraft, a system had to be put in place for delegating certain people to adopt certain manufacturing tasks to stay on the aggressive project schedule that was set for the team. One of the major challenges of this system is finding out which personnel were best suited for each specialized task of the manufacturing process. Failing to delegate personnel correctly could lead to a severe decrease in build quality of the aircraft which could result in aerodynamic or structural deficiencies during flight. To remedy the issue of the assignment of manufacturing tasks, the project manager and manufacturing lead worked together to determine who should work on each manufacturing process based on previous manufacturing experience while also inspecting the work of the individual during and after their manufacturing task was complete. The correct assignment of personnel allowed the manufacturing lead to implement a combined manufacturing strategy of linear manufacturing at the beginning of second semester which then shifted into a parallel manufacturing strategy at the end of the semester. This strategy allowed for the detailed development of build plans during the linear development of wing sections which could be distributed to the manufacturing personnel during the parallel manufacturing phase for ease of manufacturing.

The third major challenge that the team experienced during the development of the BUBO was the build quality and tolerance issues associated with working with prototypical manufacturing methods. As displayed previously in Figure 5, the primary manufacturing method for most of the airframe components was laser cutting. Laser cutters are beneficial because they can cut out multiple parts in a matter of seconds, however, they have one major drawback in that they cannot cut through materials at any angle other than straight vertical. This factor played a major role in the tolerance issues that the team experienced because the entire top wing of the aircraft is swept back at an angle; therefore, the ribs of the aircraft must have their slots cut precisely in order to fit into the bay floor without twisting drastically during assembly. To remedy this issue, the team constructed a foam model in the first semester to test the assembly methods and tolerance calculations for the final aircraft which was constructed in the second semester. This foam model verified the construction method used on the final design and informed the team that the spar/bay floor construction method would yield the best results in terms of tolerancing, strength, and manufacturing time. If any tolerancing issues came about after the development of the foam model, they could also be addressed using hand tools as the lightweight woods used to construct the aircraft were easily manipulated by a dremel tool and sharp edges.

4.6. Component Integration

To end the manufacturing section of this report it is necessary to show the final component integration of how each of the parts listed in Figure 5, as well as the electrical components were integrated into the flight-tested aircraft. This section will feature the component integration descriptions for the entire aircraft which includes the airframe, launch hook/pogo, power and electronics, controls and propulsion. Note that the components integrated in this section are not reflective of the desired final aircraft as they do not include component integration which was planned for after the COVID-19 shutdown.

Figure 9 shows the airframe integration for the aircraft. Specifically, this shows the internal integration of the low level system components such as the ribs, bay floor, spar, shear webs, elevon back wall, elevons, leading edge, leading edge sheeting, trailing edge sheeting and center pylon guide tubes. The four wing sections shown in Figure 9 interface with the center panel via aluminum rods which keep the wings from shearing off of the aircraft. In addition, the wing sections interface with the side walls via eight machine screws with cap nuts set into the outboard sections of the wing panels. Nut plates were also added to the inboard sections of the wing panels to secure the wing sections to the center panel with more horizontal security. In terms of inclusion of components, all of the planned airframe components were integrated before the project cutoff due to COVID-19 and this was one of the primary reasons for the success of the project even when the project timeline was cut short.

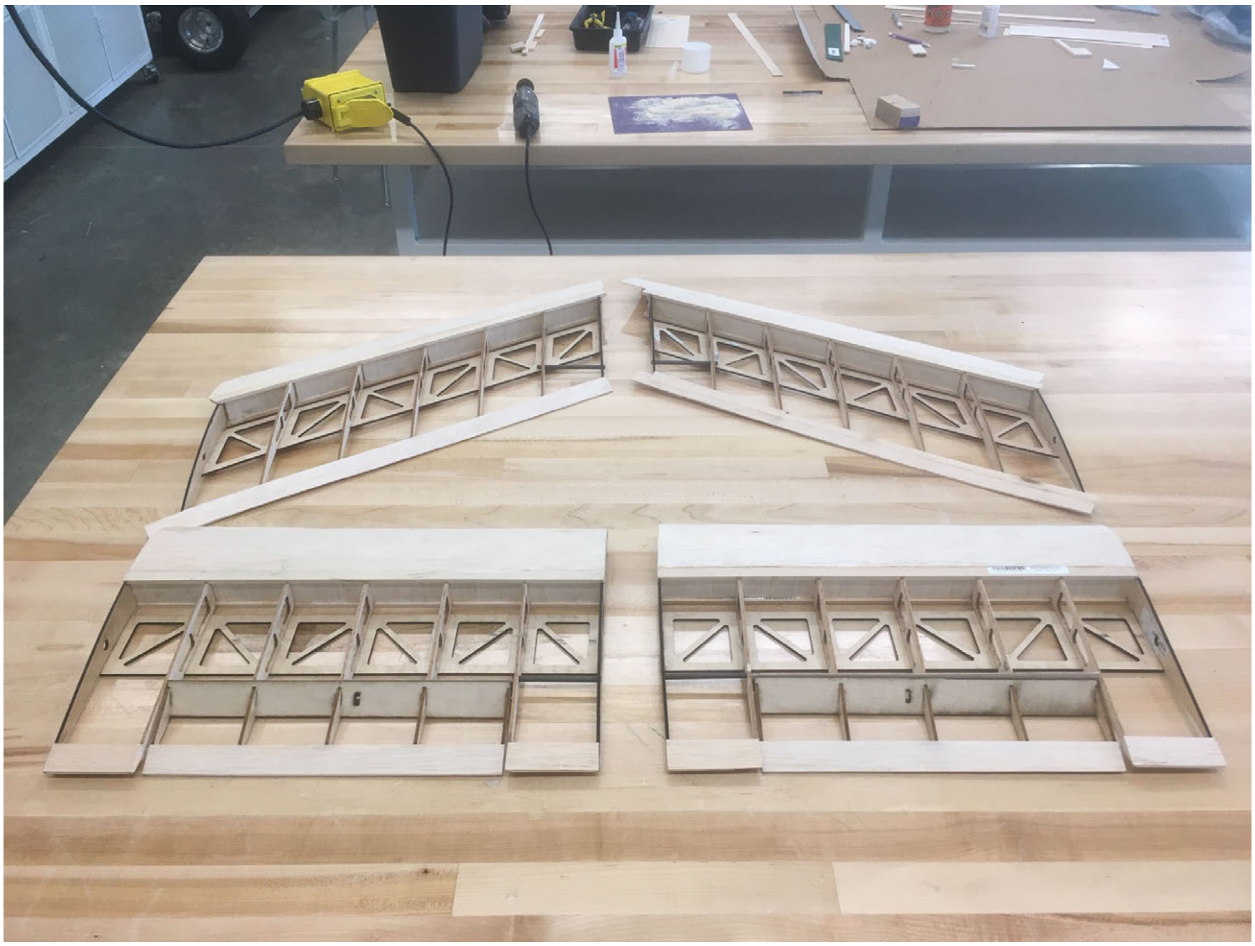

Figure 9. Wing sections showing bays used for airframe integration of various subsystem components as well as integrated elevons

The next two components integrated into the airframe to be discussed are the launch hook and pogo shown in Figure 10. As can be seen, both the launch hook and the pogo are mounted on the leading edge of the center pylon of the aircraft. The placement of these components was estimated using simple force balance calculations, and finalized immediately before the first flight test. The launch hook was attached to the center pylon via two machine screws and washers while the pogo was merely attached to the aircraft by a friction fit. The friction fit of the pogo was designed so that, in the event of the aircraft launching from the table, the pogo would keep the wings of the aircraft at a positive angle of attack until ultimately falling to the ground upon lift off. In addition, a safety tether was added to the pogo and tied to a stake in the ground which would pull the pogo off of the aircraft just in case the friction fit did not release in time.

Figure 10. Launch Hook and Pogo Integration

Figure 11 shows the electronics integration and power setup for the aircraft right before the stability glide test was performed. As can be seen, the electronic speed controller (ESC) is connected to lead wires which branch out into the wings where the batteries are housed, with additional lead wires routed down the center pylon which provide power to the propulsion unit on the center pylon. Note that for the actual flight test, the aircraft flew with four batteries (two in each top wing section) where each wing bay (space between each rib) can house two batteries. The batteries interface with the airframe using stick-on velcro strips to ensure the center of gravity of the aircraft stays in place during flight, and the battery bays are covered by two balsa wood access hatches which are folded open for this picture.

Figure 11. Power and Electronics Integration

Figure 12 shows the controls integration into the airframe of the aircraft. The controls subsystem is comprised of seven components; these being the servo, servo arm, control horn, control rod, elevon, servo mounting plate and servo lead wires. As observed in Figure 12, the servo receives power and controls signals from the servo lead wires which extend to the radio receiver in the center pylon of the aircraft. The servo has an arm which extends through the monokote skin of the aircraft to a control rod which manipulates the control horn that deflects the elevon. The servo itself is mounted to a servo mount plate via adhesive and screws where the servo mount plate is attached to the bay floor via wood screws.

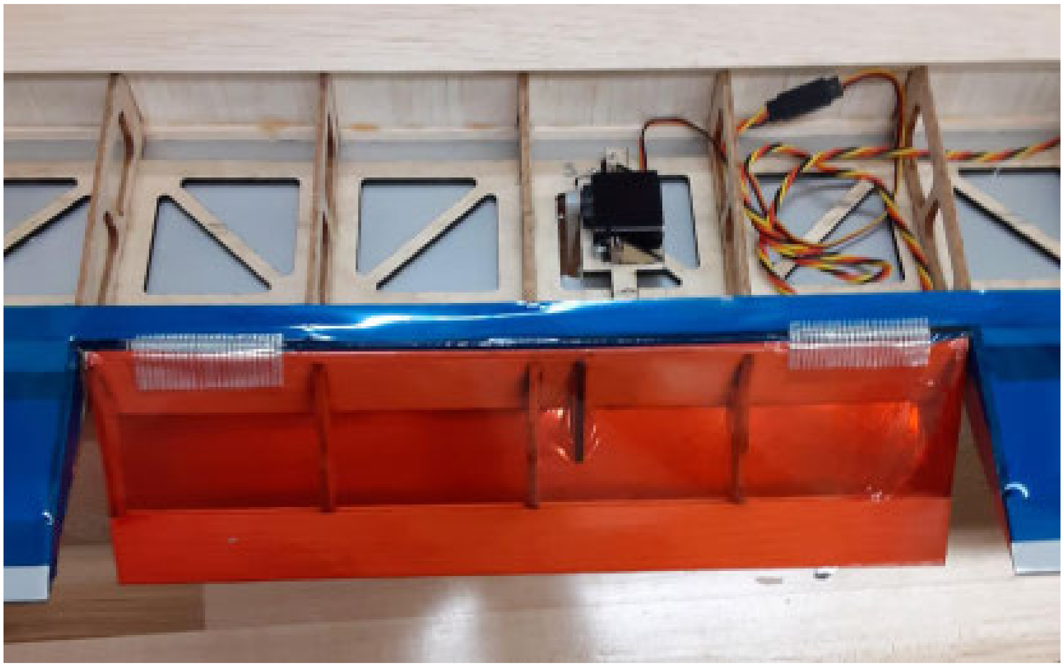

Figure 12. Controls Integration

Finally, Figure 13 presents the integration of the propulsion system on the trailing edge of the center pylon. The propulsion system is comprised of a propeller, brushless motor, motor mount, machine screws and lead wires which extend to the ESC. The propeller is attached to the brushless motor with a friction fit and cap nut where the motor is attached to the motor mount via four machine screws with washers and lock nuts to limit the possibility of the motor vibrating loose during flight. The motor mount is attached to the center pylon via machine screws and nuts at two points to ensure the security of the motor mount on the center pylon during flight.

Figure 13. Propulsion Integration

5. Verification and Validation

Author: All team members; individual contributions listed in Section 9

Verification and validation is the process of determining the accuracy of models, as well as ensuring that the design will fulfill the functional requirements and the levels of success defined early on in the project. Tests are essential in the verification and validation process, and several tests will be presented laying out what has been tested and what was planned to be tested, what results were gained from those tests, and how those results were used to verify and validate the models and functional requirements of the project.

5.1. Whiffletree Test

5.1.1. Reason for Test

The whiffletree test verified the ability of the constructed wing sections to withstand the maximum expected aerodynamic loads. It allowed for the construction of additional wing sections and for testing to progress. I practice, the test illustrated that the aircraft structure may have been over-designed and that certain modifications could be made to reduce the weight of the aircraft, thereby improving endurance, while still ensuring the integrity of the structure. Notably, just under half of the ribs could be removed from each wing while maintaining structural stability.

5.1.2. Predictive Modeling

A single loading condition for a standalone wing section was conducted using FEA. This loading condition analyzed the maximum expected flight loads, a 2.5G upwards loading during the pitching maneuver. The FEA results gave deformation/displacement of the wing section, as well as Von Mises stress. For deflection, Figure 14, the FEA modeling, predicted a maximum wing deflection of approximately $1.8mm$. Additionally, the resulting stresses, Figure 15, in the airframe did not predict failure at this load as they did not exceed any of the yield or ultimate stresses of the materials used, even with a factor of safety (FOS) of 2 included.

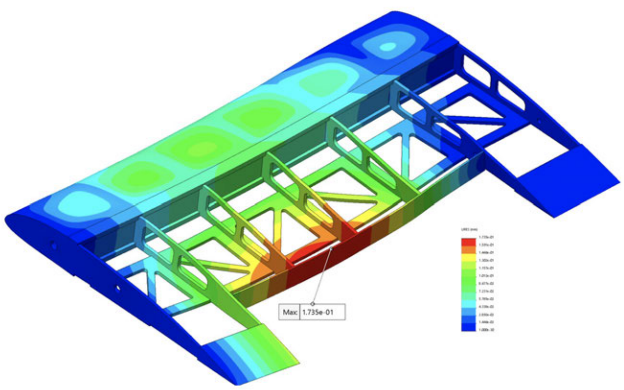

Figure 14. FEA Deflection

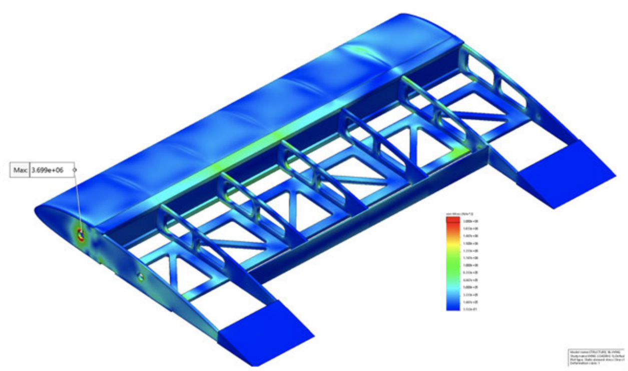

Figure 15. FEA Stress

5.1.3. Test Setup

The test was conducted using canvas straps placed over the ribs of the wing section connected to the bars used in the ASEN 2001 whiffletree lab. The weight was distributed to approximate the loads experienced during flight, determined using a *MATLAB*, script which took inputs of the expected load distribution and outputs the relative bar positioning needed to simulate this load. At the bottom of the whiffletree was a bucket used to hold the weights; the dry weight of the whiffletree setup was approximately 2 lb. A sheet of graph paper with 1cm squares was placed behind the aircraft so that displacement could be measured. Videos were recorded from 2 different angles to measure the displacement digitally. Figure 16 illustrates the setup of the whiffletree test.

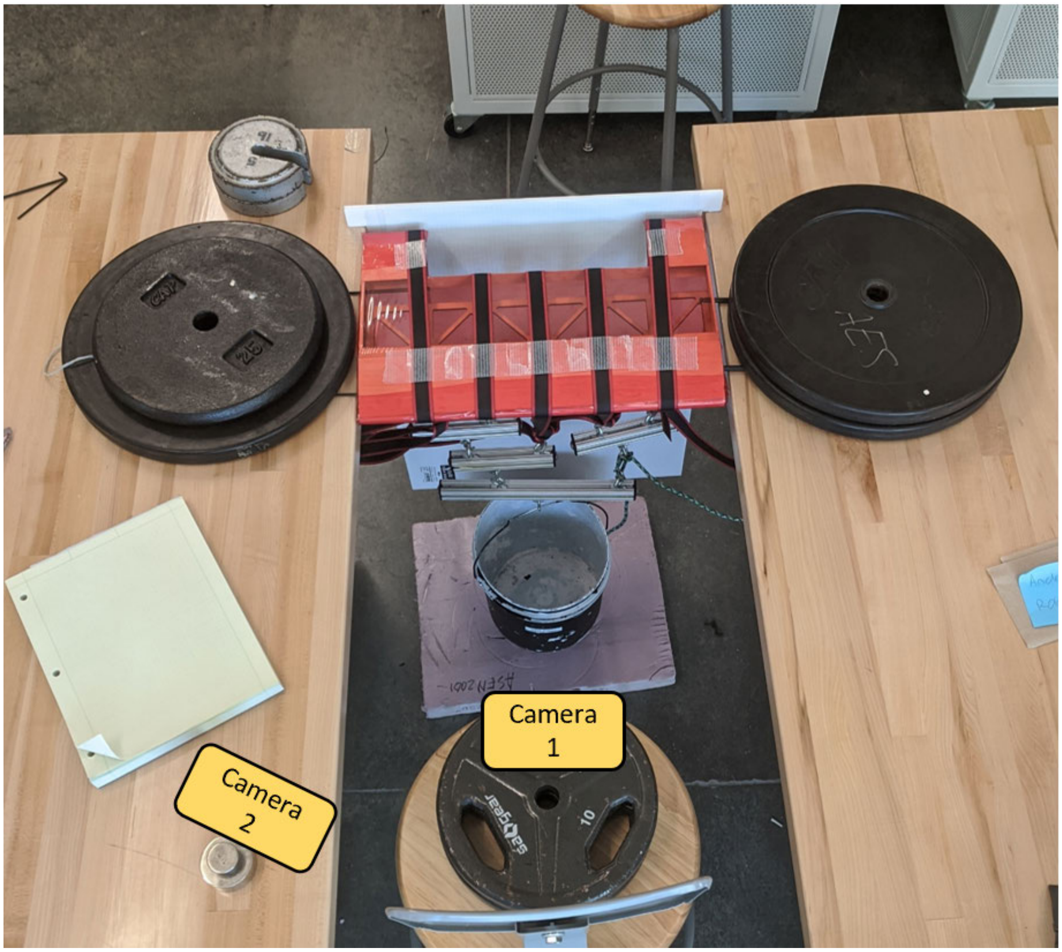

Figure 16. Whiffletree Setup

Once the setup was complete, the test began by adding weights first in 5 lb increments, then 2.5 lb increments as the structure came closer to failure. For each increment, the wing was inspected for possible failure before adding more weight. For the top wing test, weight was added until failure occurred; for the bottom wing, the bucket was filled with weights before a failure occurred.

5.1.4. Data Collected

The top wing withstood 70lb of force without failure. The only significant deformation occurred in the trailing edge of the wing, where the straps were pulling down on the edge of the wing. The displacement of the wings was under 1cm, a displacement deemed negligible, and unable to be well captured due to camera resolution. Figure 17 shows the results of the whiffletree test on the top wing section.

Figure 17. Whiffletree result - top wing

The bottom wing withstood 65lb of force, at which point it failed. The failure occurred with a horizontal crack at the middle of the three center ribs. Figure 18 shows the results for the bottom wing section with the damage circled.

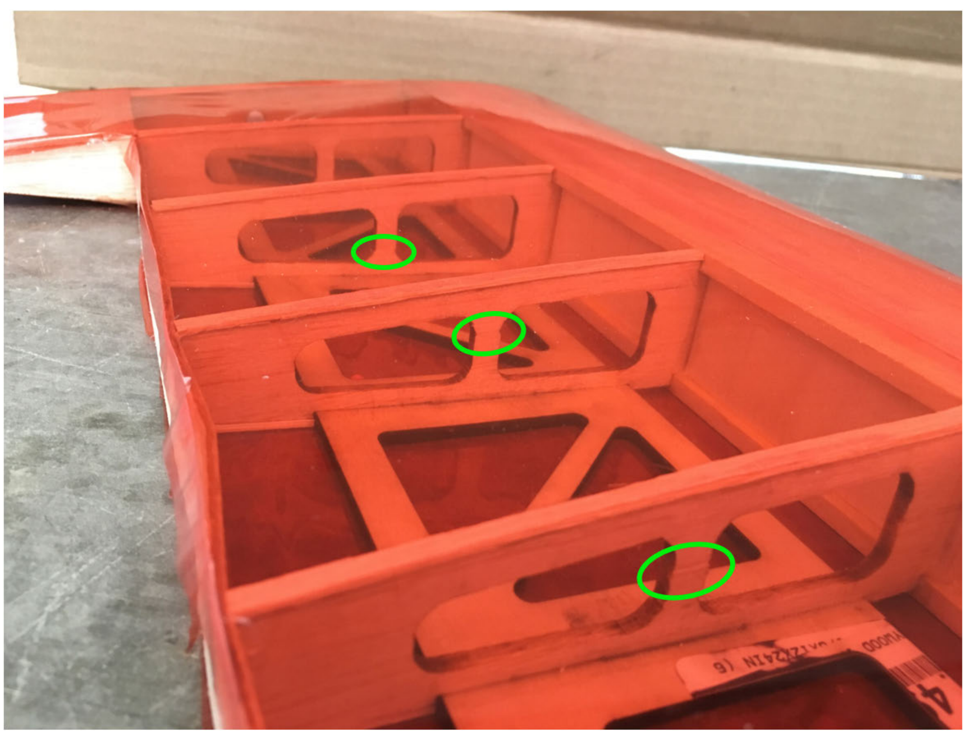

Figure 18. Whiffletree results - bottom wing

5.1.5. *Data Analysis and Comparisons to Predictive Modeling*

During the test, the deflection at the 2.5G load was too small to be measured with the cameras being used. However, the deflections measured at the maximum loads of $60+ lbf$ were less than $1cm$. Linearly scaling the predicted deflection at the 2.5G load up to $65lbf$ gives a smaller deflection than $1cm$, so with respect to deflection, these predictions slightly underestimated what was seen in the test.

Concerning stress, the ultimate load observed in the test compared to the defined maximum operational load gave the wing sections a FOS of approximately 8. This factor of safety is extremely high and means two things: first, the structural design and manufacturing process are exceptionally good, and we should not expect any significant damage during flight barring a worst-case scenario. Secondly, the structural design has been potentially over-engineered for the defined operational environment of the airframe. This was deemed not a significant concern at the time since the wing sections were not overweight. In fact, the dry weight of the airframe was almost exactly what had been projected by the CAD model. Since the chosen design did not come at any significant weight penalty and gave our aircraft excellent survivability traits, a redesign was deemed unnecessary for the first flight test. Further flights with the full 1-hour endurance requirement could have benefited from removing some ribs to maximize weight reduction.

For failure modes, the cracking of rib sections correlates reasonably well with the FEA results. The beginning of some stress concentrations can be seen at these same locations on the rib sections. Overall, no unexpected failure modes were observed, which was desirable. All of this concluded to validate the current structural design.

5.1.6. *Validation*

The whiffletree test partially validated Functional Requirement 3 for survivability. It demonstrated that the plane could withstand loads well beyond what was expected in flight. The final validation would have required flying the aircraft 10 times to see if the structure could withstand the repeated stress of multiple flights. Additionally, it meant that the Level 1 success criteria seen previously in Table 1 was satisfied.

5.2. Thrust Test

5.2.1. *Reason for Test*

The thrust test verified that the thrust produced by the motor and propeller were adequate for sustained flight. The result confirmed the motor and propeller combination, allowed for model verification, ensured the components would not overheat in-flight, and allowed testing to continue.

5.2.2. *Predictive Modeling*

The modeling completed for the propulsion system was based on vortex lattice models produced by APC Propellers, using NASA's TAIR fluid dynamics code and the geometry of APC's on-offer propellers. These models were then incorporated into a MATLAB code that would, through an involved analysis process, select the most effective possible propulsion setup, given airframe constraints. This model would also provide predicted values for thrust and power as a function of motor RPM, thereby allowing us a nearly complete understanding of the propulsion system at different throttle values. A more complete description of this model is included in the FFR.

Figures 19 and 20 are examples of the predictive modeling used for the propulsion system. Note that these models provide a good baseline from which to select a motor, but are limited by the lack of provisions for electrical heating and power considerations. For these, manufacturer specifications are required.

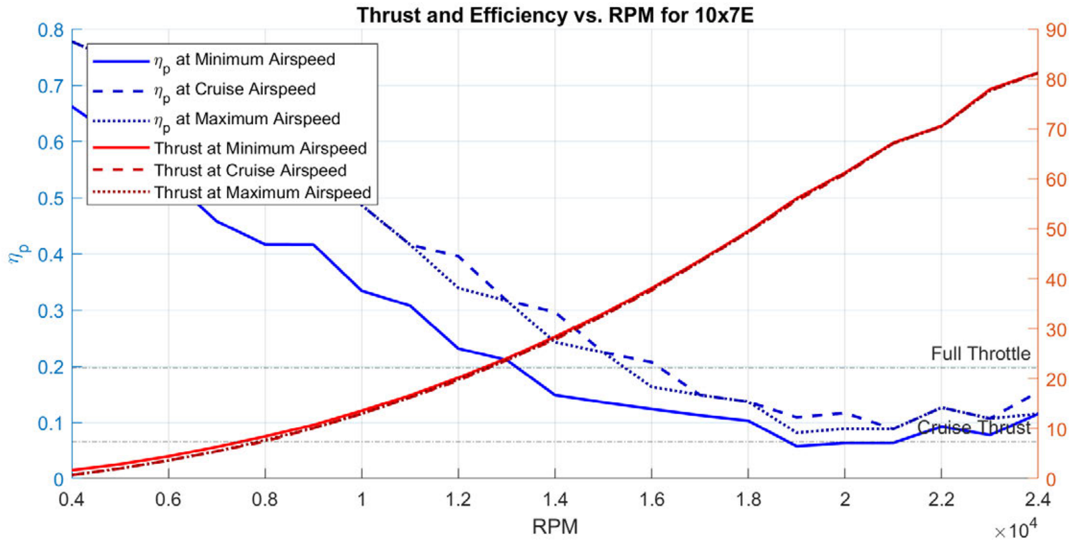

Figure 19. Example of Predicted Thrust and Efficiency

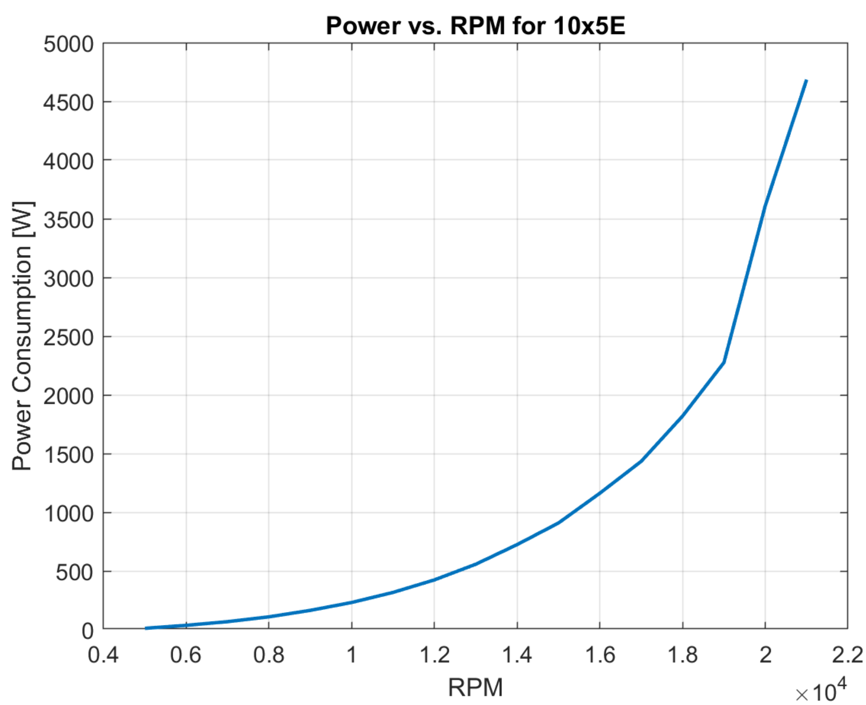

Figure 20. Example of Predicted Power Draw

5.2.3. Test Setup

The full propulsive system was tested using a static test stand on loan from the university's Design Build Fly (DBF) student team. The test was conducted outdoors to maximize safety of personnel and equipment. The motor was connected to 4 batteries to simulate conditions on the first flight test and then secured to the test stand. Once the test started the motor was slowly ramped up to 100% throttle, pausing at fixed intervals to ensure vibration was not an issue. Once at 100% it was throttled back down. Throughout the test the temperature of the batteries, ESC and motor were measured to ensure that no components were overheating due to high power draw. Following the test, all gathered data was saved and processed. The setup of the static thrust test is shown in Figure 21.

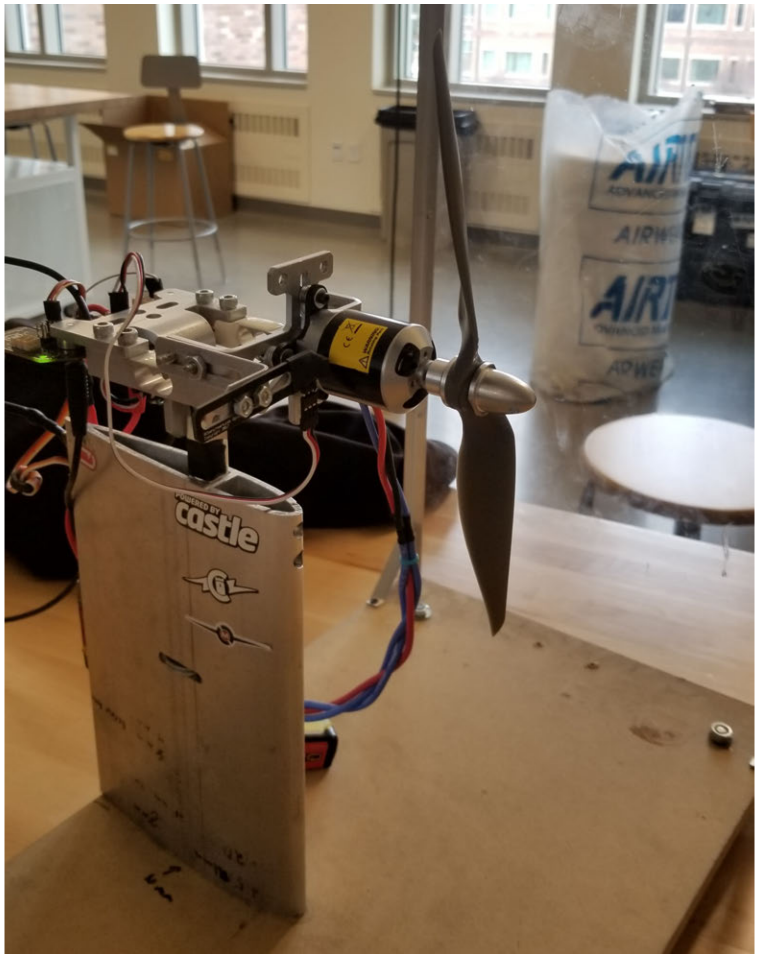

Figure 21. Thrust test setup

5.2.4. Data Collected

The DBF static thrust stand collects data for thrust, torque, current, voltage, power (both mechanical and electrical), RPM, vibration, and efficiency. Only a few of these were used in data analysis, though all are useful for verifying test accuracy. The most important aspects of the collected data are that the maximum thrust achieved is about 15 N, with a maximum electrical power draw of 400 W. These values alone, ensure that the selected propulsion system will be sufficient to fly our aircraft. A more complete discussion of the test's results and analysis follows.

5.2.5. Data Analysis and Comparisons to Predictive Modeling

The static thrust test results were generally in line with expectations from the predictive models, with some inconsistencies.

Figure 22 compares the static thrust measured against that which was predicted. There is a relatively consistent 2 N (12.5%) discrepancy between the two. This discrepancy arises from two possible sources. The predictive model used a simple air density correction to account for altitude, where in reality the translation from non-dimensional values should include several other terms. In addition, the vortex lattice modeling originally used to arrive at the non-dimensional descriptive values somewhat understates the magnitude of drag forces, which could further exacerbate the error.

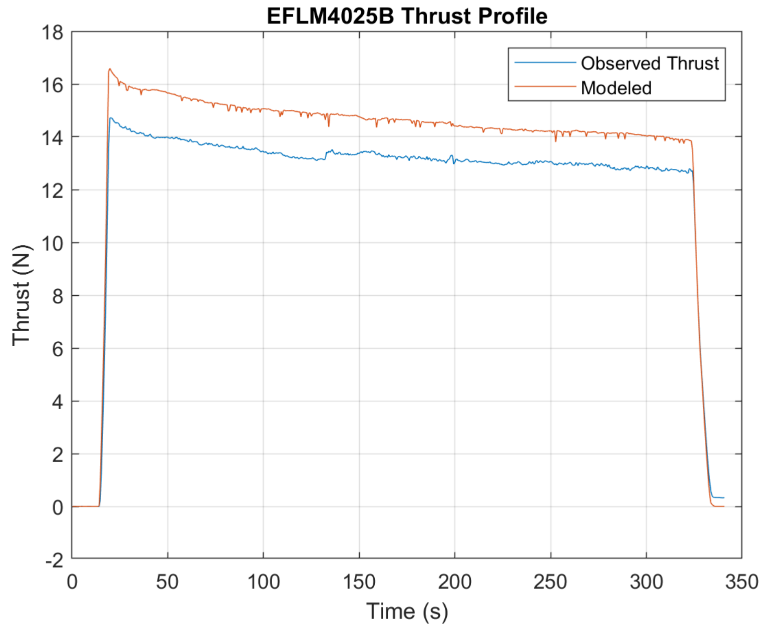

Figure 22. Thrust Profile Comparisons

Upon initial review of the test results, the first concern raised by the team was the maximum thrust value achieved by the propulsion system. 15 N, while easily sufficient to fly the aircraft, is well below the intended design thrust of 20 N. This is a far greater discrepancy than that present purely in the modeling. After further analysis, it became clear that the model, while correct, failed to account for a different aspect of motor performance.

Figure 23 shows the discrepancy in our measured motor RPM values. Motor RPM was an aspect of propulsive performance not directly dealt with in predictive modeling, as the non-dimensional performance parameters are given in terms of rotation rate directly. As such, it was simply assumed that the motors Kv value would provide a good model for the RPM at a given input voltage and throttle. Note that a more complete discussion of electric motors can be found in the FFR.

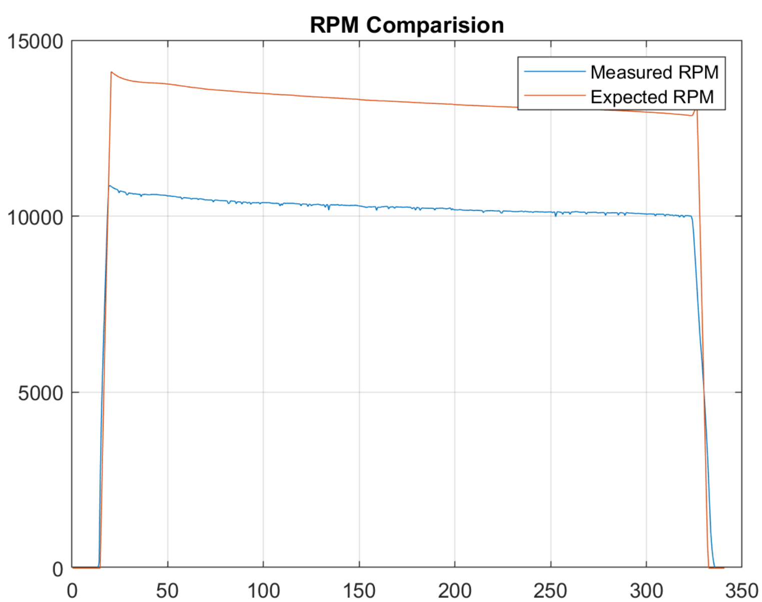

Figure 23. RPM Comparisons

This assumption was proven incorrect in the static thrust tests, with a 30% discrepancy between observed and expected values. This error almost certainly arose due to drag forces acting on the propeller, reducing its maximum possible speed. The limitations imposed by aerodynamic forces are unfortunately very hard to model accurately, and without prior knowledge of motor torque would be impossible to account for at all. Thankfully, the error represented by this mistake was mitigated by the high factors of safety built into the propulsive modeling as well as the propulsion system itself.

Figure 24 shows the power data gathered from the static thrust test, alongside the predicted values. Note that the predictive model assumes that electrical and mechanical power are equivalent values, or more concisely, that the motor has perfect efficiency. This is a patently false assumption, but one that would serve well for basic modeling purposes.

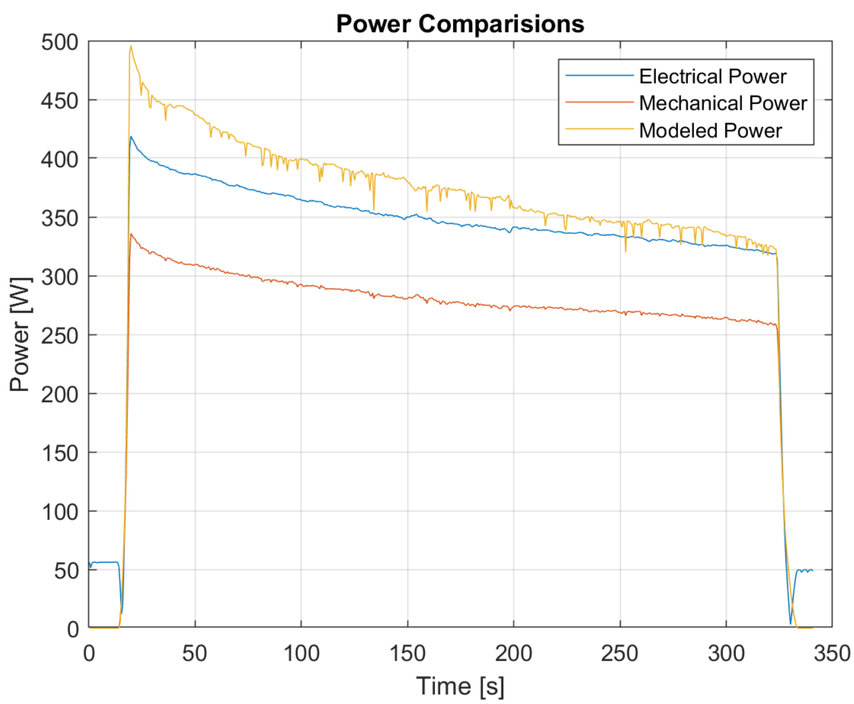

Figure 24. Power Draw Comparisons

The discrepancy noted in power draw values is of similar magnitude to the one present in the thrust profiles, with reducing inaccuracy as RPM drops. Note that the expected value for power draw exceeds the measured values at all times, which is strange but bodes well for system performance. The source of the error likely stems from the parasitic power draw present on the DBF static thrust stand, which causes the measured power draw to be lower than it actually is.

Figure 25 shows the voltage and current demanded by the motor as the test progressed. Note that the gradual reduction of voltage over time is a result of the batteries being depleted, and that the initial, steep drop in battery voltage is expected to occur. The measured current is essentially normal apart from the resting value of about -5 A, which is a product of parasitic draw on the thrust stand circuit board.

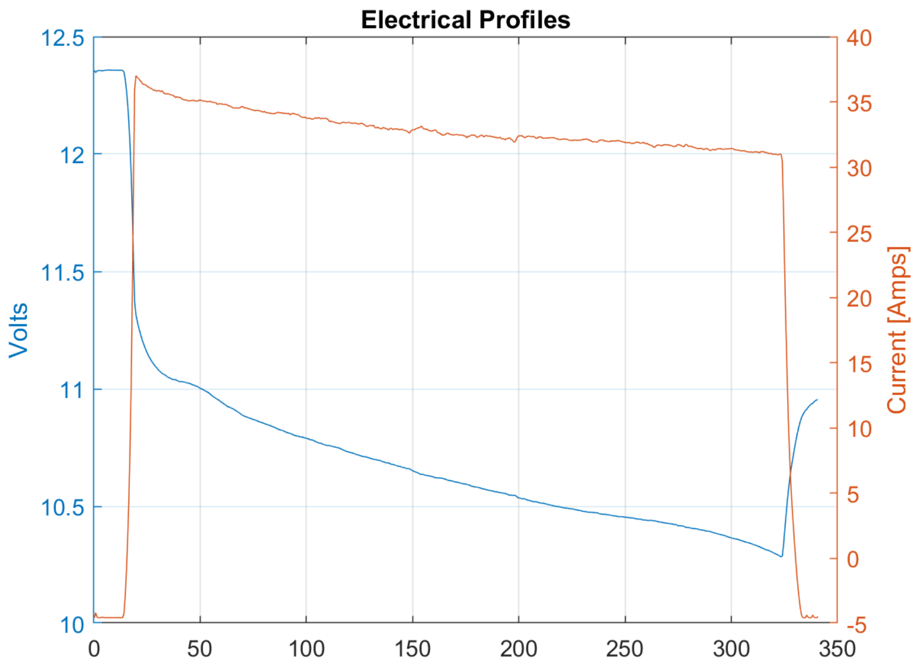

Figure 25. Voltage and Current Profiles

5.2.6. *Validation*

The thrust test partially validated Functional Requirement 4, ensuring that flight was possible given the motor and propeller combination. The power and endurance test would have validated the ability of the plane to fly for one hour.

5.3. FADS Test

5.3.1. *Reason for Test*

Initial FADS tests verified the circuit was correctly acquiring data. Further tests would have verified accuracy of data, as well as the change in accuracy as the system was integrated into the aircraft.

5.3.2. *Predictive Modeling*

There was no proper predictive modeling conducted for the FADS system tests, as this system is fundamentally difficult to predict or model. Later calibration of the system would have used neural networks to build relationships between raw data and desired outputs, making no attempt at deriving analytical relationships between the two. However, some analysis was done for the FADS system in the modeling phase, in order to determine the pressure port locations. This modeling involved using AVL to generate pressure gradients across the surface of the aircraft in order to find areas of high sensitivity. A more complete discussion of this modeling exists in the FFR.

5.3.3. *Test Setup*

The preliminary FADS circuit included an Adafruit TCA9548A multiplexer, an Arduino Teensy 3.5 microcontroller, and an Adafruit BME 280 pressure transducer. These three components were wired together the same way the full circuit would be and code was developed to gather data from the transducer; the code was modular so adding more transducers would be as simple as plugging them in and data collection could begin immediately. This early testing circuit is depicted in Figure 26 This simplified circuit proved that accurate data could be effectively collected by this setup. Further tests would have verified transducer isolation and accurate data gathering in the complete FADS setup, with the possibility of calibration and flight verification if a wind tunnel could be secured.

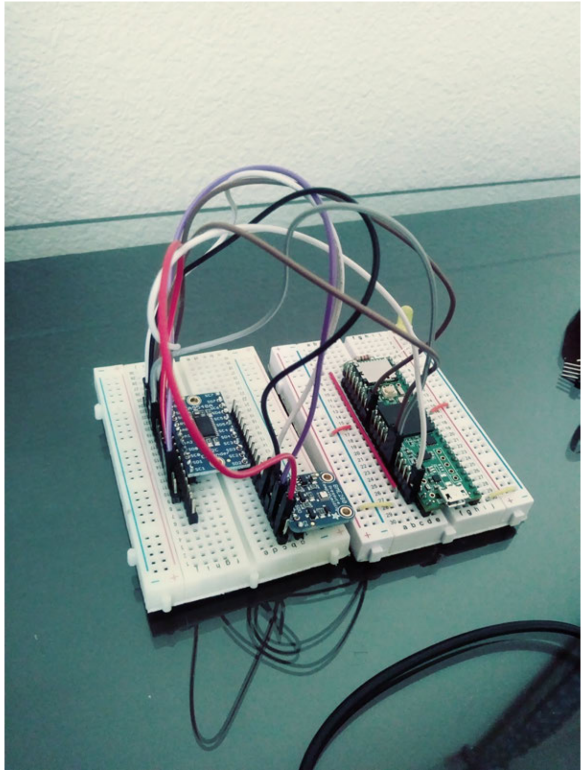

Figure 26. Preliminary FADS circuit

5.3.4. Data Collected

The BME 280 pressure transducers gathered pressure, humidity and temperature data for the duration of the test. This data is shown in the following Figures 27, 28 and 28.

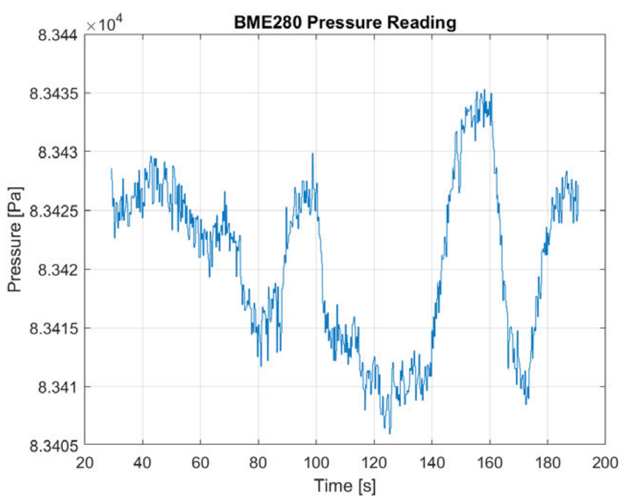

Figure 27. FADS Pressure Readings

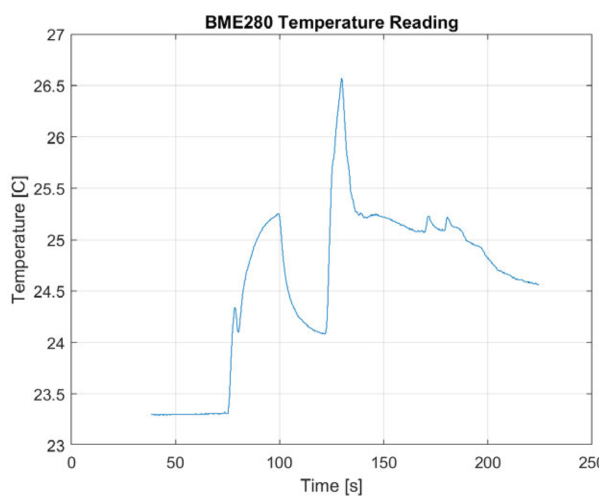

Figure 28. FADS Humidity Readings

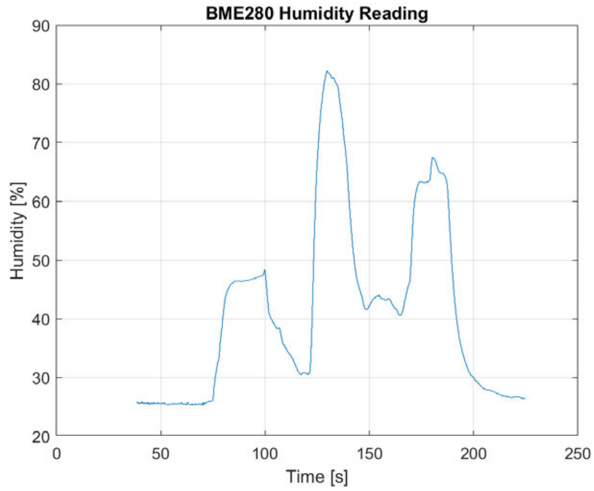

Figure 29. FADS Temperature Readings

In each of these tests, the pressure transducer was put in varying conditions in order to induce changes in each of the readings, and thus measure accuracy, sensitivity, and noise. For pressure readings, the circuit was raised and lowered such that atmospheric pressure changed over the duration of the test. For temperature and humidity readings, touching the transducer with a fingertip seemed to suffice for verification purposes.

5.3.5. Data Analysis and Comparisons to Predictive Modeling

As stated before, no predictive modeling was completed for this test. However, it is clear from the completed testing is that the pressure transducer is indeed accurate, and quite sensitive to environmental changes. For our purposes pressure readings are the most important, and even on the scale of a few meters of altitude change, the transducer is capable of measuring pressure differentials. This also serves as a verification of the manufacturer's specifications. It is also worth noting that all gathered data took up less than 200 kB on the 8 GB SD card that was used for storage, meaning several hours of data could feasibly be gathered, even with all pressure transducers operational.

5.3.6. Validation

Further FADS testing would have validated Functional Requirement 2 for the development of a FADS system. The initial test verified that data was accurately acquired outside of the aircraft, thereby satisfying the first two levels of success for the Sensor Data category, as seen previously in Figure 1.

5.4. Controls Testing

5.4.1. Reason for Test

Controls testing encompasses multiple tests, including manual control, response to PixHawk IMU data, and autopilot simulating a predetermined flight path; the autopilot test was not completed. The controls tests verified the ability of the control surfaces to respond correctly to manual and autopilot input. Initial tests showed that the current configuration did not allow the control surfaces to achieve their full range of motion, so minor changes were made to adjust this.

5.4.2. Predictive Modeling

A linearized model was developed to analyze the stability of the aircraft using AVL. State transition matrices and control input matrices were generated to simulate the dynamics of the aircraft about different flight conditions, including steady and banked flight. A MATLAB code was then used to analyze the aircraft's behavior from that generated data. Based on the requirement for the aircraft to be dynamically stable for perturbations between 0° and 10° for pitch, roll, and yaw, MATLAB simulations were performed for that range. For the iteration of the BUBO used for the flight test, the model predicted that the aircraft would be statically and dynamically stable. The results can be viewed in Figures 30 and 31.

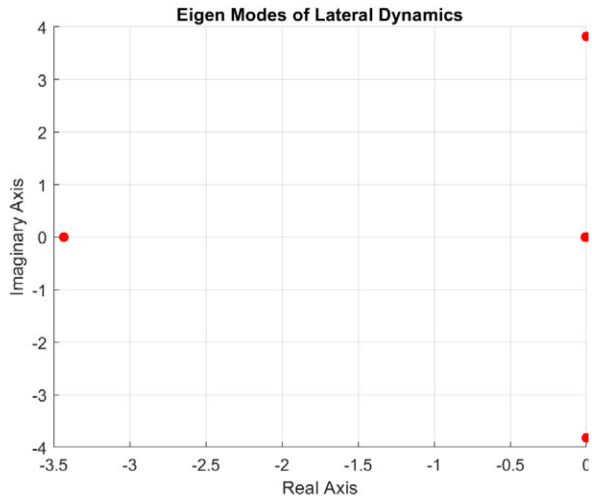

Figure 30. Eigenmodes of Longitudinal Dynamics

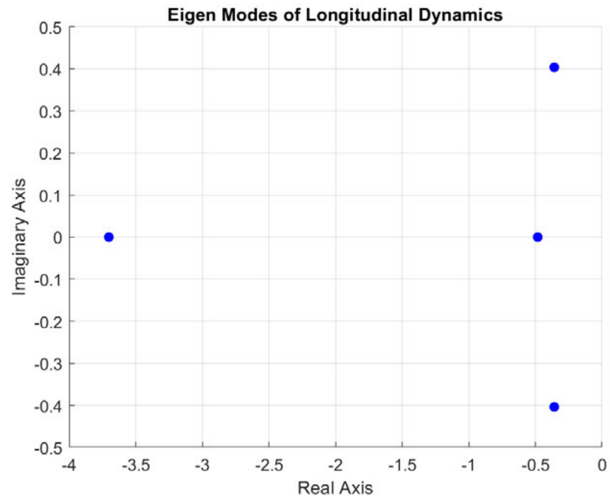

Figure 31. Eigenmodes of Lateral Dynamics

Lateral Eigenmodes	Longitudinal Eigenmodes
-0.0001 ± 3.8205i	-0.3581 ± 0.4041i
-3.4329	-3.7016
-0.0075	-0.4823

5.4.3. Test Setup

No special facilities or materials are needed for these tests. The manual control test connected the control surfaces to the remote controller and each maneuver was tested to ensure the responses were correct. The PixHawk control test connected the control surfaces to the PixHawk and the unit was rotated - the rotation was captured by the internal IMU, and a signal was sent to the servos to actuate the control surfaces in response. These responses were then compared to expectations. The final control test would have used the autopilot and ArduPilot to simulate a predetermined flight path. The elevon deflection would have been measured and compared to models.

5.4.4. Data Collected

Unfortunately, there was no measurable data that was collected as the project had to cease all testing abruptly. The goal was to collect data captured from a ground test with the control system as well as a flight test. That data would have been used in comparison with the model results. However, since the PixHawk and therefore the telemetry radio were not integrated into the flight tested iteration of the aircraft, such quantitative data was never recorded. Instead, the only measures captured were of the Cooper-Harper ratings the pilot provided for the aircraft's flight performance, which can be related to controls and stability of the aircraft, but do not provide any quantitative data for comparison.

5.4.5. Data Analysis and Comparisons to Predictive Modeling

No analysis could be performed as none of the tests were started and completed, as previously discussed.

5.4.6. Validation

While the first two controls test didn't specifically validate any Functional Requirements, they verified that controlled flight was possible. The autopilot test would have validated Functional Requirement 5 for an autopilot loiter phase of flight.

5.5. Power/Endurance Test

5.5.1. Reason for Test

The initial test verified that power draw from the smaller number of batteries used on the first test flight was safe and that the batteries would not overheat. A further endurance test would have verified that the sixteen-battery configuration planned for the later flight tests would have been able to complete a one hour flight.

5.5.2. Predictive Modeling

To fulfill Design Requirement 4.2, the aircraft must achieve an hour of endurance. In order to predict the required number of batteries to achieve that endurance goal, a model was constructed to predict the battery requirements of the aircraft, considering battery cell count, cruise velocity, and endurance required.

The endurance model requires an accurate estimation of drag on the aircraft. AVL allows computation of the aircraft's estimated drag polar, a graph of lift versus drag. This is shown in Figure 32.

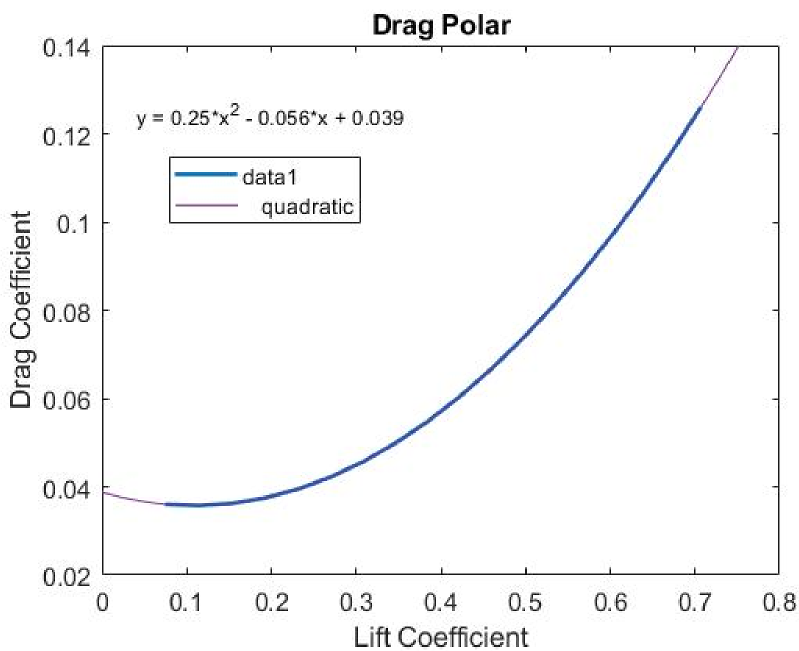

Figure 32. AVL Calculated Drag Polar

The drag polar can be defined using Equation 1.

$$C_D = k \times C_L^2 + C_{D,0} \tag{1}$$

With a parabolic fit to the calculated drag polar, the zero lift drag coefficient is found to be $C_{D,0}$ = 0.039, and the lift-based elliptical coefficient, k, is found to be 0.25. With power required for flight equal to the drag force times the flight velocity, and the drag force equal to the drag coefficient times the wing area and dynamic pressure, the power required for flight can be expressed with Equation 2.

$$P_{req} = \frac{1}{2}\rho U^3 S C_{D,0} + \frac{2W^2 k}{\rho U S} \tag{2}$$

Where W is the estimation of aircraft weight, and U is the cruise velocity. Peukert's equation, Equation 3, estimates the amount of time a battery will last.

$$t = \frac{Rt}{i^n}\left(\frac{C}{Rt}\right)^n \tag{3}$$

In this equation, t is time in hours, i is current being pulled from the battery, C is the capacity of the battery in Ah, Rt is the battery rating in hours, the discharge time over which the capacity was determined, and n is the discharge parameter, which is dependent on battery type and temperature. For small LiPos, a battery rating of one hour and discharge parameter of 1.3 can be assumed, as established by Lance Traub's *Range and Endurance Estimates for Battery-Powered Aircraft*[5]. From Watt's Law, power is equal to voltage times current, and substituting the current in Peukert's battery equation results in Equation 4.

$$P_B = V\frac{C}{Rt}\left(\frac{Rt}{t}\right)^{\frac{1}{n}} \tag{4}$$

Finally, setting power in the battery equal to power required, along with a power efficiency term, results in the endurance relationship in Equation 5.

$$\left(\frac{Rt}{t}\right)^{\frac{1}{n}}\left(\frac{C}{Rt}\right) = \frac{1}{\eta_{tot}V}\left[\frac{1}{2}\rho U^3 SC_{D,0} + \frac{2W^2k}{\rho US}\right] \tag{5}$$

Solving for endurance results in Equation 6.

$$E = t = Rt^{1-n}\left[\frac{\eta_{tot}V \times C}{\frac{1}{2}\rho U^3 SC_{D,0} + \frac{2W^2k}{\rho US}}\right]^n \tag{6}$$

As mentioned before, to get a good estimate of endurance, a good estimate of the aircraft weight must be known. As such, the endurance model runs iteratively to optimize the endurance for the weight of the aircraft. The first run assumes the aircraft weight is just the aircraft dry weight. The needed battery weight is then added for the next iteration and that process continues adding battery weight to the new estimated aircraft weight until it converges to determine a good estimation of endurance and aircraft / battery weight.

With an accurate estimation of aircraft weight and drag, additional useful information can be gained from the model. The drag condition for maximum flight endurance is given by the relationship in Equation 7.

$$C_{D,0} = \frac{1}{3}kC_L^2 \tag{7}$$

From this, the cruise velocity for maximum endurance efficiency can be calculated. The resulting relationship is shown in Equation 8.

$$U_E = \sqrt{\frac{2W}{\rho S}\sqrt{\frac{k}{3C_{D,0}}}} \tag{8}$$

For a pessimistic, worst-case model, to account for the many inefficiencies present in small, hobby grade aircraft electrical systems, a power efficiency of 50% was assumed. Using three cell LiPos, to hit the one hour endurance mark, around 16 Ah of battery capacity is estimated to be required. The BUBO uses 910 mAh battery packs to easily fit two per wing bay. The structural design allows for the ability to house even more than sixteen batteries if needed. The calculated optimum cruise speed is found to be 11.5 m/s, which is slightly lower than planned cruise speed, but isn't far off, so flight should be fairly efficient. The model estimates that sixteen batteries would weigh 12.5 N or just under three pounds, which is about 40% of the aircraft dry weight, which is in the proper range expected for a small aircraft of this size with such a lofty endurance requirement.

5.5.3. Test Setup

This test would have taken place on the DBF static thrust test stand. The configuration for the first flight test utilized just four batteries, so four batteries were connected to the motor for this initial power test. The motor was run at a constant thrust of 10 N for five minutes. Power consumption and temperature of the batteries was measured frequently to ensure safe operation for the test and in-flight. The complete endurance test would have used all sixteen batteries, with an attempted test duration of one hour.

5.5.4. Data Collected

As discussed in the propulsion testing section, motor thrust, torque, RPM, voltage, current, mechanical and electrical power, and several other values are gathered by the static thrust test stand. For the power and endurance test, the battery voltage reading is the most valuable of these, though all relevant data streams will be logged. Thrust is also of some importance, because the voltage drop over the course of the flight may result in problems remaining airborne later in the flight.

5.5.5. *Data Analysis and Comparisons to Predictive Modeling*

Because this test was not conducted before the cutoff date, there is no data to compare our predictive models to. Nonetheless, a preliminary attempt can be made using the data gathered during the short propulsion test. During this test, thrust dropped from 15 to 13 N over the course of the 5 minute test. Assuming that the full endurance test utilizes 4 times the number of batteries used during the short test, and that 10 N is the threshold required for sustained flight, we can expect the full endurance test to continue for about 50 minutes. Taking into consideration the fact that the short endurance test was conducted at full throttle, rather than a steady 10 N as we might expect from actual flight, an hour of flight time is well within the reach of our propulsion system.

5.5.6. *Validation*

The sixteen-battery configuration power and endurance test would have validated Functional Requirement 4 for reaching an endurance of 1 hour, as well as the related Level 3 success criteria in the Flight category.

5.6. Stability/Glide Test

5.6.1. *Reason for Test*

The stability and glide test verified that the aircraft was stable and controllable enough to continue on to the flight test. A glide has much less potential for catastrophic failure than a full launch, so it was used to verify that the center of pressure and weight distribution allowed for longitudinal stability.

5.6.2. *Predictive Modeling*

The aerodynamic model produced in AVL predicted that with the minimal mass configuration used in the glide test the stall speed was around 6.5 m/s. The center of pressure (cp) is located at 20.2 cm ahead of the trailing edge of the bottom wing, according to this model. By placing the 4 batteries used in the glide test as far forward as possible the center of gravity (cg) was balanced about this point. This means that, according to the AVL model, the glide test configured BUBO is longitudinally stable at speeds above 6.5 m/s, and should be able to glide successfully and respond to controls.

5.6.3. *Test Setup*

The test was performed in a parking lot with a smooth, straight, and slightly downhill path into the wind. Two team members, wearing helmets and riding on skateboards, held a tube that went through holes on the side panels of the aircraft allowing for free longitudinal rotation. The goal was to allow the aircraft to travel approximately level to the ground and near or slightly above stall speed, at which point the controls could be used to pitch the aircraft to an angle of attack that provided lift. Figure 33 shows how the aircraft was supported during the glide test.

Figure 33. Glide test setup

5.6.4. Data Collected

No hard data was collected for this test. However, the test qualitatively demonstrated that gliding and control of the aircraft was possible. At the maximum safe speed, the aircraft was able to pitch up and lift up so that it was no longer resting on the tube, proving that it had achieved enough lift for flight and was stable in a glide.

5.6.5. Data Analysis and Comparisons to Predictive Modeling

No numerical data was collected to be compared to the model. However, the qualitative results of the test match with the behavior expected based on modelling. The controls produced the expected pitching direction. The data modelled in AVL led the team to believe the BUBO could perform a glide above stall speed, and this behavior was verified.

5.6.6. Validation

The test didn't specifically validate any functional requirements, but enabled the flight test to continue which validated several functional requirements. Without first verifying the aircraft's glide capability the team could not have progressed to a full flight test.

5.7. Flight Test

5.7.1. Reason for Test

The flight test was the culmination of nearly all the tests and systems developed over the course of this project. It proved the airworthiness of the airframe and served as a starting point for further iterations, which would have proved the survivability and re-flight capabilities outlined in the design requirements, as well as the addition of other systems such as FADS and the autopilot.

5.7.2. Predictive Modeling

The flight characteristics in loiter were modelled in AVL, including steady level flight and a banked turn. CFD model was used to produce state matrices for linearized dynamic modelling about loiter conditions to confirm that the plane was controllable with the chosen gains and elevon control surfaces. The modes produced by this modelling are shown in the Controls Testing section in Figures 30 and 31. All of the modes shown are negative on the real axis, meaning the BUBO should be stable about these flight conditions.

AVL was also used to model other basic flight characteristics including a stall speed of 6.5m/s, a cruise velocity of 13m/s, and a trim angle of attack of 5 degrees. The predicted control deflection at this trim state is 1.5 degrees. The low magnitude control deflection at trim means that the longitudinal moments produced by aerodynamic forces and weight distribution are well balanced.

Based on predictive modelling of flight characteristics and control capabilities, as well as physical data collected in the glide test the team was confident that controlled flight was achievable.

5.7.3. Test Setup

The flight test was conducted at CU Boulder South on a breezy day. Setup consisted of setting up the tables that acted as a ramp for the aircraft and setting up the bungie system which provided the initial acceleration to the aircraft. Once the aircraft was ready to fly and the pre-flight checklist was complete, the aircraft was launched with a force of approximately 45lbs - measured using a fishhook scale attached to the bungie before launch. The aircraft climbed to an altitude of about 100 feet, at which point several maneuvers were attempted, such as banked turns and power-off stall. Once these maneuvers were completed after about 5 minutes of flight, the aircraft was brought to a landing. The aircraft was then inspected for damage and an estimate for a re-flight time was given. Cooper-Harper ratings were recorded for each maneuver in order to determine which aspects of flight may have warranted design changes. An image of the aircraft in-flight is shown in Figure 34.

Figure 34. BUBO in-flight

5.7.4. Data Collected

The plane successfully flew and landed with minimal damage; the only significant damage was to the aircraft boom, which would have taken very little time to replace. This is shown in Figure 35.

Figure 35. BUBO post-flight

Cooper-Harper ratings were acquired for all phases of flight as well as power-off stall, which handled exceptionally well. The list of the Cooper-Harper ratings for each maneuver are available in Figure 36.

Maneuver	Rating	Description
Takeoff	7	Major deficiencies
Ascent	4	Minor deficiencies
Steady flight	2	Good
30° banked turn	5	Moderate deficiencies
Descent	3	Fair
Landing	4	Minor deficiencies
Steady level stall	1	Excellent

Figure 36. Cooper-Harper ratings for all maneuvers tested in first flight test

5.7.5. Data Analysis and Comparisons to Predictive Modeling

The flight test did not result in any numerical data to compare to modeling. The qualitative analysis provided by our pilot, Jeremy, matches with the behavior expected based on AVL and controls modeling. The low stall speed and small intrinsic pitching moment discussed earlier are consistent with the incredibly docile stall characteristics demonstrated during the power off stall maneuver. The BUBO slowed down before landing very successfully, which is also indicative of the low stall speed predicted by AVL. These behaviors will make the BUBO a safe, stable, and reliable platform for the FADS system.

5.7.6. Validation

The flight test partially validated Functional Requirement 3 - full validation would require 10 flights without major damage. It also partially validated Functional Requirement 4 proving that sustained powered flight was possible - full validation would have required an hour-long flight. Further flight tests would have also validated Functional Requirement 2 with the FADS system integration and Functional Requirement 5 with the autopilot integration.

6. Risk Assessment and Mitigation

Author: Jesse Williams

This section will identify three different types of risks associated with the project, strategies that were employed to mitigate them, and how effectively those strategies reduced the risk. Risks from all aspects of the project have been investigated including technical, logistical, and safety risks. While many more risks were considered, only one from each category will be investigated in detail; the full risk matrix is available in Appendix B. A risk matrix based on the FAA's was used in assessing risks, with scores assigned based on the likelihood and severity of a risk/failure. A score of 1 indicates very low likelihood or a failure that has a minor impact on the project, while a score of 5 is very likely or would be catastrophic to the project. Scores were assigned both before and after mitigation, to determine the overall impact the mitigation strategy had on the risk.

6.1. Technical Challenge - Static Margin

One major technical risk faced in this project was the unstable "Tumble Mode" associated with a negative static margin; that is, the center of pressure was located ahead of the center of gravity. This mode was excited by a sudden deceleration in the airspeed, meaning that as the aircraft approached stall it would likely lead to a hard pitching down motion that would cause it to tumble and crash. Fixing this required moving the center of pressure back, the center of gravity forward, or both.

Initial strategies focused on minor adjustments to the design, such as moving internal components like batteries to shift the center of gravity, or adjusting the stagger between the wings to relocate the center of pressure. These alone were not enough to produce a positive static margin, so more significant design changes had to be considered. Ultimately, the decision was made to add a ballast attached to a boom, shifting the center of gravity to a predetermined location. This successfully provided a positive static margin, but it also introduced a large negative pitching moment. This was corrected by changing the airfoils from Clark-Y on top and bottom to a cambered foil on top and a reflexed foil on bottom. The new foil combination produces a positive pitching moment that counteracts the unfavorable weight distribution. With this, the aircraft was found to be controllable and have no unstable eigenmodes.

Figure 37 shows how the risk related to the aircraft stability changed as these mitigation strategies were employed.

Figure 37. Change in risk after mitigation

6.2. Logistical Challenge - Thrust Testing

Thrust testing was initially planned to be one of the first tests conducted and seemed to be fairly straightforward. Difficulties arose when it was found that there was no easily available dynamometer for testing. Building one from scratch would be a significant effort that the team simply did not have time for. Instead, the team turned to DBF, who had a dynamometer on hand. As it turned out, their dynamometer was not working and would take time to repair. This issue meant that delays to propulsion testing were not short term and that plans must change to accommodate this. Rather than relying on the propulsion test to verify motor and propeller choice, the models had to be relied on to make the final choice, and testing would simply verify the models. This was risky, but it was seen as the only move that could be made due to the circumstances.

The final motor and propeller combination were found by the models to be somewhat overpowered compared to the mission requirements, so there was room for inaccuracy in the models. It turned out that this factor of safety was necessary, as once the propulsion test finally occurred the combination was found to be slightly weaker than expected for several possible reasons. The margin of safety was smaller than expected, but the motor and propeller were still enough to enable a successful flight.

Figure 38 shows how the risk related to the issues with thrust testing changed as these mitigation strategies were employed.

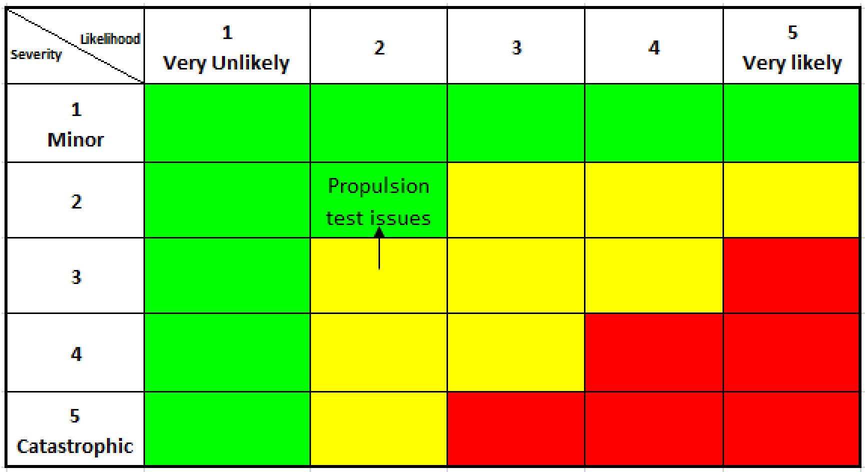

Figure 38. Change in risk after mitigation

6.3. Safety Challenge - LiPo Batteries

LiPo batteries are great for their power density and low form-factor, but have the drawback of being somewhat dangerous. They are sensitive to overcharging and are highly flammable if damaged. This required safety considerations to be made not only in-flight but also when not in use. Safety considerations made for the LiPo batteries included safely charging with someone always present, storing them in a battery protector bag when not in use, and securing them with velcro when the batteries were placed in the aircraft for flight. They were also always carefully stored at proper storage charge voltage. These actions minimized the likelihood of an accident occurring and reduced the severity of an incident if one were to occur. No unsafe incidents occurred with the batteries throughout the duration of the project.

Figure 39 shows how the risk related to the LiPo batteries changed as these mitigation strategies were employed.

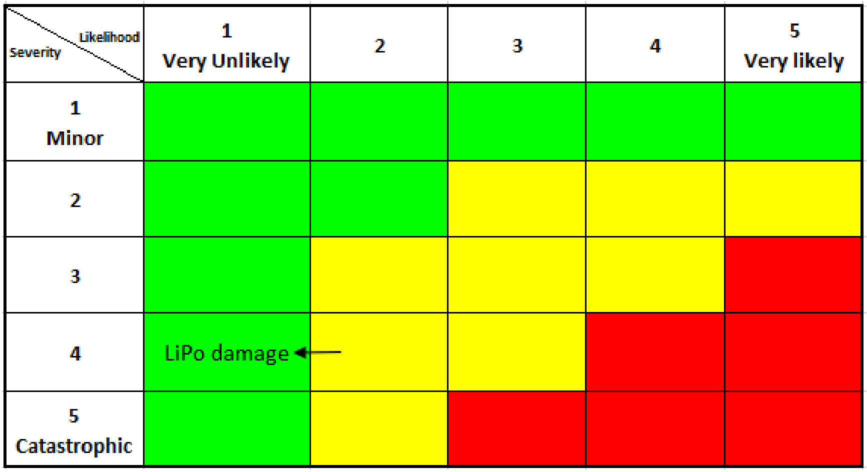

Figure 39. Change in risk after mitigation

7. Project Planning

Author: Kaitlyn Olson, Nickolas Mororo

7.1. Organization Chart

The organization of the BUBO BUBO team is displayed in Figure 40.

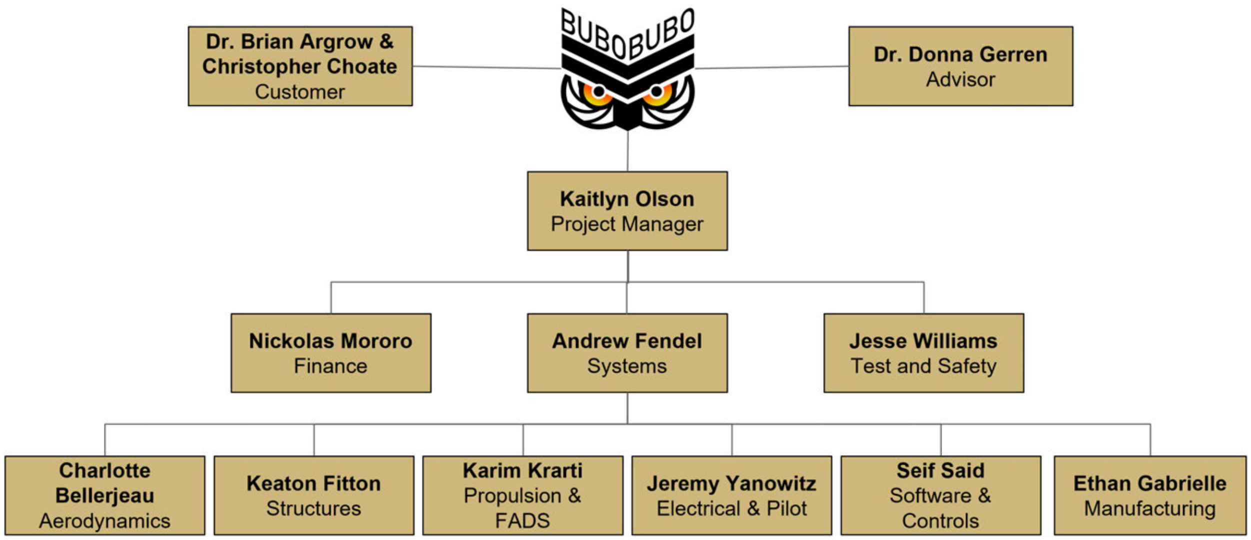

Figure 40. BUBO BUBO Team Organization Chart

The project manager holds team and client meetings, keeps the team organized, facilitates communication between team members, and ensures all scheduling and deadlines are upheld. The financial lead is responsible for the funding, budgets, and purchases of the team. The systems lead oversees the progress of each sub-team, ensuring their system can be integrated into the airframe while satisfying all the requirements laid out in Section 3.2. The test and safety lead is responsible for the planning, coordination, and execution of all tests that will be used to verify the work of the technical leads. They also ensure these tests and the systems which they investigate are safe. The six technical leads, aerodynamics, structures, propulsion and FADS, electrical, software and controls, and manufacturing, are each responsible for the design of their respective subsystem. These technical leads perform modeling, analysis, prototyping, and minor testing for the areas for which they are responsible. The work breakdown structure in Section 7.2 provides further detail about the undertakings and responsibilities of each of these technical leads as they oversee the development of their critical project element. Each of the ten members of the BUBO BUBO team assists in areas outside of their primary focus when necessary, and together are responsible for all deliverables the team must submit. These deliverables are collected by the customers, Dr. Brian Argrow and Christopher Choate, and our advisor, Dr. Donna Gerren, all of whom provide relevant feedback and counseling.

7.2. Work Breakdown Structure

The work breakdown structure for Team BUBO BUBO can be found in the Figure 41. This shows a high level breakdown of the work products for the team, broken into nine categories; deliverables, management, manufacturing, along with the six critical project elements (aerodynamics, structures, autopilot and controls, power and avionics, propulsion, and FADS). The status of each work product is signified by the following color code; green shows that the work has been completed, yellow shows that work was in progress at the time of the cutoff, and red signifies work that was unable to be completed.

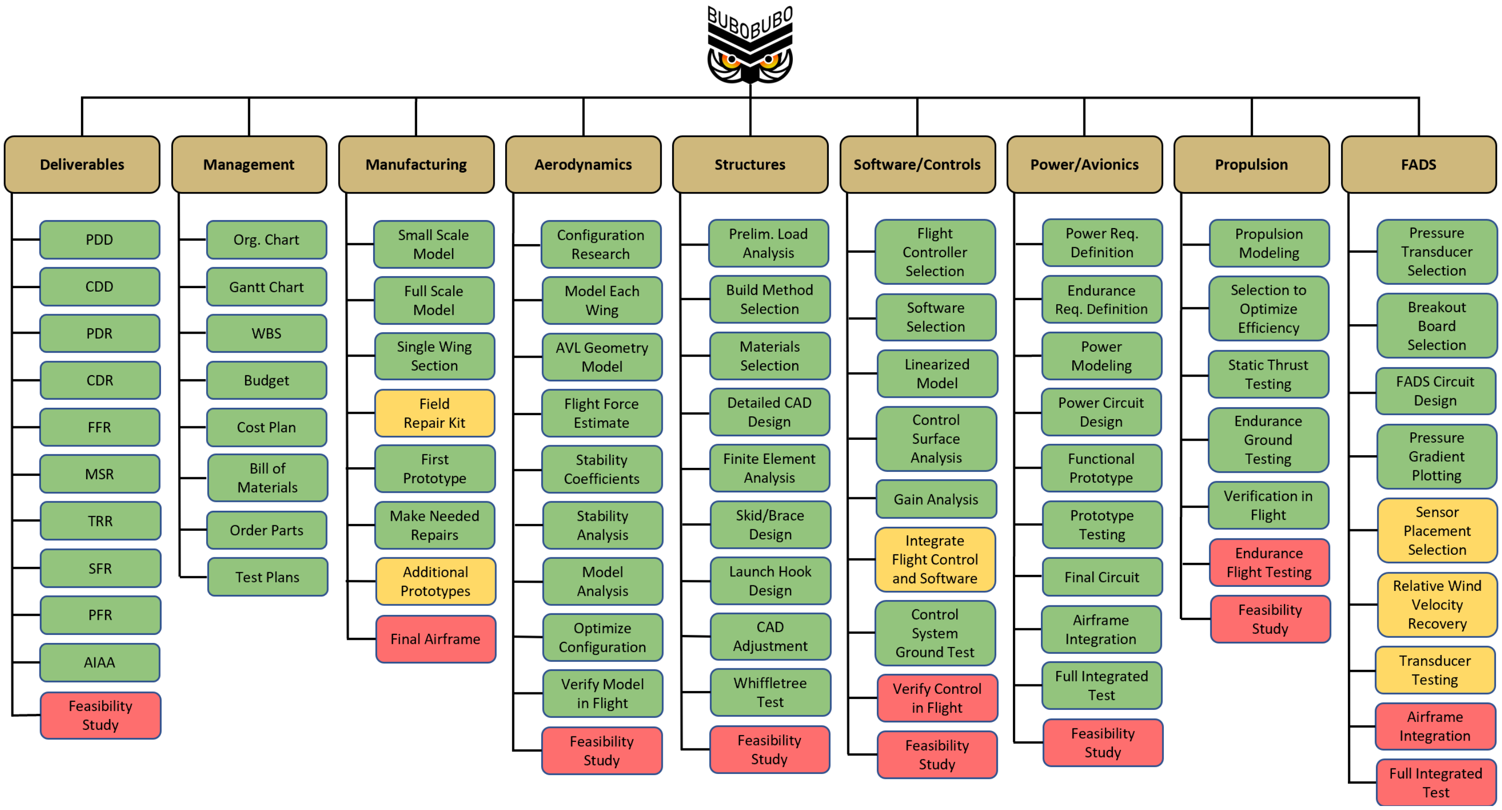

Figure 41. Work Breakdown Structure for BUBO BUBO

The work products shown for each category were determined through careful collaboration with the entire design team, particularly with each respective lead. As can be seen in Figure 41, the majority of work that was incomplete is related to the feasibility study and further aircraft iterations.

7.3. Work Plan

Figure 42 outlines the work plan for BUBO BUBO in the spring semester in the form of a Gantt chart. Purple events indicate manufacturing and prototyping, red events indicate planned testing, yellow events indicate the preparation of deliverables, and yellow diamonds indicate the submission of deliverables. The critical path is shown in green.

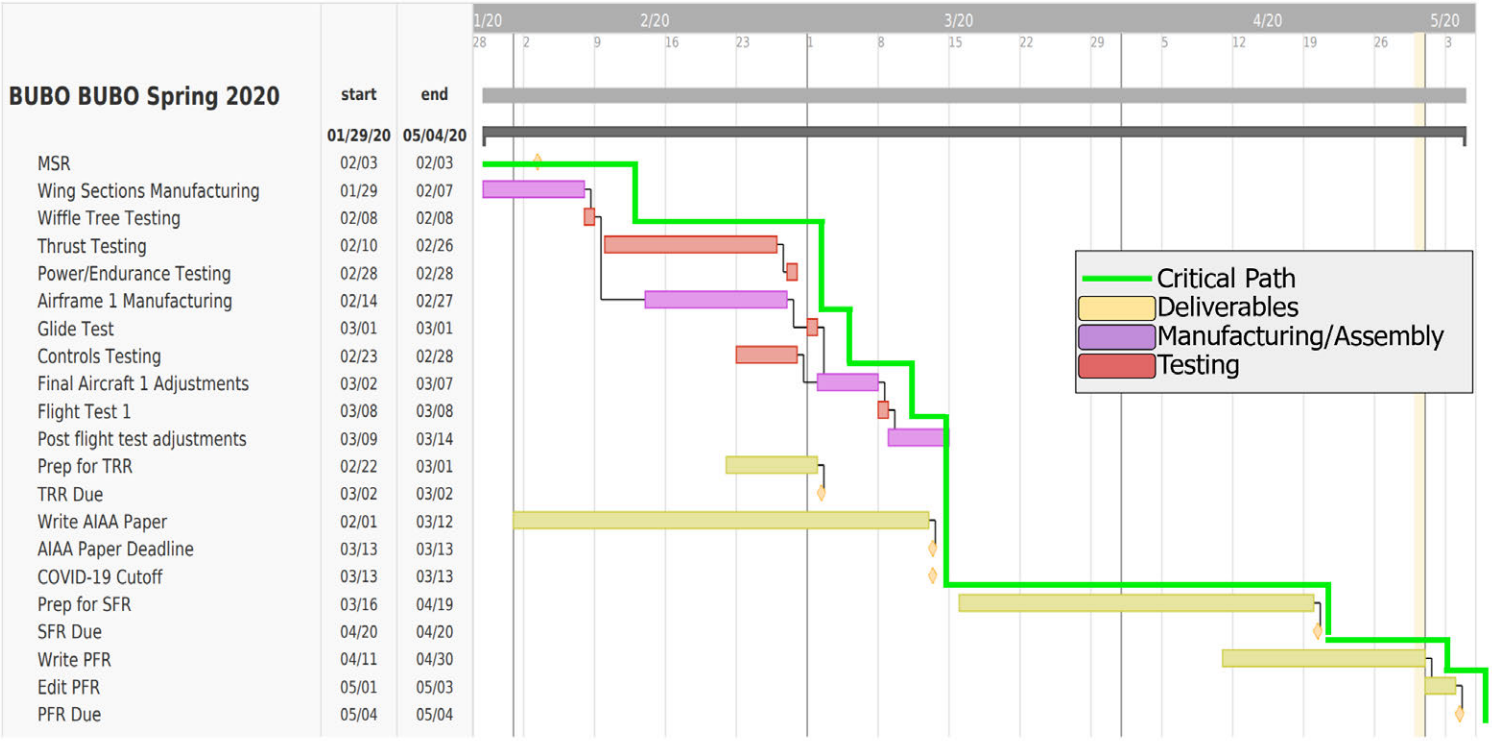

Figure 42. BUBO BUBO work plan. Critical path is shown in green.

The nature of aircraft projects result in the majority of the work being on the critical path. In this case, the critical path starts with wing section manufacturing.

The schedule was created using a backwards sequencing technique, starting with a goal date of completion and working backwards to establish what steps needed to be completed, when, in order for that goal completion date to be met. During this scheduling, high risk elements and activities were identified with the systems lead and given due margin to ensure any mistakes or delays did not significantly impact the schedule.

7.4. Cost Plan

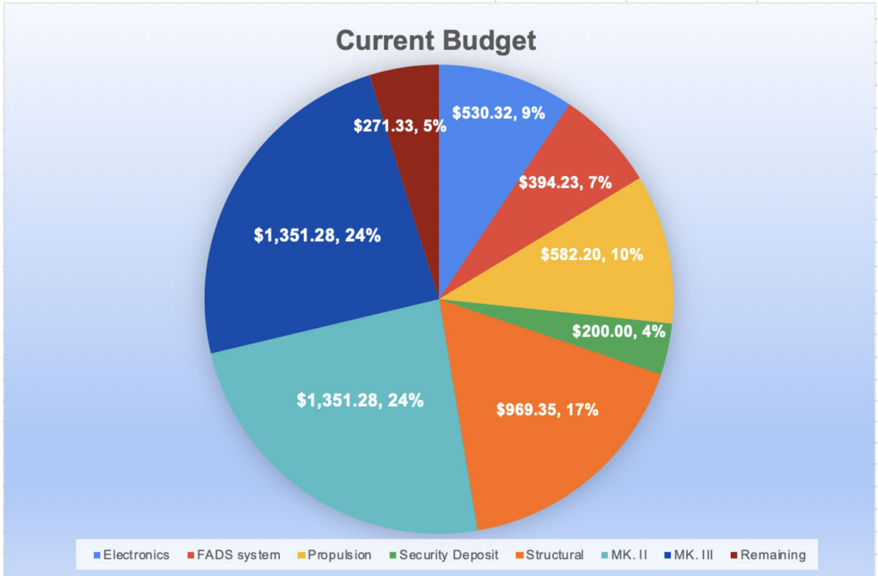

Figure 43. Final Budget Breakdown

The actual project budget turned out to be significantly less than the expected budget from the Fall Semester. The main reason for this positive budget outcome was the team's ability to implement cost-beneficial materials and manufacturing methods. Furthermore, some of the required RC components were donated by team members, driving the cost further down. Through these donations and procurement from both locally based stores as well as online suppliers, the team was able to source all the necessary parts to build new planes from the ground-up. Figure 43 shows a pie-chart with the final budget breakdown for BUBO BUBO. The team had more than enough headroom to construct two more iterations of the aircraft with completely independent avionics and electronics systems. The remaining balance was to be kept as collateral to any eventuality that might happen with the subsystems.

Figure 44. Expected Budget

Figure 45. Actual Budget

The budget for a single BUBO was also below the numbers predicted in the Fall. The primary cause of this change in budget were the changes done to the architecture of the FADS system. The subsystem lead was able to come up with an alternative design that saved close to 52% of the previously expected value. All this led to a decrease of approximately 25% in the total cost of a single aircraft. Finally, Figures 44 and 45, present a visual representation of the expected and the actual budgets for a single UAS. Nonetheless, these quantities did not include any of the fixed costs involved in operating and/or manufacturing. Therefore, items such as the remote controller and manufacturing tools were not accounted for. Finally, Figure 46, shows a comprehensive comparison between the expected and actual cost of each one of the subsystems.

Subsystem	Expected	Actual	Difference	% change
Electronics	$757.71	$521.47	-$236.24	-31.18%
Power	$451.54	$525.69	+$74.15	+16.42%
Structural	$237.90	$304.12	+$66.22	+27.84%
FADS	$966.08	$455.08	-$511.00	-52.89%
Total	$2,413.23	$1,806.36	-$606.87	-25.15%

Figure 46. Total Budget Evolution

7.5. Test Plan

Figure 47 outlines the test plan for the duration of the project. All testing done occurred during the spring semester, starting in January and ending at the testing cutoff. Seven major tests were conducted: whiffletree, thrust, power/endurance, controls, glide, flight, and FADS. Each test has its own color, with bars showing the duration of a task and yellow diamonds representing milestones. The critical path is shown in red.

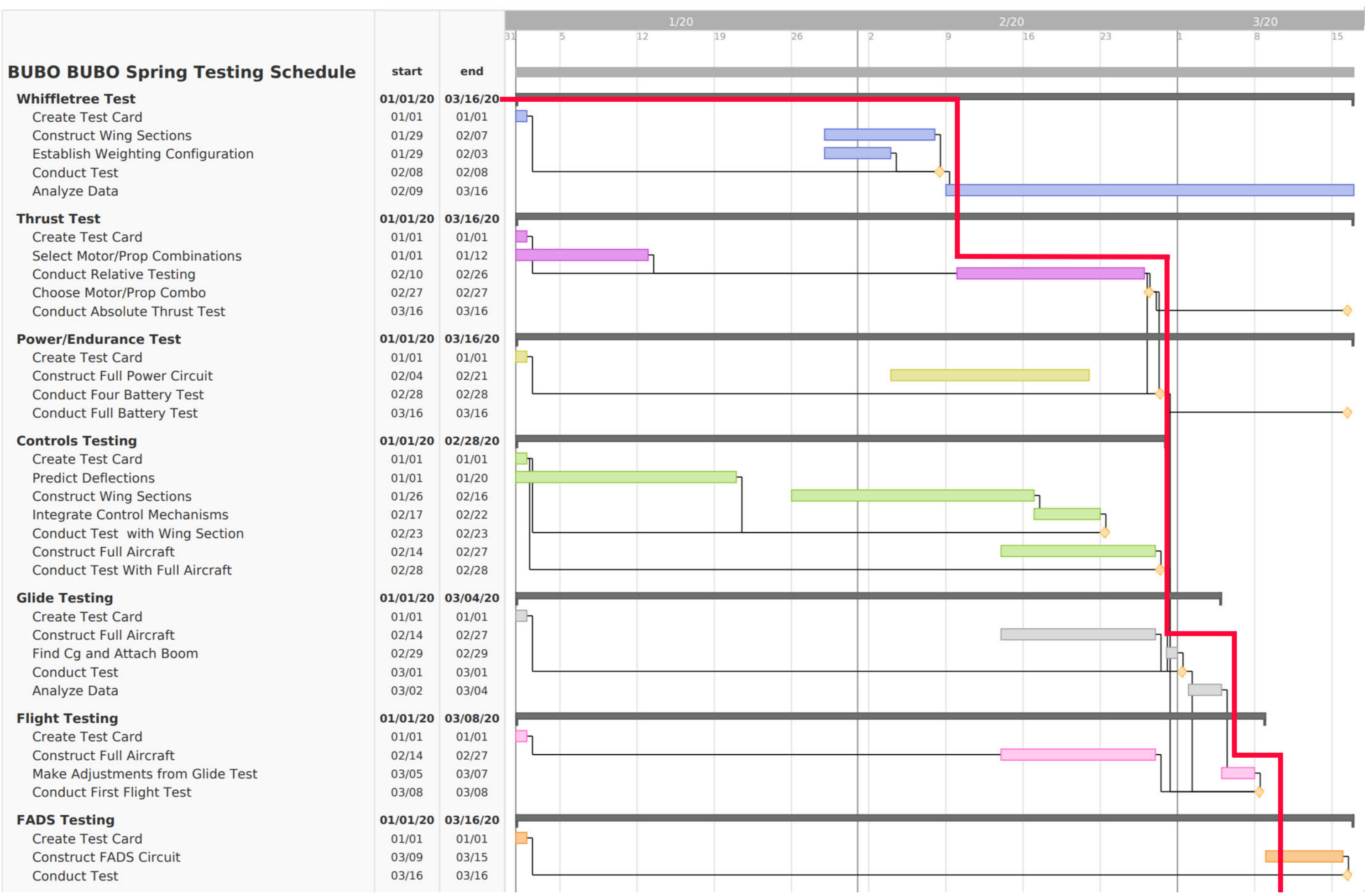

Figure 47. BUBO BUBO test plan. Critical path is shown in red.

All testing was conducted on campus at the University of Colorado Boulder, with all but the flight test occurring on East Campus. The flight test was conducted at CU Boulder South with permission and advisement from CU Director of Flight Operations Dan Hesselius.

8. Lessons Learned

Over the course of the past year, the team encountered a myriad of problems and challenges in all aspects of the project. From these difficulties, many important lessons were learned, from general engineering projects perspectives, as well as lessons specifically relating to certain project disciplines, such and systems engineering and project management.

One of the biggest lessons learned in this project was the importance of correctly using a top-down design approach from the very beginning of the design. This lesson came from the multitude of issues and delays that resulted from the necessity for a change in airfoils at a late stage in the design process.

In the initial design phases, the team had neither the knowledge nor the access to proper modeling tools (such as Computational Fluid Dynamics, or CFD, software) to conduct a formal trade study on airfoil shapes. Therefore, we followed recommendations from experts such as Dan Hesselius, CU's Director of Flight Operations, and initially selected a Clark Y airfoil. This particular airfoil was selected due to its flat-bottomed nature providing ease of manufacturing, while still providing adequate lift to sustain flight for an aircraft with similar wing area and characteristics to the BUBO. For these reasons, the Clark-Y is extremely common in aircraft projects, especially in UAVs. Other airfoil shapes were considered only in a passing manner, as the team had little tangible information outside of this expert input and simple two-dimensional lift calculations to form a basis for the decision. Therefore, the Clark-Y airfoil shape was hard-coded into the initial aircraft structural model, and used as the highest level of a top down geometric design, with all subsequent designs and modeling based off of this shape.

As the fidelity of aerodynamic modeling increased with the use of AVL, it became obvious that the aircraft had serious longitudinal stability issues in the form of an easily excitable, highly unstable mode. As discussed in Section 6.1, this risk was mitigated by adding a ballasted boom to the front of the aircraft to shift the CG forward, thereby making the static margin positive and the aircraft longitudinally stable. This effectively eliminated the risk of exciting this unstable "Tumble Mode"; however, it presented its own problem in the form of an unfavorable negative pitching moment that was too strong for the control system to properly address. This problem could not be addressed with any sort of further mass redistribution, and after thorough investigation it was decided that the best option moving forward would be to change the airfoils on both the top and bottom wings, to the respective cambered NACA 6412 and reflexed NACA 23112 foils seen in the final design. While this solution did give the aircraft a naturally neutral pitching moment with minimal control input, it presented a major problem for the structural modeling of the aircraft, as the initial airfoil was defined assuming it would not be changed. The Clark-Y had become so embedded in the geometry of all structural members in the CAD model that changing the shape caused all previous associations, and therefore the entire geometry of the aircraft, to break. The team had to devote a significant amount of work through a series of strictly defined change control processes over the course of a month to redefine all necessary structural and CAD models before manufacturing could begin.

From this mishap, it became glaringly obvious how important high level adaptability is when implementing such a top down design. With the entire design dependent on this top level, it is imperative that lower level design dependencies are defined such that any changes made to the top level do not compromise the references used by lower level components of the design. This was not the case in the first iteration of design, and the team ensured that every iteration thereafter had easily altered defining qualities (such as airfoil shape) at all levels.

Another key lesson learned came from the management of the team's schedule, which is most pertinent to the management of the project itself. In the first semester, the schedule was fairly loosely defined due to the fact that most work at this time was purely theoretical and therefore hard to set many tangible deadlines for beyond full completion of tasks. As the second semester began, however, more regimented scheduling practices were put in place is ensure project success.

The aforementioned airfoil change was a very large catalyst for this shift in scheduling philosophy. As the first semester ended, the team was faced with the daunting task of finishing any remaining design work while simultaneously reworking the structural design laid out in the original CAD to fit the new geometric constraints. Almost half of the team was needed to complete the reworking of the CAD, and as such, the rest of the team had to be far more efficient with their design work to support the project's progress. This was accomplished by organizing all tasks left to be completed and planning them out on an extremely detailed, day-to-day basis. This took considerable effort, as previous scheduling iterations had far less definition, but ultimately allowed for the team to stay on track and hold better accountability. With this level of detail in place, it was far easier to adjust the schedule should delays arise. Additionally, if a task was finished earlier than planned, those team members who otherwise would have been working on that task could be assigned to help with other work, thereby helping to accelerate the schedule. This was especially important towards the end of the project testing window, as having a clearly laid out plan made fast tracking tasks much easier when it became obvious that a COVID-19 related cutoff was imminent. This ability to quickly reschedule and track necessary tasks was instrumental in the team's successful flight testing before the cutoff, and highlighted the importance of having all key workflow processes fully defined in the schedule.

Outside of the management and systems side of the project, perhaps the most important general engineering lesson learned from this design process was to not let the design process be overly influenced by those outside of the customer and design team, and on a similar vein, not relying heavily on similar outside entities. Design decisions should ultimately be up to the team so long as they satisfy the requirements defined by the customer, and such decisions should be finalized based on confidence of the team, not input from others unfamiliar with the project.

Throughout the project, the team received push back from members of the PAB with regards to flight testing without first modeling and testing the aircraft in a wind tunnel. Multiple attempts were made to satisfy this request, but ultimately the team was barred from utilizing any wind tunnels of the size needed to complete the desired testing. Instead, the team opted for a manual glide test, as described in Section 5.6. Though wind tunnel testing was still recommended by PAB members, and those in charge of wind tunnel operations were very much made aware of these requests, access was still not made available. At this point, the team decided to proceed with flight testing due to a shared sense of confidence in the extensive glide testing and CFD modeling accomplished. All work pointed towards successful flight being achievable, and thus the team proceeded despite not getting the verification of wind tunnel testing. As evidenced by the overwhelming success of the completed flight test, particularly in the steady loiter portion of the flight profile, this confidence was well founded, and though it would have added to the verification process, the team felt entirely justified in not using a wind tunnel.

A somewhat similar situation occurred with the static thrust test stand. The department did not have a working test stand at the beginning of the year, although it was made very clear that some sort of thrust testing would be needed for verification before flight testing could take place. The team agreed with this assessment; however, locating a working test apparatus still proved incredibly challenging. Eventually, the DBF team at CU was kind enough to allow for use of their test stand, although there was assumed to be an issue with the data collection board, as discussed in Section 5.2, that resulted in the observed thrust data being negatively offset from the predicted curve obtained through extensive modeling. The team was assured that the test stand's manufacturer would diagnose and recommend a fix for the issue, however this fix never came to fruition. It was then decided as a team that the modeling, coupled with data from the motor and propeller suppliers, provided an accurate enough prediction to proceed with flight testing using the selected propulsive setup. This confidence was further backed up by the similarities in the profiles of the thrust curves, and the problem with the test stand was narrowed down to an issue in RPM reporting, which would lead to a purely translational offset. Finally, it was determined that even if the thrust stand was properly recording data and all modeling was off, the motor still produced adequate thrust to sustain flight, albeit with a slight efficiency penalty.

Using these conclusions, the team proceeded with flight testing without having absolute agreement between the predicted and observed thrust values. This decision was not without push-back, as the PAB expressed concerns about uncertainties in the propulsion system. Ultimately this was no issue, again as evidenced by the total success that was flight testing. This only further drove home the point that ultimately design decisions are up to the project team, and although the advice from outside sources, such as non-advisory members of the PAB, should be duly noted and considered, it should not always be taken as an absolute requirement.

Thanks to the team's ability to quickly apply lessons they have collectively learned, these lessons truly did help make the project into an overwhelming success. Effective top down design, efficient and well documented scheduling, an independent found sense of confidence in the team's abilities, and many more small lessons learned along the way were all paramount in the ability to finish the project in a successful manner, even when the timeline was drastically reduced due to the threat of COVID-19. These lessons are applicable to engineering projects far beyond the confines of this course, and can be applied throughout engineering careers. As such, these lessons will help guide the members of this team towards success in life, much as they did for this project.

9. Individual Report Contributions

Bellerjeau, Charlotte:

- Aerodynamic Design
- Stability Test Modelling
- Flight Test Modelling
- Static Margin Risk Assessment

Fendel, Andrew:

- Objectives
- Functional Requirements
- Design Requirements Flowdown
- Lessons Learned
- General editing of every section

Fitton, Keaton:

- Airframe Design
- Whiffletree Test

Gabrielle, Ethan:

- Mechanical Manufacturing
- Manufacturing Challenges
- Component Integration

Krarti, Karim:

- Thrust Testing
- FADS Testing
- Endurance Testing

Mororo, Nickolas:

- Cost Plan
- Review and Corrections

Olson, Kaitlyn:

- Project Purpose
- Objectives
- Functional Requirements
- Concept of Operations
- Trade Studies
- Design Requirements Flowdown
- Organization Chart
- Work Breakdown Structure

- Work Plan
- Test Plan
- General editing of every section
- General outlining of every section

Said, Seif:

- Final Design - Control system
- Software Manufacturing Scope
- Controls Testing

Williams, Jesse:

- Risk Analysis
- Test Scheduling
- Test Cards/Checklists

Yanowitz, Jeremy:

- Electrical Design
- Electrical Manufacturing
- Electrical Testing
- Flight Testing Pilot

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Appendix A: Trade Studies

This section detailed the preliminary design work performed by the team in order to determine the overall design. This design phase was mainly completed through ten comprehensive trade studies, which resulted in the overall baseline design that has been continued on throughout the semester. Following is a detailed look at each of these studies, broken up by the corresponding critical project element that each investigation falls under. For each trade study, the designs will be explained, along with a table of pros and cons. The exact method, weighting, and results of each respective study will then be reported, and the final design selection given.

Aerodynamics and Stability

Wing Configuration

The range of wing configurations considered reflect several variations in wing sweep and shape. Other variations in configuration such as stagger, gap, and decalage have been researched, but were not decided on at this phase in the design process.

Delta Wing

The delta wing has a pentagonal shape and is most distinct from the others in its low relative aspect ratio, as seen in Figure 48. As a result, this configuration is expected to experience more drag. This delta wing was also used in the Eagle Owl designed by team SCUA in 2013, which is referred to among other things in the pros and cons, Table 2.

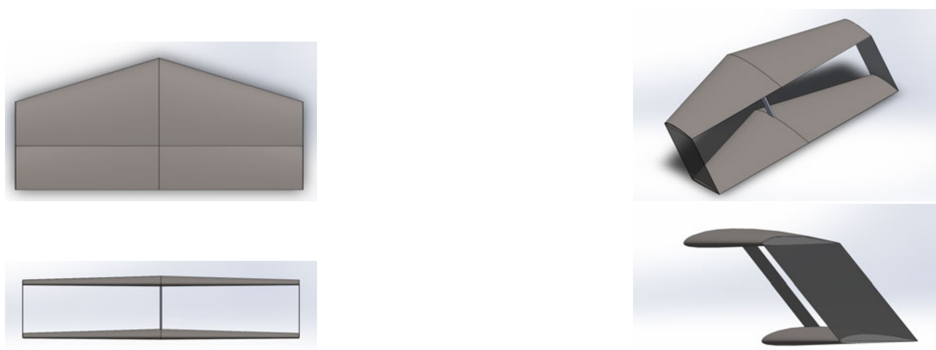

Figure 48. Sample Delta Wing Design

Table 2. Delta Wing Pros and Cons

Pros	Cons
- Sweep adds lateral stability - Flight heritage with SCUA - Previous FADS research - Most internal volume for other systems - Structural stability	- Lower aspect ratio for given span - Excess surface area adds drag - High drag coefficient at low speeds - Potential for increased flow interaction between wings

Reflected Sweep

The reflected sweep design, shown in Figure 49, features a top wing with negative sweep and a bottom wing with positive sweep. This configuration has been proven by CFD analysis and wind tunnel testing in research at other universities to have high stability and relative lift coefficients. The main disadvantage in this design is the presence of multiple pointed corners, each of which introduces vulnerability to the structure. These and other factors are listed in the pros and cons of Table 3.

Figure 49. Sample Reflected Sweep Design

Table 3. Reflected Sweep Pros and Cons

Pros	Cons
- Sweep variation adds lateral and longitudinal stability -Decreased interaction between wings increases lift	- Low structural stability - Complex manufacture - Difficult system (propulsion) integration

Straight Wings

The straight wing configuration seen in Figure 50 has a rectangular form most noted for its simplicity. This design was selected by team ARES last year. Although this configuration may be advantageous for manufacturing, it poses severe challenges for the flight stability of the aircraft. These and other pros and cons are listed in Table 4.

Figure 50. Sample Straight Wing Design

Table 4. Straight Wings Pros and Cons

Pros	Cons
- Ease of manufacture - Project heritage with ARES - Ease of aerodynamic modelling - Structural stability	- Low aerodynamic stability - Lack of existing data on flight characteristics

Single Sweep

The single sweep design has a top wing with negative sweep and a straight bottom wing, as visualized in Figure 51. It has the stability advantages that come with a change in sweep angle between the two wings, and the structural simplicity of one straight wing. This option reaches a compromise between several different project priorities, which can be seen in the pros and cons of Table 5.

Figure 51. Sample Single Sweep Design

Table 5. Single Sweep Pros and Cons

Pros	**Cons**
- Sweep variation adds lateral and longitudinal stability -Straight wing adds simplicity of manufacture and system integration	- More wing interaction than diamond at tips - Low internal volume - Structural vulnerability at tip of top wing

Symmetric Sweep

The symmetric sweep design shown in Figure 52 features two identical negative swept wings, staggered apart positively. It has the lateral stability advantages of a swept wing, but lacks the longitudinal stability granted by a difference in sweep angle between the two wings. It also has the manufacturing benefit of two identical wings. These factors and others are listed in the pros and cons of Table 14.

Figure 52. Sample Symmetric Sweep Design

Table 6. Symmetric Sweep Pros and Cons

Pros	**Cons**
- High aspect ratio for given span - Sweep adds lateral stability - Low wing interaction with constant chord along span	- Less longitudinal stability due to same sweep - Structural vulnerability at tip of top wing

Wing Configuration Trade Study

Criteria

The criteria for this trade study include flight performance, structural integrity, systems integration, and manufacturability. These were chosen as each factor in itself can cause the mission to fail if it is neglected, and each stands alone as a distinct requirement for the airframe. The flight performance score will be based on the stability and relative aerodynamic performance of each design. These evaluations will be based on outside research conducted on box wing aircraft configurations and shapes. The structural integrity portion will be assessed based on the simplicity and the number of potential failure points. Systems integration scores indicate the ease with which other subsystems can be installed effectively on the airframe, such as electronics and sensors inside the airframe, or propulsion systems on the wing. Finally, manufacturability is based on how easy it will be to construct the proposed design, which will be a deciding factor in the delivery of a successful product. The weighting for each of these categories is shown in the following Table 15.

Table 7. Weighting of Trade Criteria

Criterion:	*Flight Performance*	*Manufacturability*	*Structural Integrity*	*System Integration*
Weight:	0.35	0.15	0.30	0.20

Flight Performance - The scoring for flight performance is based on research performed in the past century on box wing performance while selectively varying a few key parameters including relative sweep, aspect ratio, and stagger, and is shown in Table 8. CFD analysis of several box wing configurations indicates the most longitudinal stability and lift when the wings have a sweep differential of 30 degrees or more. Lateral stability is increased with the addition of negative sweep. These and other design characteristics that demonstrate higher lift coefficients, lower induced drag, and more stability have received the highest scores and the rest of the scores were assigned relatively.

Table 8. *Flight Performance* Scoring Definition

Flight Performance (Similarity to Theoretical Ideal Characteristics):	*Least Similar*		*Moderate Similarity*		*Most Similar*
Score:	1	2	3	4	5

Manufacturability - The criteria for scoring this category is based on the perceived complexity of each design. Assuming the construction method is the same for each, the score is based on estimated time and resources for construction. If the manufacturing techniques are the same for each design the new skills that will need to be acquired and cost of materials are about the same, so the only difference is in the actual construction time and difficulty. It is possible that with damage to the aircraft during testing, a reconstruct or repair may be required, so this time difference could be compounded over the course of the year. The scores are assigned relatively for this section as well due to the difficulty in giving a precise time estimate at this stage in the design process, as shown in the following Table 9.

Table 9. *Manufacturability* Scoring Definition

Manufacturability (Relative Predicted Manufacturing Time):	*Most Time*		*Moderate Time*		*Least Time*
Score:	1	2	3	4	5

Structural Integrity - As complex structural analysis cannot be performed on each model in a timely manner, the scoring of structural integrity is based on simplicity of the required structural design and the number of perceived points of failure relative to the other design options being considered. Since the scoring is from one to five and there are five design options being considered, the worst design is assigned a one and the best a five, with the remaining design options falling in between, as shown in Table 19.

Table 10. *Structural Integrity* Scoring Definition

Structural Integrity:	*Highest*		*Moderate*		*Lowest*
Score:	1	2	3	4	5

System Integration - Since a box-wing configuration implies that there is no fuselage to house the avionics and battery components inside of, these components will have to be housed inside the airframe itself. The scoring was defined by the number of straight wing sections and the internal space inside of the wing, and is given in the following Table 11. This is driven by the assumption that a straight wing will more easily accept avionics components within the airframe, and that a larger wing allows for more internal space for components.

Table 11. *System Integration* Scoring Definition

System Integration (Relative Simplicity and Internal Volume):	*Most*		*Moderate*		*Least*
Score:	1	2	3	4	5

Delta Wing Scores

Flight Performance: **2** - The high degree of overlap between the two wings, assuming the stagger is set to one chord length, means that less lift will be generated overall. In addition, the increased area will lead to more drag than the other designs with the same span.

Manufacturability: **3** -The wings are the exact same shape for this configuration, which would make manufacturing inherently easier. However, the swept shape as well as the added material increase the complexity and time required. The balance of these two factors gives the delta wing a moderate score.

Structural Integrity: **5** - The delta wing configuration not only consists of two wing sections that both allow for continuous spars across the entire wingspan (unlike a swept wing), but it also adds more volume to the wing sections and therefore more internal structure. This is demonstrated with this design more than the other design options, therefore this design received the highest score.

System Integration: **4** - The increased internal volume is the largest positive factor for system integration in this case. This shape would have the most space inside the wing for housing other components.

Straight Wing Scores

Flight Performance: **1** - This design is predicted to have the least stability, based on the lack of sweep, or relative sweep differential between the two wings. This also decreases the expected lift coefficient for the straight wing design.

Manufacturability: **5** - The straight wing would be the most simple and least time consuming design to manufacture. The cross section of the wing would be the same along the span of both wings, greatly simplifying the manufacture and construction.

Structural Integrity: **4** - The straight wing configuration allows for continuous spars to span across the entire wingspan of both wings. Unlike the delta wing, the straight wing has less wing volume near the centerline and therefore less internal structure, such as ribs and spars, to stiffen the structure. The only clear points of potential failure are at the wingtips where they connect to the end panels, therefore this design is second best and receives a score of four.

System Integration: **3** - The straight wing received a high score for system integration based on the apparent simplicity of integrating the propulsion system. A propeller or propellers could be placed at any point along the wings with the same distance to the center of gravity. The propulsive forces for this configuration would be the easiest to balance. However, the internal volume would be less than most of the other designs.

Reflected Sweep Scores

Flight Performance: **5** - The reflected wing allows for optimum variation in sweep angle between the two wings which maximizes the theoretical lift coefficient and longitudinal stability. This wing configuration is the theoretical idealized design for a box wing arrived at by several research studies utilizing both CFD analysis and wind tunnel testing.

Manufacturability: **2** - This design received the lowest score for manufacturability based on the added complexity of sweep and having two different wings to build. The combination of these two factors makes this the most difficult wing to build in terms of time and complexity, which adds the potential for error and more lost time.

Structural Integrity: **2** - The reflected sweep configuration introduces several potential points of failure, particularly along the centerline where the sweep transitions. Because there are no straight wing sections, there can be no continuous spars spanning the entire wingspan. With this considered, it is still a design better than the symmetric sweep configuration because this results in a greater positive stagger along the centerline. This is ideal for landing scenarios because it allows for a more distributed landing skid across the airframe, thus resulting in less concentrated forces.

System Integration: **2** - The lack of a straight wing section and the greater influence of stagger on the distance between the wings makes propulsion integration the most difficult for this design. In addition, the integration of the FADS system is made more difficult by the complex angles of the design and the lack of available research on optimum pressure port placement.

Single Sweep Scores

Flight Performance: **4** - The Single sweep has the advantage of a sweep differential between the two wings which provides more lift and longitudinal stability. The sweep on the top wing adds lateral stability, which is reinforced with positive stagger, because the top wing is he first to interact with the airflow. This combination of flight performance features is a slightly more moderate version of the ideal case presented in the reflected sweep design.

Manufacturability: **4** - A straight wing planform is the simplest design to manufacture. Having only one swept wing and one straight wing simplifies the manufacturing process.

Structural Integrity: **3** - The single-sweep design has the favorable stability from a straight wing along the bottom. While the centerline on the top wing introduces a potential point of failure, it is a good middle-of-the-road option that still minimizes potential failure modes.

System Integration: **4** - As with the other categories, a straight wing on the bottom allows for simple bays to be made within the wing sections for housing components. In addition, the swept top wing gives more clearance for the propulsion system to be potentially located between the wings along the centerline.

Symmetric Sweep Scores

Flight Performance: **3** - This design received a moderate score. Some sweep is more laterally stable than no sweep, but it lost points because of the increased flow interference between the two identical wings.

Manufacturability: **3** - While a swept wing is more complex than a straight wing, having both the top and bottom wings be an identical or near-identical design would help simplify the manufacturing process.

Structural Integrity: **1** - Having no straight spars across the span of the aircraft leads to more potential for aeroelasticity issues, specifically with the swept wing sections bending back and inwards towards the centerline. Additionally, both wings have points of higher potential failure along the centerline where the sweep transitions.

System Integration: **3** - Integrating avionics components into a swept wing is not much different from a straight wing, however the shape of the bays is now more constrained to the sweep of the wing. This design also lends itself to a pusher-propeller configuration due to the negative space behind the wings along the centerline.

Scoring Summary

The results of the Wing Configuration trade study in Table 12 show that the Single Sweep configuration is the best design option of those considered. Moving forward, this will be the base airframe configuration that both scaled versions of the aircraft will be designed from.

Table 12. *Wing Configuration* Trade Study Matrix

		Delta Wing	Straight Wing	Reflected Sweep	Single Sweep	Symmetric Sweep
Evaluation Criteria	**Weighting**	**Score**	**Score**	**Score**	**Score**	**Score**
Flight Performance	0.35	2	1	5	4	3
Manufacturability	0.15	3	5	2	4	3
Structural Integrity	0.3	5	4	2	3	1
System Integration	0.2	4	3	2	4	3
Total Score (Normalized to 5)		**3.45**	**2.9**	**3.05**	**3.7**	**2.4**

Boom Configuration

The boom configuration trade study includes the location and number of booms used to address the negative static margin problem. This decision is also affected by the amount of ballast required to balance the plane. We have assumed a fully loaded scenario for the sake of this trade study and have included an range of ballast masses. After choosing a boom configuration a ballast mass will be selected in pre-flight preparation based on the priorities of each individual flight test.

One Centered Boom

This design choice includes a single boom attached to the center pylon directly underneath the top wing with a weight at the end. The single

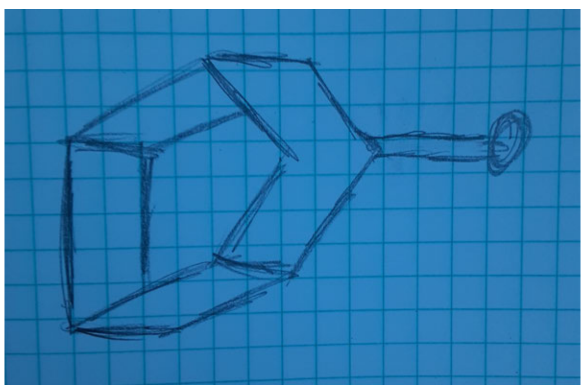

Figure 53. Single Centered Boom Design Concept

Table 13. Single Boom Pros and Cons

Pros	**Cons**
- Simpler construction - Less required boom projection - Less total added mass	- Greater mass on end of boom - Possible air data disruption

Two Booms Attached to Side Walls

The double boom design features one boom attached to each side wall with a ballast at the end of each boom. The potential benefits are less mass required on the end of each boom, meaning less vibration potentially making the aircraft unstable. The motivation behind this proposed design is to create a corridor of completely undisturbed airflow for the FADS sensors.

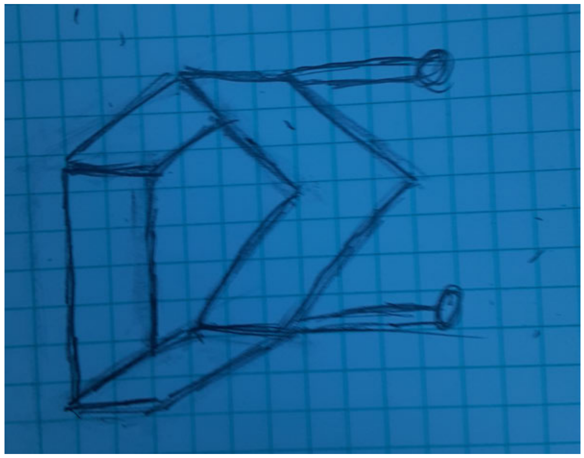

Figure 54. Double Boom Design Concept

Table 14. Two Booms Pros and Cons

Pros	**Cons**
- Cleaner air data	- More total added mass
- Less mass on end of boom	- Greater boom projection

Boom Configuration Trade Study

Criteria

The criteria for this trade study include required mass, boom projection, data interference, and vibration potential. These factors are most likely to interfere with the performance of the aircraft as a whole. All additional mass will increase demand on the power system and decrease endurance, while making takeoff and landing more difficult by raising the stall speed. Boom projection effects the performance of the aircraft by making it structurally unsound and more likely to sustain damage on landing. Data interference is a priority for our customer, who would like the FADS system to be as undisturbed as possible. Finally, vibration caused by the ballast may lead to or exacerbate unstable behavior in flight, so it should be minimized. The weighting of each of the criteria is shown in the table below.

Table 15. Weighting of Trade Criteria

Criterion:	*Boom Projection*	*Total Added Mass*	*Data Interference*	*Potential Vibration*
Weight:	0.25	0.30	0.30	0.15

Boom Projection

The amount of boom projection in front of the top wing should be minimized to reduce vibration. Some projection is good because it will absorb shock on landing, but too much will be structurally unsound and aesthetically displeasing. This criteria is evaluated base on calculating the required boom length and accounting for the mounting location to determine how much of the dowel is projecting in front of the plane, This is done for multiple fixed ballast weights.

Table 16. *Structural Integrity* Scoring Definition

Boom Projection:	*Most*		*Moderate*		*Least*
Score:	1	2	3	4	5

Added Mass with Fixed Ballast

The amount of mass added by the combined boom and ballast should be minimized for the sake of endurance and stall speed. A heavier plane will be harder to launch, fly, and power. The total added mass is calculated using the same methodology as for the boom projection criteria. The weight of the ballast as well as the boom itself is taken into account for several fixed ballast weights.

Table 17. *Total Added Mass* Scoring Definition

Total Added Mass:	*Most*		*Moderate*		*Least*
Score:	1	2	3	4	5

Data Interference

Data interference is evaluated by comparing the leading edge area of the top wing that is free from turbulence. This area would be available for FADS sensor placement in completely clean airflow.

Table 18. *Data Interference* Scoring Definition

Data Interference:	*Most*		*Moderate*		*Least*
Score:	1	2	3	4	5

Potential Vibration

The potential vibration of each design is evaluated by comparing the amount of mass that would have to be aced at the end of each boom. A larger mass at the end of a boom will lead to more vibration which could cause stability issues.

Table 19. *Potential Vibration* Scoring Definition

Potential Vibration:	*Most*		*Moderate*		*Least*
Score:	1	2	3	4	5

One Centered Boom: Scoring

Boom Projection - **4**: The single boom design leads to less projection in front of the top wing than the double boom design for every ballast mass modelled.
Total Added Mass - **5**The combined mass of the ballast weights and the wooden dowels for the single boom design is less for every ballast mass modelled.
Data Interference - **2**: The downside of the single boom design is its placement directly in front of the center of the top wing. The turbulence created by the boom and ballast may interfere with data collection.
Potential Vibration - **3** The amount of mass required at the end of the boom is greater for the single boom design which may lead to more vibration and less stability.

Two Booms Attached to Side Walls: Scoring

Boom Projection - **2**: The boom projection in front of the top wing is greater for the double boom design than for the single, which may be less structurally stable.
Total Added Mass - **2**: The total mass added by the double boom design is greater than that of the single boom, which leads to poorer flight performance and more demand on power and propulsion.
Data Interference - **5**: The greatest benefit of the double boom design is its low interference with the FADS data collection. Attaching the ballast to the side walls leaves the front of the swept wing uninterrupted for sensors placement.
Potential Vibration - **4**: The mass at he end of each boom is less for this design, decreasing the potential for vibration. However, the scores for this criteria are very close for each design because the difference between them is

small and the magnitude of the modelled vibration is low.

Scoring Summary

The finals scores for each boom design are shown below. The single centered boom was selected with a final score of 3.55 compared to the 3.2 earned by the double boom design. This decision is largely due to the fact that this project prioritized the development of a flying platform for the FADS system. Improvement of data collection comes second to flight performance for this iteration of the Eagle Owl legacy project. The exact nature of the centered boom's interference with the FADS sensors could be investigated in future iterations using AVL or wind tunnel models.

Table 20. *Boom Configuration* Trade Study Matrix

		One Boom	Two Booms
Criteria	**Weight**	**Score**	**Score**
Boom Projection	0.25	4	2
Added Mass	0.30	5	3
Data Interference	0.30	2	5
Vibration Potential	0.15	3	4
Total Score (Normalized to 5)		**3.55**	**3.2**

Controls

Autopilot Controller

In order to aid the pilot in controlling the aircraft and achieve steady flight, an autopilot flight controller is required. The flight controller will receive commands from the RC pilot for complicated maneuvers such as takeoff and landing. The autopilot will only be operated for loitering. The autopilot will be activated through a switch available on the vehicle controller for the RC pilot to use. A software and a flight controller board will be chosen through a weighted criteria score. The autopilot system configurations chosen for the study are ArduPilot Mega, BetaFlight F4, iNAV Matek F405, PixHawk 2 (Cube), and PixHawk 4.

ArduPilot Mega

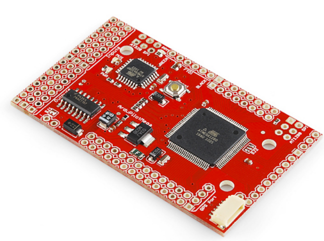

Figure 55. ArduPilot Mega

The ArduPilot Mega is a versatile autopilot that is used for a variety of vehicles including fixed wing aircraft, multirotor helicopters, and traditional helicopters. The ArduPilot software used for the flight controller is designed to ensure that no modification of the source code is necessary to adapt the controller to a specific flight case or airframe. In addition, there are algorithms available from the developers and the community for a multitude of airframes. However, the flight controller does not come with any sensors or GPS receivers. The pros and cons of the ArduPilot Mega can be viewed in Table 21.

Table 21. ArduPilot Pros and Cons

Pros	Cons
- Availability of algorithms for different airframes - Weighs the least out of the available options - Require little to no source code modification	- Difficult to find on the market - Does not come with sensors

BetaFlight F4

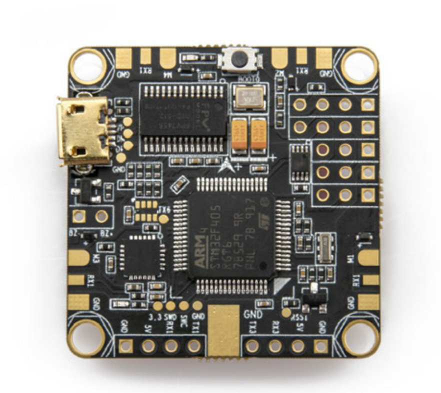

Figure 56. BetaFlight F4

The BetaFlight F4 flight controller is used for multi-rotor UAV vehicles, though the firmware and the flight controller board can be modified and optimized for a fixed wing aircraft. The flight controller does not come with the necessary cables for setup. In addition, the BetaFlight F4 has only an accelerometer and a gyroscope with no altitude measuring sensors such as a magnetometer or a barometer. However, the flight controller has one of the highest processing capabilities for control response. The pros and cons of the BetaFlight F4 can be viewed in Table 22.

Table 22. BetaFlight Pros and Cons

Pros	Cons
- High processing capabilities - Has an overall more compact build - Developer/community support	- Designed and optimized for quadcopters - Does not have many servo outputs

iNAV Matek F405

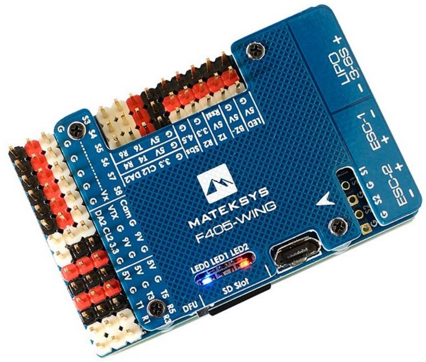

Figure 57. iNAV Matek F405

The iNAV Matek F405 is a flight controller that is optimized specifically for fixed wing flight. It is relatively new and has not been tested as much as the other options. The iNAV Matek F405 uses the same processor as the BetaFlight F4. Thus, it possesses high processcing capabilities. The support available for this configuration is not substantial enough to predict any problems that might arise. The pros and cons of the iNAV Matek F405 can be viewed in Table 23.

Table 23. iNAV Pros and Cons

Pros	Cons
- High processing capability - Optimized for fixed wing flight - Requires little to no source code modification	- No substantial community/developer support - The least tested configuration out of the available options

PixHawk 2 (Cube)

Figure 58. PixHawk 2

PixHawk 2 is the conventionally used PixHawk product, specifically, in CU's UAV programs such as IRISS. The product comes with the same kit that is provided with PixHawk 4. It has lower processing capabilities than the PixHawk 4. Furthermore, it is the heaviest option with a weight of 200 grams. However, it has been tested and developed extensively which will facilitate further studies in its use and the possible complications that might arise. PixHawk 2 operates on the same firmware as PixHawk 4, and is priced at $238 which makes it one of the more expensive options along with the PixHawk 4. The pros and cons of the PixHawk 2 can be viewed in Table 24.

Table 24. PixHawk 2 Pros and Cons

Pros	Cons
- Controller has extensive community support - Triple redundant on power supply - Pixhawk 4 has the largest community support - CU heritage	- Weighs the heaviest of the options available - Cost

PixHawk 4

Figure 59. PixHawk 4

The PixHawk 4 is one of the newest flight controllers from the options stated above. It comes with a kit that includes a power management board, a GPS module, and a variety of cables for the inputs and outputs of the board. PixHawk 4 has a high processing capability, and contains multiple sensors, a barometer, an accelerometer, a gyroscope, and a magnetometer. The software and the flight controller are designed to operate on different multirotor and fixed wing configurations. As a result, little to no programming will be required. The firmware used for PixHawk 4 has extensive support, and the controller is priced at $211. The pros and cons of the PixHawk 4 can be viewed in Table 25.

Table 25. PixHawk 4 Pros and Cons

Pros	Cons
- High processing capability - Triple redundant on power supply - PX4 Software has the largest community support	- Newly released hardware, with no extensive community support - Has not been considerably tested - Cost

Autopilot Trade Study

Criteria

The most important criteria for the autopilot/flight controller are optimization, available support, complexity of setup, controls response time, weight, and price. It is important to determine the optimization level of the flight controller for a fixed wing vehicle; it will be time consuming to reconfigure a flight controller that is designed for quad copters for a fixed wing vehicle. It is important to ensure that an abundant amount of support is available to understand the configuration of the flight controller. The flight controller setup must be simple as to not crowd the interior of the wing frame and ensure equal weight distribution. Ideally, the flight controller would also come with a kit that includes all the necessary cables and connectors. The highest weighted criterion is the control response time. It is vital for the aircraft to respond to the turbulence that will cause the aircraft to lose altitude or fly off-path in a short amount of time. The aircraft must return to the flight path promptly. The price and weight are also important factors to consider. If the flight controller contributes significantly to the weight of the aircraft, it will be necessary to consider that factor into the overall design of the aircraft. If the flight controller is costly and is damaged in one of the test flights, it may become problematic to replace it. The assigned weights for this study are given in the following Table 26.

Table 26. Weighting of Autopilot Trade Criteria

Criterion	*Optimization*	*Available Support*	*Complexity of Setup*	*Controls Response Time*	*Weight*	*Price*
Weight	0.15	0.15	0.2	0.3	0.05	0.1

Optimization - This criterion specifies the level of optimization the flight controller has for fixed wing flight. Some controllers have general use for multi-rotor vehicles and fixed wing vehicles. Others are on the extremes and are designed more for either multi-rotor vehicles or fixed wing vehicles. Flight controllers optimized for fixed wing flight will have more outputs (more than 4) as to connect to multiple control surfaces and the propulsion system. In addition, the software will not require any modification if there are readily available airframe options for the control algorithms. The derived scoring system is given in Table 27.

Table 27. *Optimization* Scoring Definition

Optimization:	*Not Optimized*	*Low*	*Moderate*	*High*	*Fully optimized*
Score :	1	2	3	4	5

Available Support - The available support from developers/community will be a critical factor in assessing and solving any unforeseen complications that might arise. A higher level of support will result in less time consumption for setup. Furthermore, the extent of tests performed on the flight controller in the community will allow for the prediction of possible complications and the modification of the source code if necessary. For flight controllers with moderate to very high levels of support, there are dedicated websites and forums to troubleshoot commonly encountered issues, as well as general instructions on how to modify the physical board or the software if needed. This resulted in the following scoring system shown in the following Table 28.

Table 28. *Available Support* Scoring Definition

Available Support:	*Scarce*	*Low*	*Moderate*	*High*	*Very High*
Score :	1	2	3	4	5

Complexity of Setup - This criterion specifies the level of detail needed to set up the software/flight controller outputs with other systems such as the propulsion and mechanical systems. The flight controller must be capable of producing the necessary voltage outputs to maneuver the servos and to toggle the thrust. The flight controller must also be compatible with various fixed wing structures as it will be placed inside the structure of the wing. The setup must also not create uneven weight distributions that might affect the overall performance of the aircraft. Scoring for this criterion is given in the following Table 29.

Table 29. *Complexity of Setup* Scoring Definition

Complexity of Setup:	*Difficult*	*High*	*Moderate*	*Low*	*Elementary*
Score :	1	2	3	4	5

Control Response & Accuracy - The control system must respond in a specified amount of time to return the aircraft into the original flight path and be within a certain accuracy. The specified time and accuracy are 7 seconds and 15 meters, respectively. This criterion is essential for determining the best performance; however, all of the flight controllers fall within these requirements for standard day conditions in Boulder where the wind speed is typically under 5 m/s. To account for unpredictable weather changes, the highest possible processing capability must be used. This resulted in the following scoring system in Table 30.

Table 30. *Control Response & Accuracy* Scoring Definition

Control Response & Accuracy:	*Very Low*	*Low*	*Moderate*	*High*	*Very High*
Score :	1	2	3	4	5

Weight - It is important to consider the weight that the flight controller will contribute to the overall system. The weight of the flight controller must not affect other design parameters significantly. However, it is not a crucial factor in choosing a flight controller. Thus, it is given the smallest weighting. The scoring for autopilot weight are shown in Table 31

Table 31. *Weight* Scoring Definition

Weight:	*Very Heavy*	*Heavy*	*Moderate*	*Light*	*Very Light*
Score :	1	2	3	4	5

Price - The price will be critical for the replacement of the flight controller. It is not expected that the flight controller will be damaged; however, it is important to consider the possibility of a second purchase. It is essential that it does not exceed the allocated amount from the budget. The resulting scoring system for pricing is given in the following Table 32

Table 32. *Price* Scoring Definition

Price:	*Very High*	*High*	*Moderate*	*Low*	*Very Low*
Score :	1	2	3	4	5

PixHawk 4 Scores

Optimization: **3** - PixHawk 4 is designed for general use and not specifically for fixed wing aircraft.

Available Support: **2** - The PixHawk 4 uses PX4 which is software with extensive support; however, the actual flight controller does not have much support.

Complexity of Setup: **3** - PixHawk 4 is relatively new and thus poses some potential for integration issues. It has not been tested much at all.

Control Response & Accuracy: **4** - PixHawk 4 has one of the highest processing capabilities from the given options.

Weight: **4** - PixHawk 4 weighs approximately 15.8 grams

Price: **1** - PixHawk 4 is one of the more expensive options at a price of $211.

PixHawk 2 Scores

Optimization: **4** - PixHawk 2 has been used considerably for fixed wing flight. It is also commonly used at CU for the development of UAVs.

Available Support: **5** - PixHawk 2 has been a popular choice for fixed wing flight, specifically, at CU. It has been tested and modified for many airframes and flight cases.

Complexity of Setup: **4** - There are many sources for the setup of PixHawk 2 such as the UAV developers at CU.

Control Response & Accuracy: **3** PixHawk 2 has a moderate processing capability that will achieve the requirements of the response.

Weight: **2** - PixHawk 2 is the heaviest option, weighing 200 grams.

Price: **1** - PixHawk 2 is the most expensive option from the 5 flight controllers at a price of $238.

BetaFlight F4 Scores

Optimization: **1** - The BetaFlight F4 was mainly designed for quad copters in terms of software and hardware.

Available Support: **3** - There is moderate support for fixed wing flights with the BetaFlight F4. However, the support is mainly for quad copters.

Complexity of Setup: **2** - The BetaFlight F4 will require reconfiguration to support fixed wing flight.

Control Response & Accuracy: **4** - The BetaFlight F4 is another option that has high processing capabilities.

Weight: **5** - The Betaflight F4 weighs approximately 6.6 grams

Price: **3** - The Betaflight F4 is priced at $40.

ArduPilot Mega Scores

Optimization: **4** - ArduPilot Mega is a highly versatile configuration that is used for a variety of vehicles including fixed wing vehicles

Available Support: **3** - ArduPilot Mega has moderate support for fixed wing flight.

Complexity of Setup: **2** - The ArduPilot Mega has potential for difficulty in setup due to its general use.

Control Response & Accuracy: **3** - The ArduPilot Mega has a moderate processing capability.

Weight: **4** - The ArduPilot Mega weighs approximately 22 grams.

Price: **3** - The ArduPilot Mega is priced at $40.

iNAV Matek F405 Scores

Optimization: **4** - iNAV Matek F405 has all the necessary specifications for a fixed wing vehicle. It has a versatile software for flight design.

Available Support: **2** - The iNAV Matek F405 is a relatively new configuration and thus has little support available.

Complexity of Setup: **4** - The setup is easy due to the flexibility of the software

Control Response & Accuracy: **3** - The iNAV Matek F405 has a moderate processing capability

Weight: **4** - The iNAV Matek F405 has a weight of 25 grams.

Price: **3** - The iNAV Matek F405 is priced at $50.

Scoring Summary

The full results of this trade study are shown in the following Table 33. PixHawk 2 had the highest total score. Optimization, available support, and complexity of setup are very important criteria for the flight controller, and the Pixhawk 2 scores exceptionally across all three.

Table 33. ***Autopilot*** **Trade Study Matrix**

		PixHawk 4	**PixHawk 2**	**BetaFlight F4**	**ArduPilot Mega**	**iNAV Matek F405**
Evaluation Criteria	**Weighting**	**Score**	**Score**	**Score**	**Score**	**Score**
Optimization	0.15	3	4	1	4	4
Available Support	0.15	2	5	3	3	2
Complexity of Setup	0.2	3	4	2	2	4
Control Response and Accuracy	0.3	4	3	4	3	3
Weight	0.1	4	2	5	4	4
Price	0.05	1	1	3	3	3
Total Score (Normalized to 5)		**3.2**	**3.4**	**3.1**	**3.1**	**3.35**

FADS

FADS Configuration

Though the design of the FADS system is not technically a part of this project, the loss of legacy hardware in this area has created the opportunity to potentially redesign the system to serve the project's requirements and limitations. The purpose of the FADS system is to derive the relative wind vector of the flow around the aircraft. It does this by sampling pressure at several points across the aircraft surface. Wind vector can then be calculated via either basic fluid computations or a neural network solution.

Traditional Setup

One possible layout for the FADS system is heavily based on the work by Dr. Roger Laurence. This prior work was based on a centralized transducer bay, with all sensor transducers integrated in a set of PCBs. The circuit board is fitted with a covering that maintains pneumatic isolation of each pressure transducer. Sampling points are accessed using thin urethane tubing. This method aids in modularity and electronic design of our system, though it poses a significant challenge from a manufacturing and integration perspective, and its inherent pros and cons are shown in the following Table 34.

Table 34. Traditional FADS Pros and Cons

Pros	Cons
- Flight Tested - Ease of Replacement - Protects Components	- Implementation poses a challenge - Heavier -Requires more Design and Manufcaturing complexity

Simplified Setup

An alternative layout is a more dispersed FADS system, in which pressure transducers are placed adjacent to the desired sampling points, with no tubing or casing needed. Instead, data and power wiring would be fed to transducer positions directly, significantly reducing the mass of the FADS system. The biggest drawback of this layout is that it is untested. Though the basic premise is arguably more accurate than the traditional layout, and will suffer from much less lag due to surface proximity, this kind of FADS system has never been attempted before, opening it up for any number of unforeseen failures. Beyond the simple risk of the unknown, there are several structural and integration concerns that come along with this layout. Pressure transducers near the surface of the aircraft are much more vulnerable to damage during takeoff and landing, and feeding bundles of wires to the extremities of the aircraft can be just as difficult to account for as the pneumatic tubing. Perhaps worst of all, this FADS setup will make modularity and replacement of components difficult without significant time investment. The pros and cons of this setup are shown in Table 35.

Table 35. Simplified FADS Pros and Cons

Pros	Cons
- Ease of Manufacturing and Design - More Accurate - Reduced Mass	- Implementation poses a challenge - Has not been tested -Vulnerable to damage and difficult to replace or repair

FADS Trade Study

Criteria

The most important criteria for this subsystem is that of flight turnaround and field repair. Having a system that will break during every flight cycle and will require several hours to extract and replace is unacceptable. The speed of this replacement scheme is important largely because of the functional requirement which calls for quick turnaround as well as the implementation of a FADS. The level of accuracy in the latter component need not be verified. In general, the approach to FADS design is driven by the basic implementation requirement, not that of functionality. The final aircraft should be configured to accept a FADS system, but not necessarily boast a working example. For that reason, accuracy of each option is weighted rather lightly. In addition, manufacturing difficulty is weighted less to avoid over-correcting for this consideration, as previous teams have. Even the most technically complex FADS system is not completely infeasible to construct, and the traditional setup will require no more than some 3D printed components and tube integration to see to fruition. These weights are reported in the following Table 36.

Table 36. Weighting of Trade Criteria

Criterion	*Implementation*	*Manufacturing*	*Weight*	*Vulnerability and Repair*
Weight	0.30	0.15	0.15	0.40

Implementation - A measure of the expected difficulty in incorporating the FADS system into the structure of the aircraft. This includes the support structures, holes, and electronic wiring required to operate the FADS system. Scoring for this criterion is shown in Table 37.

Table 37. ***Implementation*** **Scoring Definition**

Implementation:	*Difficult*	*High*	*Moderate*	*Low*	*Elementary*
Score :	1	2	3	4	5

Manufacturing - The scoring given in Table 38 represents a measure of the expected difficulty in manufacturing the FADS system. This includes all components that need to be made entirely by our team, such as casings and wiring setups.

Table 38. ***Manufacturing*** **Scoring Definition**

Manufacturing:	*Difficult*	*High*	*Moderate*	*Low*	*Elementary*
Score :	1	2	3	4	5

Weight - The expected mass of the FADS system, and the resulting impact it will have on all other systems considerations. The resulting scoring system is given in the following Table 39.

Table 39. ***Weight*** **Scoring Definition**

Weight:	*Significant*	*High*	*Moderate*	*Low*	*Negligible*
Score :	1	2	3	4	5

Vulnerability and Repair - A measure of the expected complications in flight and during repair and redeployment cycles of the aircraft. This scoring, shown in Table 40 includes the likelihood of component damage as well as the turnaround time that may result from replacement or repair of the subsystem.

Table 40. ***Vulnerability and Repair*** **Scoring Definition**

Vulnerability and Repair:	*Difficult*	*High*	*Moderate*	*Low*	*Elementary*
Score :	1	2	3	4	5

Traditional

Implementation: **3** - The traditional FADS layout involves potentially significant disruption of the aircraft structure to incorporate FADS sensor bays and pneumatic tubing.

Manufacturing: **2** - The casing and tubing systems of the traditional FADS system could present serious manufacturing complications.

Weight: **3** - Casing and tubing will be slightly heavier than wire bundles.

Vulnerability and Repair: **5** - By incorporating pressure transducers into the wing structure, the somewhat expensive sensing equipment is spared the worst of launch and landing damage.

Simplified

Implementation: **3** - The difficulties in implementing the simplified FADS system will likely be just as complex as those for the traditional system, with tubing replaced by wiring, and separate, miniaturized support structures in place of a single large one.

Manufacturing: **5** - There are few components in need of manufacture with the simplified FADS system. Indeed, all components can be purchased commercially and incorporated relatively easily.

Weight: **4** - Wires will be slightly lighter than tubing and casing, but not by very much.

Vulnerability and Repair: **1** - Transducers directly on the surface of the aircraft are in danger of being seriously damaged during landings, which are not expected to be graceful. In addition, the decentralized approach makes timely part replacement almost impossible.

Scoring Summary

The results of this trade study are shown in Table 41. The traditional FADS system is clearly the superior of the two. Its significant advantages in the field repair and replacement domain are critical for the success of the project's basic driving design parameters.

Table 41. *FADS Configuration* Trade Study Matrix

		Traditional	**Simplified**
Evaluation Criteria	**Weighting**	**Score**	**Score**
Implementation	0.30	3	3
Manufacturing	0.15	2	5
Weight	0.15	3	4
Vulnerability and Repair	0.40	5	1
Total Score (Normalized to 5)		**3.65**	**2.65**

Power

Battery Type

Many types of batteries are commonly used to power small Unmanned Aerial System (sUAS) aircraft and hobby grade RC aircraft. This trade study examines the feasibility of Lithium-Ion Polymer (LiPo), Lithium-Ion (Li-Ion), Nickel Cadmium (NiCd), Nickel-Metal Hydride (NiMH), and Sealed Lead Acid (SLA) batteries.

LiPo

Lithium-ion Polymer (LiPo) batteries are the industry standard for powering RC and sUAS aircraft. This is well deserved due to their excellent energy density and flexible, light form factor. Lithium-based batteries are more sensitive to overcharging than other battery types, and are flammability hazards when damaged, increasing their risk compared to non-lithium battery types. The pros and cons for LiPo batteries are listed in Table 42.

Table 42. LiPo Pros and Cons

Pros	**Cons**
- Low profile - Flexible form factor - Light weight - Safer than Li-Ion - Widely available - Industry standard	- Lower energy density than Li-Ion - Not overcharge tolerant - Dangerous if damaged

Li-Ion

Lithium Ion (Li-Ion) batteries have extremely high energy density and are very stable over long periods of time, having very low self-discharge and requiring little maintenance. However, they are one of the most dangerous types of batteries, requiring protection circuits and being subject to transport regulations as a result. Their premium performance also comes with a high price tag, and, as with LiPo batteries, they are a flammability hazard when damaged, increasing their risk compared to non-lithium based battery types. The pros and cons of Li-Ion batteries are listed in Table 43.

Table 43. Li-Ion Pros and Cons

Pros	Cons
- High energy density	- Not safe - protection circuit required
- Relatively low self-discharge	- Subject to transport regulations
- Low maintenance	- Expensive

NiCd

Nickel Cadmium (NiCd) batteries are tried and true, a mature and well-understood technology. They charge quickly and simply, perform well under load, and are forgiving and consistent. They are also reliable and very economical. Unfortunately, they have very low energy density and must be used and recharged constantly to be maximally effective. This particularity is due to their high self-discharge and the memory effect, which is a growth of crystals on the cell plates that causes a large loss of performance over time and is only delayed by exercising the battery. The pros and cons for NiCd batteries are listed in Table 44.

Table 44. NiCd Pros and Cons

Pros	Cons
- Fast and simple charge	- Low energy density
- Good load performance	- Memory effect
- Forgiving and consistent	- High self-discharge
- Economical	- Environmentally unfriendly

NiMH

Nickel-Metal Hydride (NiMH) batteries aim to fix the biggest problems with NiCd batteries, offering higher energy density and showing much more resilience to the memory effect. These upgrades don't come without significant down-grades, however. NiMH batteries are less durable than NiCd, suffer under load performance, and have higher self-discharge. They also use a more complicated charge and have a limited service life. It is "widely accepted that NiMH is an interim step to Lithium battery technology"[?] . The pros and cons for NiMH batteries are listed in Table 45.

Table 45. NiMH Pros and Cons

Pros	Cons
- Higher energy density than NiCd	- Limited service life
- Less prone to memory	- Difficult charge
	- High self-discharge
	- High maintenance requirement

SLA

The Sealed Lead Acid (SLA) battery is an inexpensive and reliable battery. They are not subject to memory but instead suffer from sulfation, where if stored in a non-charged state, the battery can become difficult if not impossible to recharge. They can never be fully charged due to gassing and water depletion, and lose capacity when deep-cycled, meaning the battery prefers to stay in a medium-charged state. They also have a very slow charge and low energy density, along with being environmentally unfriendly due to the lead. The pros and cons for SLA batteries are listed in Table 46.

Table 46. SLA Pros and Cons

Pros	Cons
- Inexpensive - Reliable - Low self-discharge - Low maintenance	- Hard to store - Low energy density - Limited lifetime

Battery Type Trade Study

Criteria

The most important criteria for an aircraft battery are energy density, current output, and risk. High energy density is critical to have the maximum capacity at a minimum weight, allowing the achievement of a one hour flight time with a light aircraft. The current output is important as all power required by the high current draw propulsion system, and the rest of the aircraft electronics are all coming from one power source with the one circuit/parallel battery power configuration traded on. Risk is also significant, as it is key to keep the overall risk level low as aircraft inherently have more risk factors than land-based craft. This top tier of important criteria is weighted to 20%.

The next tier of importance, weighted to 15%, is voltage output and self-discharge. Voltage output is less important than current, as voltage can be stepped up or down. However, it can be passively stepped down but requires an active circuit to be stepped up, so it is a benefit to only have to step down voltage, therefore, have a higher voltage battery. Self-discharge is important as batteries will be charged in advance and then used after some time in which they can self-discharge; however, this amount of time will be limited to hours, not days, so it is not the most important.

The lowest tier of importance, weighted 10%, consists only of the batteries' maintenance requirement. This criterion is important if extra complications are to be avoided, however with how often batteries will be changed, charged, and used, there are plenty of opportunities for maintenance, and the batteries will be regularly exercised.

These weights are compiled in the following Table 47.

Table 47. Weighting of Trade Criteria

Criterion:	*Energy Density*	*Voltage Output*	*Current Output*	*Risk*	*Self Discharge*	*Maintenance*
Weight:	0.20	0.15	0.20	0.20	0.15	0.10

Energy Density - Gravimetric energy density is measured in Wh/kg, and average energy density for the battery type will be used. Higher energy density is better, as seen in Table 48.

Table 48. *Energy Density* Scoring Definition

Energy Density (Wh/kg):	*~40*	*~60*	*~90*	*~115*	*~135*
Score :	1	2	3	4	5

Voltage Output - Voltage output is measured in volts, looking at nominal voltage per cell of an average battery. Higher voltage is better as it is easier to step down voltage than step up, as shown in Table 49.

Table 49. *Voltage Output* Scoring Definition

Voltage Output (V):	*0.5*	*1*	*1.25*	*2*	*3.6*
Score :	1	2	3	4	5

Current Output - Battery current output is measured with Coulomb's C scale, where a 2200mAh 1C battery will provide 2.2A for 1 hour. This criterion will use the battery average best result load current, where higher is better as it provides more current for the propulsion system. This scoring system is given in Table 50

Table 50. ***Current Output*** **Scoring Definition**

Current Output (C):	*0.05*	*0.1*	*0.2*	*0.5*	*1*
Score :	1	2	3	4	5

Risk - Risk is a combined metric of battery overcharge tolerance, charge difficulty, and damage risk. As it is a unitless metric, it will be measured in general levels, where lower risk is better, as shwon in Table 51.

Table 51. ***Risk*** **Scoring Definition**

Risk (Unitless):	*Very high*	*High*	*Moderate*	*Low*	*Very low*
Score :	1	2	3	4	5

Self Discharge - The self-discharge rate is measured in capacity percentage of depletion per month. Average battery expected rates when stored at room temperature are used, with lower rates being ideal, as can be seen in the following Table 52.

Table 52. ***Self Discharge*** **Scoring Definition**

Self Discharge (capacity/month):	*40%*	*30%*	*20%*	*10%*	*5%*
Score :	1	2	3	4	5

Maintenance Requirement - A battery's maintenance requirement is measured in Mean Time To Failure (MTTF) when not regularly exercised or when in storage. As Table 53shows, the highest/ideal level is batteries that don't require maintenance, with shorter times being worse.

Table 53. ***Maintenance*** **Scoring Definition**

Maintenance (days):	*25*	*45*	*75*	*135*	*inf*
Score :	1	2	3	4	5

LiPo Scores

Energy Density: **4** - LiPo batteries have an average energy density of 115 Wh/kg, just slightly less than Li-Ion.

Voltage Output: **5** - LiPo batteries have a nominal 3.6V per cell.

Current Output: **5** - LiPo batteries have a best result load current of 1C.

Risk: **3** - LiPo batteries have moderate risk, are a flammability hazard when damaged, but are otherwise safe.

Self Discharge: **4** - LiPo batteries have an average self-discharge rate of 10% capacity per month.

Maintenance: **5** - LiPo batteries do not require periodic maintenance or exercising.

Li-Ion Scores

Energy Density: **5** - Li-Ion batteries have an average energy density of 135 Wh/kg, the best of considered.

Voltage Output: **5** - Li-Ion batteries have a nominal 3.6V per cell.

Current Output: **5** - Li-Ion batteries have a best result load current of 1C.

Risk: **2** - Li-Ion batteries are the most dangerous battery type looked at for this trade study, being extremely overcharge intolerant, requiring protection circuits, and being subject to export control due to this high level of risk.

Self Discharge: **4** - Li-Ion batteries have an average self-discharge rate of 10% capacity per month.

Maintenance: **5** - Li-Ion batteries do not require periodic maintenance or exercising.

NiCd Scores

Energy Density: **2** - NiCd batteries have an average energy density of 60 Wh/kg, slightly higher than SLA.

Voltage Output: **3** - NiCd batteries have a nominal 1.25V per cell.

Current Output: **5** - NiCd batteries have a best result load current of 1C.

Risk: **4** - NiCd batteries are consistent, forgiving, have moderate overcharge tolerance, and overall low risk.
Self Discharge: **3** - NiCd batteries have an average self-discharge rate of 20% capacity per month.
Maintenance: **2** - NiCd batteries have significant memory effect issues and must be exercised every 45 days or risk becoming unusable.

NiMH Scores

Energy Density: **3** - NiMH batteries have an average energy density of 90 Wh/kg, a substantial increase over NiCd.
Voltage Output: **3** - NiMH batteries have a nominal 1.25V per cell.
Current Output: **4** - NiMH batteries have a best result load current of 0.5C.
Risk: **3** - NiMH batteries have low overcharge tolerance, a difficult charge, and a short service-life, making them a moderate risk.
Self Discharge: **2** - NiMH batteries have an average self-discharge rate of 30% capacity per month, the worst of all battery types looked at.
Maintenance: **3** - NiMH batteries have a slight memory effect and must be exercised every 75 days or risk becoming unusable.

SLA Scores

Energy Density: **1** - SLA batteries have an average energy density of 40 Wh/kg, the worst of all battery types looked at.
Voltage Output: **4** - SLA batteries have a nominal 2V per cell.
Current Output: **3** - SLA batteries have a best result load current of 0.2C.
Risk: **5** - SLA batteries are extremely forgiving and reliable, and are the safest of all battery types looked at.
Self Discharge: **5** - SLA batteries have an average self-discharge rate of 5% capacity per month, better even than lithium batteries.
Maintenance: **4** - SLA batteries develop sulfation after 135 days between cycles, which is less significant than the memory effect of Nickel batteries but still notable.

Scoring Summary

The following Table 54 are the results of the Battery Type trade study. LiPo and Li-Ion batteries are tied for the best option, followed by SLA, NiCd, and NiMH at the bottom. The criteria looked at for the trade study does not include the accessibility/universality of a battery type, so that is used to break the tie between LiPo and Li-Ion. As LiPo batteries are the industry standard and are very accessible, LiPo batteries are the ideal choice to go forward with for this project.

Table 54. ***Battery Type*** **Trade Study Matrix**

		LiPo	**Li-Ion**	**NiCd**	**NiMH**	**SLA**
Evaluation Criteria	**Weighting**	**Score**	**Score**	**Score**	**Score**	**Score**
Energy Density	0.20	4	5	2	3	1
Voltage Output	0.15	5	5	3	3	4
Current Output	0.20	5	5	5	4	3
Risk	0.20	3	2	4	3	5
Self-Discharge	0.15	4	4	3	2	5
Maintenance Requirement	0.10	5	5	2	3	4
Total Score (Normalized to 5)		**4.25**	**4.25**	**3.30**	**3.05**	**3.55**

Microcontroller Architecture

The purpose of having a microcontroller for this project is to have a system in place for the processing and storing of pressure transducer data from the FADS system to storage which can be offloaded from the vehicle and analyzed either in the field or in a lab. Three microcontrollers will be presented in this section, each of which were picked for a trade study because of their compact size, availability and processing speed compared to most microcontrollers on the market. A good microcontroller should make it easy for the user of the aircraft to collect data from the atmosphere and retrieve that data in a simple process for analysis after the mission is complete.

Arduino

The first option for consideration for the data storage microcontroller is an Arduino. Arduinos are known for being small and compact while at the same time having a large amount of documentation online for the user to effectively implement the microcontroller into any system they wish. The following Table 55 lists the pros and cons found from the manufacturers website for using an Arduino to store pressure transducer data. Note that it is vital that the microcontroller be a system that the team has used before, thus, team experience is also considered in the pros and cons.

Table 55. Arduino Pros and Cons

Pros	Cons
- High team experience - C and C++ based - Heavy documentation - Easily integrated - Built in ADC	- Moderate processing speed - No OS

FPGA

The FPGA (field-programmable gate array) is a microcontroller that is known for having fast processing speeds while maintaining a small profile for mounting onto vehicles. The fast processing speeds of FPGA's makes them an ideal option for this project, as more data can bring higher fidelity results to the customer. FPGA's do have a downside, however, as they are based on hardware description language (HDL), which means that the user needs to program every function of the FPGA from the ground up. This creates a large amount of work for such a simple operations as data storage. The pros and cons for the FPGA microcontroller are given in Table 9.

Table 56. FPGA Pros and Cons

Pros	Cons
- Behavior is user specified - Re-programmable in field - Fast processing	- No team experience - HDL based - Heavy development for simple functions

Raspberry Pi

The Raspberry Pi is the last microcontroller for consideration in this list of three storage devices. Raspberry Pi's have many advantages, including the use of operating systems and the ability to be modular. However, only two members of the design team have any experience using Raspberry Pi, and learning how to code with a this microcontroller is an extended process that takes months to master. In addition, Raspberry Pi's have many systems on-board that are not necessary for the scope of what the data capture system has to accomplish; these systems in turn waste power and add additional weight to the aircraft that is unnecessary. The pros and cons for the Raspberry Pi microcontroller are given in Table 57.

Table 57. Raspberry Pi Pros and Cons

Pros	Cons
- OS for standard data storage methods - High modularity - Python based - Plugin support	- Difficult to learn - Heavy and large - Excess systems drawing power - Slow startup

Microcontroller Architecture Trade Study

Criteria

The data storage microcontroller selection is of little concern to the final goal of producing a flying unmanned aerial system. As such, the criteria for the microcontroller trade study were selected based on the parameters which would make implementing data storage to the design of the vehicle simple and efficient. Therefore, ease of use is the primary criterion for the microcontroller with 30% weight as the controller's only function is to store data from sensors onto local storage; thus, the least amount of time possible must be spent configuring the microcontroller for storage of data. Modularity, team experience, and sampling rate have all bee given a weight of 20% since they are each important to the success of the mission but not as important as ease of use, which will free up the team's time. Modularity is essential as adding data capture boards to the controller may help data be processed faster. Team experience was given the same weight as modularity because, in the event of any programming mistakes, the rest of the team may step in to help based on previous knowledge of the microcontroller. The sampling rate was also given a weight of 20% due to the sampling requirement for this project is relatively simple at 6 Hz sampling frequency which can be stretched to a more lofty goal like 10 Hz and beyond. Finally, availability was given a 15% weight because all of the analyzed options are readily available online; however, if a microcontroller fails, it is essential to know which of them can be purchased on short notice. These weights are compiled in the following Table 58.

Table 58. Weighting of Trade Criteria

Criterion:	*Ease of Use*	*Modularity*	*Team Experience*	*Sampling Rate*	*Availability*
Weight:	0.30	0.20	0.20	0.20	0.10

Ease of Use - The first criterion is ease of use, which is defined by how much documentation there is available to the team to assist with any programming issues that could be a result of learning a new way to program a microcontroller. The highest achievable level for ease of use is that there is online documentation for storing data from custom sensors as this is the primary purpose of the controller in this project, as shown in the scoring breakdown given in Table 59.

Table 59. *Ease of Use* Scoring Definition

Ease of Use:	*No Info*	*Little Info*	*Manufacturer Info*	*Community Info*	*Sensor Data Storage Info*
Score :	1	2	3	4	5

Modularity - The second criterion is modularity which is defined by the range of modular products which can be purchased with a given microcontroller. As an example, Arduinos can be purchased with many additional cuircuit boards which add to the capability of the Arduino to perform certain functions (functions such as storing data from sensors). Modular products that are sold with a microcontroller can include but are not limited to GPS sensors, data processing boards, barometers, and accelerometers. The scoring system used to evaluate modularity is given in Table 60.

Table 60. *Modularity* Scoring Definition

Modularity:	*Very Low*	*Low*	*Moderate*	*High*	*Very High*
Score :	1	2	3	4	5

Team Experience - The third criterion is team experience, which is defined by the amount of prior knowledge that the team has given a specific kind of microcontroller. The highest achievable level for team experience is if all team members are fluent with the architecture and can process data with no assistance from external sources, as shown in Table 61.

Table 61. *Team Experience* Scoring Definition

Team Experience:	*None*	*Basic Knowledge*	*Well Versed*	*Classes Taken*	*Mastered Architecture*
Score :	1	2	3	4	5

Sampling Rate - The fourth criterion is the sampling rate, which is the frequency at which the microcontroller is storing data. Note that for the levels of scoring, there are no specific values given in hertz; this is because a particular board configuration of a controller architecture may have faster processing capabilities than another board configuration. Thus, the scoring will be done based on general trends in the processing speed of the architecture rather than the specific quantified values for the sampling rate, as seen in Table 62.

Table 62. ***Sampling Rate*** **Scoring Definition**

Sampling Rate:	*Very slow*	*Slow*	*Moderate*	*Fast*	*Very fast*
Score :	1	2	3	4	5

Availability - The fifth criterion is the availability, which is defined by the commonality of the controller through different avenues of purchase, such as websites and box stores. As an example, Arduinos can be found in typical box stores such as Best Buy, where FPGA's might only be able to be purchased online; in this example, the Arduino would be the more available microcontroller. These evaluations of availability translated into the following scoring system, shown in Table **??**.

Table 63. ***Availability*** **Scoring Definition**

Availability:	*None*	*Second Hand Only*	*Special Order*	*Few Retailers*	*Online and In Store*
Score :	1	2	3	4	5

Arduino

Ease of Use: **4** - Arduino is known for its use in STEM high schools for teaching students how to learn microcontroller programming and systems engineering. Thus, there is plenty of documentation if the team needs it, making Arduino easy to use.

Modularity: **5** - Arduino offers many upgrade boards that can interface with a standard Arduino to add functions to the original microcontroller. Thus, Arduino earns a 5 in this category.

Team Experience: **3** - Every member of the team has at least some experience with coding an Arduino due to electronics for aerospace engineers at CU.

Sampling Rate: **3** - Due to the small processing power of most Arduinos, its sampling rate isn't quite as fast as the ones for an FPGA or a Raspberry Pi.

Availability: **5** - Arduinos can be purchased almost anywhere standardized electronics such as laptops can be purchased (in stores or online). Therefore, Arduinos are available to the point where if one fails on the team, a new Arduino is easily attainable in a short amount of time.

FPGA

Ease of Use: **2** - FPGA is coded using a language called HDL (hardware description language), which means that the architecture is built from the ground up by the user. This particularity makes this system, not a viable option since the microcontroller is not the primary goal of the project.

Modularity: **4** - Much like the Arduino, additional boards that add functions to the FPGA can be purchased. However, the way the additional boards are used is determined by the architecture created by the user.

Team Experience: **1** - Only one member of the team has experience programming an FPGA.

Sampling Rate: **5** - Since FPGAs are mostly used for logical operations, the sampling rate for the FPGA is the highest out of all the controllers due to the user's ability to make the processes of the controller more efficient.

Availability: **4** - FPGAs are not as readily available as Arduinos, but they can still be purchased off of most electronics websites. However, if the board fails, it may be challenging to find a fast replacement.

Raspberry Pi

Ease of Use: **3** - Since the Raspberry Pi has an operating system, the user may interface in the same way someone can interface with a regular computer. However, this microcontroller is coded in Python, thus making them slightly more challenging to program.

Modularity: **3** - Like the other two controllers, Raspberry Pis can be purchased with additional circuit boards to increase their functionality. Note that because the system runs off of an operating system and is coded in Python, interfacing with the modular boards can be challenging.

Team Experience: **2** - Two of the team members have experience working with Raspberry Pis, but little experience coding with them.

Sampling Rate: **4** - Raspberry Pis usually have powerful processors for being microcontrollers. However, the fact that the data must be processed through an operating system instead of stored directly to a storage device like an FPGA makes the sampling rate slightly slower for Raspberry Pi.

Availability: **5** - Much like Arduinos, Raspberry Pis can be found in stores as well as online readily and are easily available to the team.

Scoring Summary

The results of the trade study for the data storage microcontroller are given in Table 64. Note that the Arduino architecture surpassed the FPGA and Raspberry Pi for scoring since the Arduino scored the highest in the most important criteria for the trade study, which were ease of use, modularity, and team experience. Due to the overall unimportance of the data storing method, the team selected the microcontroller that scored highest in ease of use, as well as in the total score. It is vital that programming a data storage path does not take up the team's precious work time.

Table 64. ***Microcontroller Architecture*** **Trade Study Matrix**

		Arduino	**FPGA**	**Raspberry Pi**
Evaluation Criteria	**Weighting**	**Score**	**Score**	**Score**
Ease of use	0.30	4	2	3
Modularity	0.20	5	4	3
Team experience	0.20	3	1	2
Sampling Rate	0.20	3	5	4
Availability	0.10	5	4	5
Total Score (Normalized to 5)		**3.90**	**3.00**	**3.20**

Power Configuration

There are many ways to power an aircraft, from one central power source being distributed to the different subsystems to multiple power sources for the multiple systems. This trade study examines one circuit configurations with both one battery and multiple, along with two and three circuit configurations.

One Circuit / One Battery

The first method to power the aircraft is one large battery hooked up to a central, custom designed Power Distribution Board (PDB). This configuration, shown in Figure 60, is the simplest and requires the least number of parts. This circuit would take power from the battery and condition it, however, required to supply the voltage and current requirements of the different subsystems of the aircraft, namely Propulsion, Control, and Data. Although likely the most straightforward setup, it requires a lot of space, as the single battery must be able to power the entire craft, and would likely be large and heavy. Batteries of such size also come with price tags of equal magnitude, to the point that the batteries would likely become a sizeable budgetary sink of the project. Having only one power source also makes a fail-safe system impossible, making power loss a guaranteed fatal occurrence. The pros and cons for the one circuit, one battery configuration are listed in Table 9.

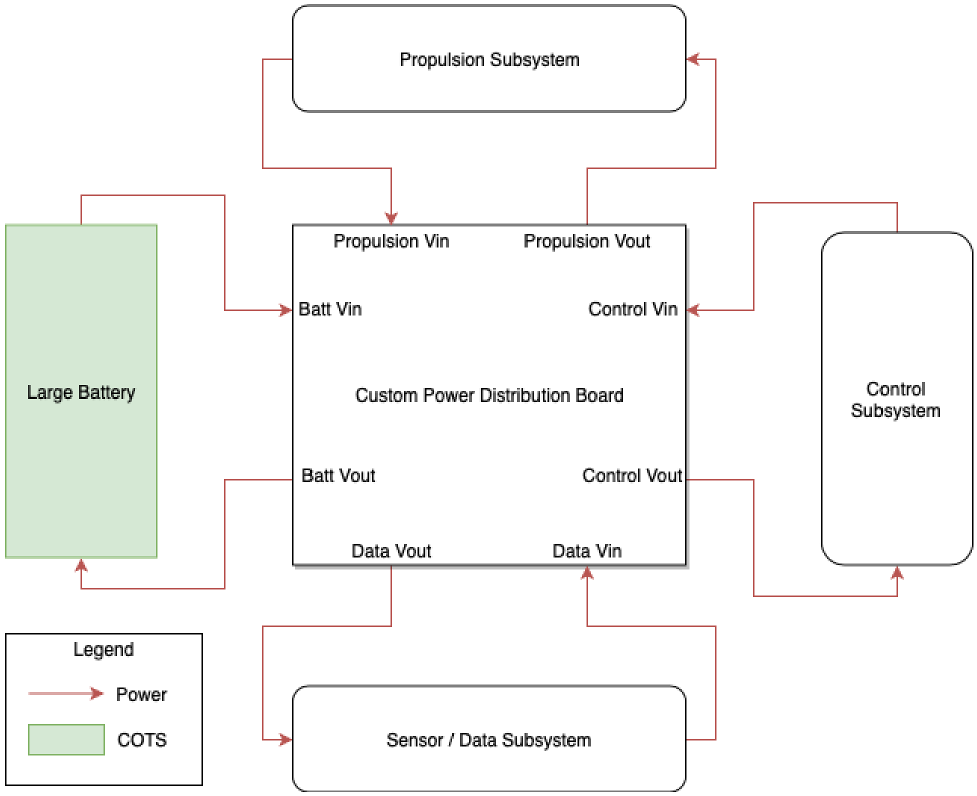

Figure 60. Power Configuration Diagram

Table 65. One Circuit / One Battery Pros and Cons

Pros	**Cons**
- Most simple setup	- Single point of failure
- Light weight	- PDB design required
- Reliable	- Expensive battery
	- Large battery form factor

One Circuit / Parallel Batteries

This power configuration, seen in Figure 61, is very similar to the one battery, one circuit configuration, and manages to solve many of that configuration's issues as well. The large, heavy, and expensive single battery is replaced with multiple light, small, and cheap and accessible batteries. This configuration maintains simplicity while allowing for a fail-safe system, where power loss in one battery doesn't guarantee failure as the other batteries still operate in parallel and can supply at least enough power to land the aircraft safely. The most complicated part of this power configuration is the design requirement of the PDB, which, while not insubstantial, is within the scope and ability of the project group. The pros and cons for the one circuit, parallel batteries configuration are listed in Table 66.

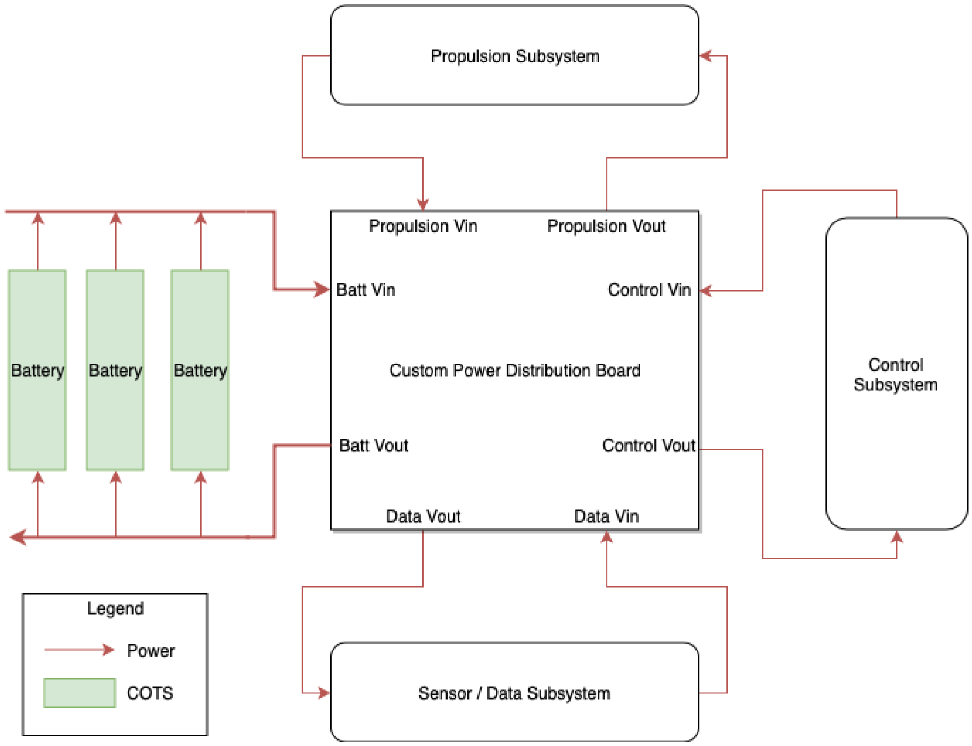

Figure 61. Power Configuration Diagram

Table 66. One Circuit / Parallel Batteries Pros and Cons

Pros	Cons
- Cheaper, more accessible batteries - Maintains simplicity - Reliable - Parallel batteries act as fail-safes	- Could be heavier than one battery - PDB design required

Two Circuits

This power configuration splits the aircraft's electronics into two distinct circuits powered by separate batteries, the Propulsion subsystem getting a large battery to itself with power going straight to the motor, and a smaller battery powering a more straightforward PDB design that directs the power to the Control and Data subsystems. This design can be seen in Figure 62. The PDB would be much easier to design than the one circuit configuration as it would be dealing with much lower current requirements. This configuration also has the advantage of a one-way fail-safe system, where if the propulsion subsystem experiences power-loss, control to the aircraft can remain, and a glided-in landing can be still possible. However, having multiple battery systems will likely be heavier than a one circuit system and could be more prone to failure due to complications. The pros and cons for the two circuits power configuration are listed in Table 67.

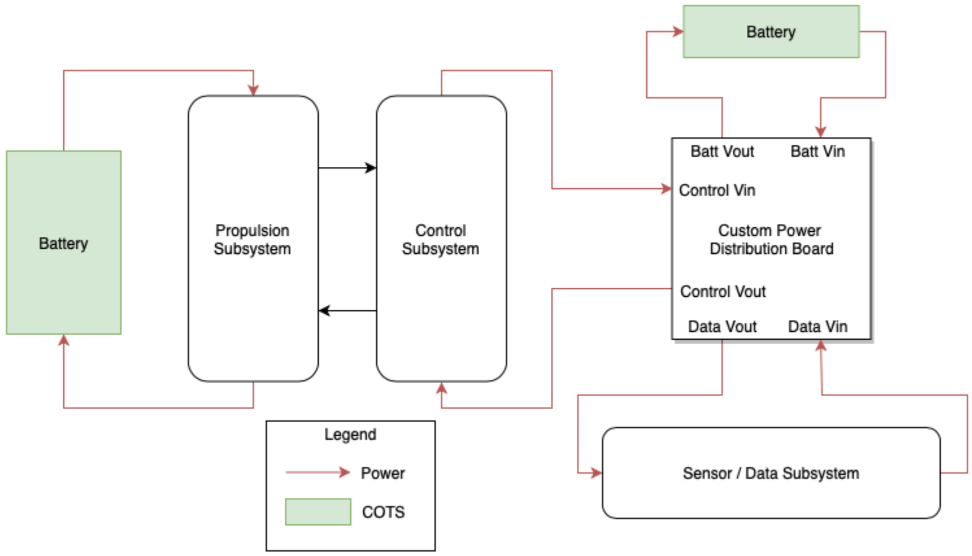

Figure 62. Power Configuration Diagram

Table 67. Two Circuits Pros and Cons

Pros	**Cons**
- Control survives propulsion failure - Less design required PDB	- Complicated - Only one-way fail-safe - Heavy

Three Circuits

The final power configuration examined for this trade study is having a battery to power each subsystem on the aircraft, roughly three circuits in total, as shown in Figure 63. This setup avoids the design requirement of the PDB, as batteries could be picked to be tailored to each subsystem, requiring no extra power management or conditioning. All those batteries, however, could mean a significant weight and space requirement. The separation of the subsystems also invites circuit interactions, and each circuit would have to be carefully grounded and insulated from the others. A backup\fail-safe system would be possible just like the two circuit configuration, but failures would likely happen more often as the configuration is so complicated. The pros and cons for the three circuits power configuration are listed in Table 68.

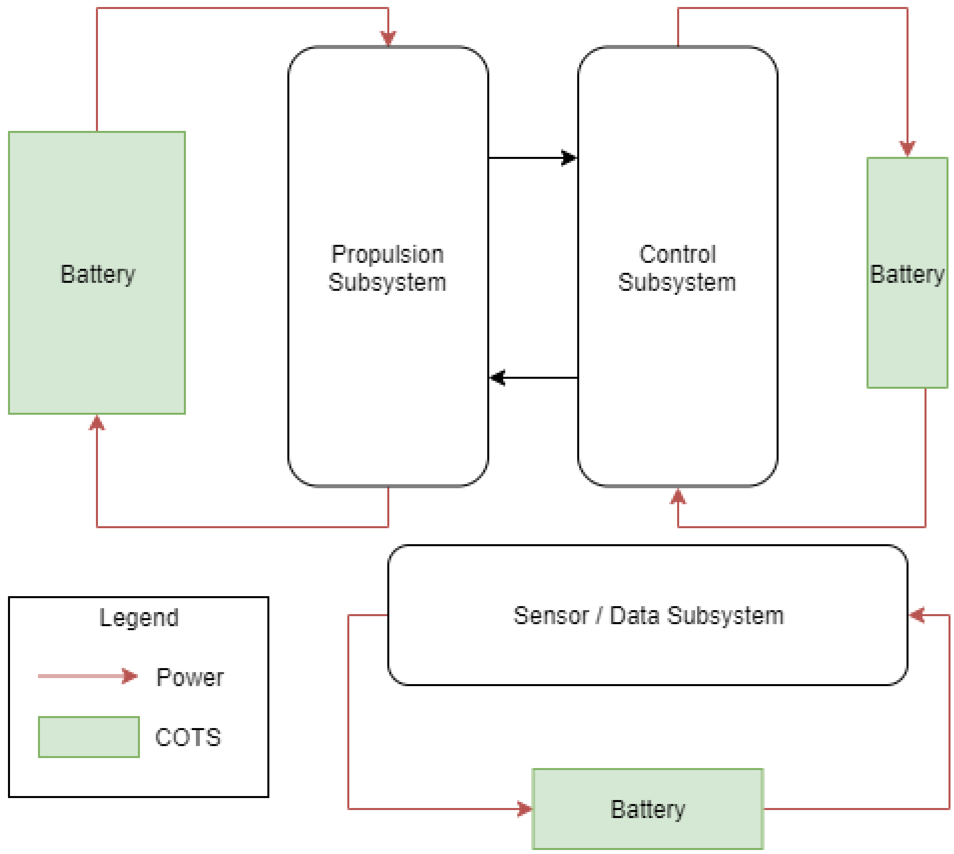

Figure 63. Power Configuration Diagram

Table 68. Three Circuits Pros and Cons

Pros	**Cons**
- No PDB required - Backup / fail-safe system possible	- Very complicated - Heavy - Circuit interactions

Power Configuration Trade Study

Criteria

The most important criteria for the aircraft's power configuration are weight and cost. Weight is an obvious important metric, as aircraft need to be as light as possible in order to fly as efficiently as possible, with low wing-loading. Cost is also essential for this trade study, as the one battery configuration is so much more expensive than using the smaller, more accessible batteries, it is worried that the large batteries could become quite the budgetary sink on the project. These criteria will be weighted to 0.25 each.

The next tier of importance down, weighted at 0.20, is risk. This criterion encapsulates the likelihood of failure, the possibility of a fail-safe system, and possible circuit interactions. These are all very important to the aircraft, which naturally have a large amount of risk associated with them, so it is essential to try to minimize the additional risk as much as possible to keep the overall risk level low.

The final tier of importance, weighted to 0.15, includes the design requirement and space requirement of the power configuration. The design requirement, mostly affected by a configurations need for a custom PDB, is a low priority for this project, as the design should be well within the scope and skills of this project group. Volume is, of course, important as there must be space on the aircraft to place the required power configuration; however, space is much less important than weight, so the weighting of these criteria is low, as seen in the following Table 69.

Table 69. Weighting of Trade Criteria

Criterion:	*Weight*	*Design Requirement*	*Volume*	*Risk*	*Relative Cost*
Weight:	0.25	0.15	0.15	0.20	0.25

Weight - The expected weight/mass of a power configuration, while usually measured, will instead be comparatively scaled across the trade study, as it can only be estimated at this stage in design. This modeling results in the following scoring system shown in Table 70.

Table 70. *Weight* Scoring Definition

Weight (kg):	*Heaviest*	*Heavy*	*Moderate*	*Light*	*Lightest*
Score :	1	2	3	4	5

Design Requirement - The expected amount of time required to design the power configuration, while usually measured, will instead be scaled across the trade study, as it can only be estimated at this stage in the design, as seen in Table 71.

Table 71. *Design Requirement* Scoring Definition

Design Requirement (h):	*Highest*	*High*	*Moderate*	*Low*	*Lowest*
Score :	1	2	3	4	5

Volume - The expected space requirement of the power configuration, while usually measured, will instead be scaled across the trade study as seen in Table 72, as it can only be estimated at this stage in the design.

Table 72. *Volume* Scoring Definition

Volume (m^3):	*Highest*	*High*	*Moderate*	*Low*	*Lowest*
Score :	1	2	3	4	5

Risk - Risk is a combined metric of the likelihood of failure, the possibility of a fail-safe system, and possible circuit interactions. As it is a unitless metric, it will be measured in general levels, where lower risk is better. These levels are shown in the following Table 73.

Table 73. *Risk* Scoring Definition

Risk (Unitless):	*Very High*	*High*	*Moderate*	*Low*	*Very Low*
Score :	1	2	3	4	5

Relative Cost - Relative cost is measured in comparative price across the power configuration, as seen in Table 74. This metric is mostly looking at the cost of the battery, and will be estimated at this stage in the design.

Table 74. *Relative Cost* Scoring Definition

Relative Cost ($):	*Highest*	*High*	*Moderate*	*Low*	*Lowest*
Score :	1	2	3	4	5

One Circuit / One Battery Scores

Weight: **5** - One circuit / one battery is likely the lightest configuration possible due to the simplicity.

Design Requirement: **3** - One circuit / one battery has a moderate design requirement due to the complicated PDB required.

Volume: **3** - One circuit / one battery has a moderate space requirement due to the large size of the battery powering the entire aircraft.

Risk: **4** - The simplicity of the one circuit / one battery configuration minimizes risk; however, no fail-safe system is possible with only one battery.

Relative Cost: **2** - This is likely one of the most expensive power configurations due to the high price of such a large battery.

One Circuit / Parallel Batteries Scores

Weight: **4** - Due to the increase in the number of batteries, this configuration is likely slightly heavier than the one battery configuration, however, it maintains the simplicity of one circuit and therefore is still relatively light.

Design Requirement: **3** - One circuit/parallel batteries has a moderate design requirement due to the complicated PDB required.

Volume: **5** - With small batteries and a simple power configuration, one circuit/parallel batteries is likely the least space using power configuration.

Risk: **5** - The parallel batteries can act as fail-safes for each other, as if one battery loses power, the aircraft maintains power from the others. With the simplicity maintained (and therefore no circuit interactions), the one circuit/parallel batteries power configuration is very safe.

Relative Cost: **5** - The expensive single battery is replaced with multiple cheap, accessible batteries, making the one circuit/parallel batteries power configuration very economical.

Two Circuits

Weight: **3** - Two circuits are more complicated than one, and with multiple batteries, this power configuration is likely heavier than the one circuit configurations.

Design Requirement: **4** - The two circuit configuration uses a much less complicated PDB, reducing the design required for this power configuration.

Volume: **4** - Two circuits likely take up more space than one with parallel batteries, but still use less than the enormous size of the one single battery.

Risk: **5** - The two circuit power configuration is one-way fail-safe, as control can remain if propulsion fails. There is moderate circuit interaction levels from the two circuits. Overall, this power configuration pretty safe.

Relative Cost: **4** - While cheaper than the single large battery, this system still probably is more expensive than the one circuit, parallel batteries configuration due to its complication.

Three Circuits

Weight: **3** - The three circuit power configuration is very complicated, has many batteries, and would likely, therefore, be moderately heavy.

Design Requirement: **5** - Three circuits means power to each subsystem can be tailored to exactly what is needed, and therefore no PDB design is required for this power configuration.

Volume: **3** - With the many batteries three circuits requires, and the required insulation to prevent circuit interactions, three circuits would likely be moderately space heavy.

Risk: **4** - Three circuits allows for a fail-safe system, and keeping each subsystem independent increases the likelihood for a safe recovery after any power failure. However, with the complications and circuit interactions, there is still room for risk in this power configuration.

Relative Cost: **3** - With three circuits requiring three separate sets of batteries, this power configuration is likely moderately priced.

Scoring Summary

Table 75 shows the results of the Power Configuration trade study. The One Circuit / Parallel Batteries configuration came out as the clear winner of the study and seems the most logical choice of configuration overall. Therefore, the baseline design will go forward with the one circuit, parallel power configuration.

Table 75. ***Power Configuration*** **Trade Study Matrix**

		One Circuit One Battery	**One Circuit Parallel**	**Two Circuits**	**Three Circuits**
Evaluation Criteria	**Weighting**	**Score**	**Score**	**Score**	**Score**
Weight	0.25	5	4	3	3
Design Requirement	0.15	3	3	4	5
Volume	0.15	3	5	4	3
Risk	0.20	4	5	5	4
Relative Cost	0.25	2	5	4	3
Total Score (Normalized to 5)		**3.45**	**4.45**	**3.95**	**3.50**

Propulsion

Propulsion Configuration

The box-wing design profoundly influences the configuration of the propulsive elements of the aircraft. It is crucial to select the proper setup so that internal moments, weight, and power consumption are diminished while efficiency, thrust, and stability are prioritized.

The choice between different kinds of propulsive units is not part of this study, as the choice of feasible solutions is extremely limited. RC aircraft rarely step outside the domain of electric motors in the modern industry. Alternatives to a standard propeller, such as a gas-powered or a miniaturized jet propulsion unit exist, but are either inefficient, impractical, or wildly outside the limitations of the team's budget and expertise. As such only configurations of a standard electric motor/propeller combo were examined.

Double Pusher / Reflexed

The double pusher design, shown in Figure 64, consists of a twin motor assembly. These motors are to be located at the trailing edge of the wing, configured such that the propellers are behind most of the airframe, pushing the aircraft forward. This assembly would hold the motor casings far from the ground, preventing damage during landing. However, the shape of the airfoils would have to be modified to account for the off-center thrust vector, as well as the implementation of the motors into the wing structure. When mounted on the top wing, the bottom wing must present reflexed camber to produce pitch stability. This arrangement would significantly limit the operational capacity of the aircraft, as only a small range of flight speeds would allow for pitch stability. Finally, the motors would have to be housed at a certain distance underneath the airfoil, so no losses in the thrust are experienced. The pros and cons for such a setup are given in Table 76.

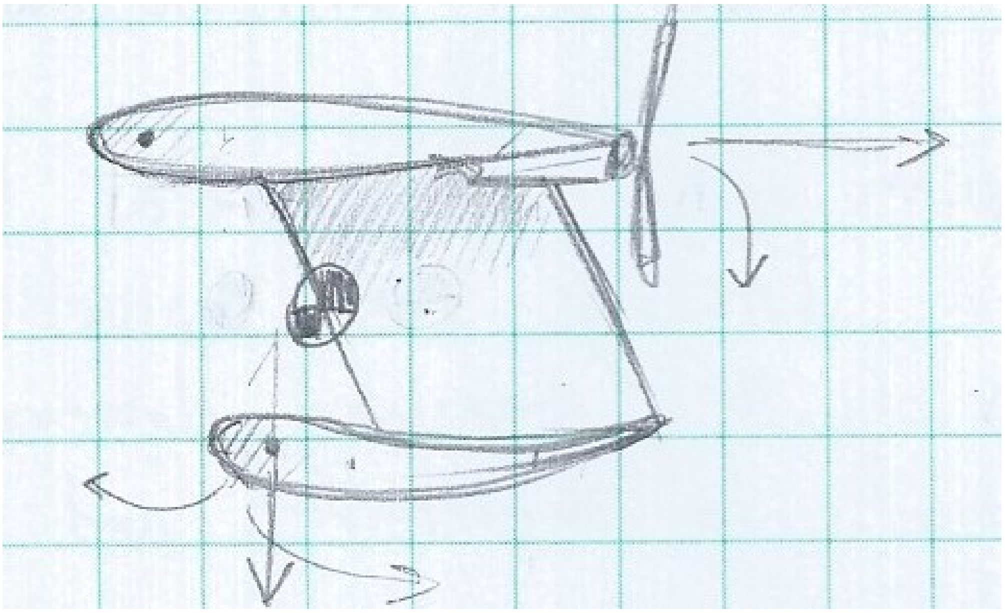

Figure 64. Double Pusher with Reflexed Wing, Side View

Table 76. Double Pusher / Reflexed Pros and Cons

Pros	**Cons**
- Negligible flow disturbances and data noise - Decreased mass and power consumption - Pitch stable at effective speed - Distributed structural load - Easy maintenance	- Thrust loss due to disturbed wing flow - Precise machining of the lower airfoil - Small operation range of speeds - Extra mass on the system - More power is necessary

Puller Configuration (Double/Single + Reflexed Wing)

The puller configuration, seen in Figure 65, consists of a motor assembly ahead of the airframe. This configuration presents a significant increase in propulsive performance, as the flow of air over the wing is accelerated by the propellers, generating more lift and improving the overall performance of the aircraft. Nevertheless, this configuration presents difficulties in protecting the motors, as the aircraft likely would tip over on landing with this configuration. Just as in the wing-mounted pusher case, flight stability can only be achieved when a reflexed wing is introduced to the system to counterbalance the propulsive pitching moment. The operational speed range of the aircraft is significantly decreased to maintain equilibrium. Pros and cons of the puller configuration are given in Table 77.

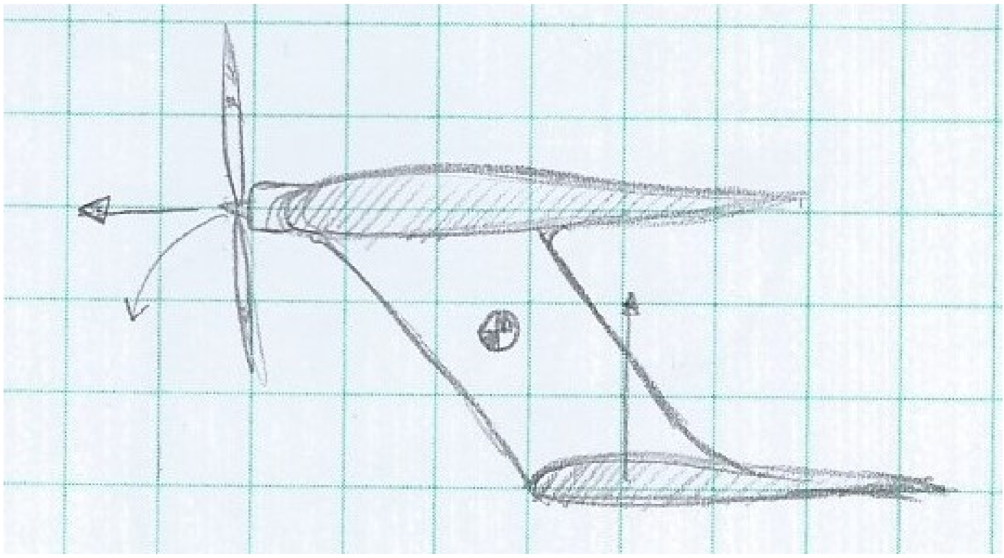

Figure 65. Puller Configuration, Side View

Table 77. Puller Configuration Pros and Cons

Pros	Cons
- Generates more lift at lower velocities - Simple to manufacture/ integrate - Lower power requirements - Higher endurance	- No protection against crash landing - Noisy data / Disruption of airflow - Pitch unstable in positive stagger - Requires precise machining - Small range of flight speeds

Single Pusher/ Centered (No Reflex)

This design consists of a single motor located in between both wings, as seen in Figure 66. This setup presents significant benefits to the overall performance and maneuverability of the aircraft. The central location means that the thrust vector acts along the center of gravity, negating the unwanted moment. Additionally, one motor means less weight and therefore less power required to operate the box wing. The propulsion system would also be protected in the case of a tumble landing, as there are structural components on all sides of the motor. The pros and cons of a single center mounted motor are listed in Table 78

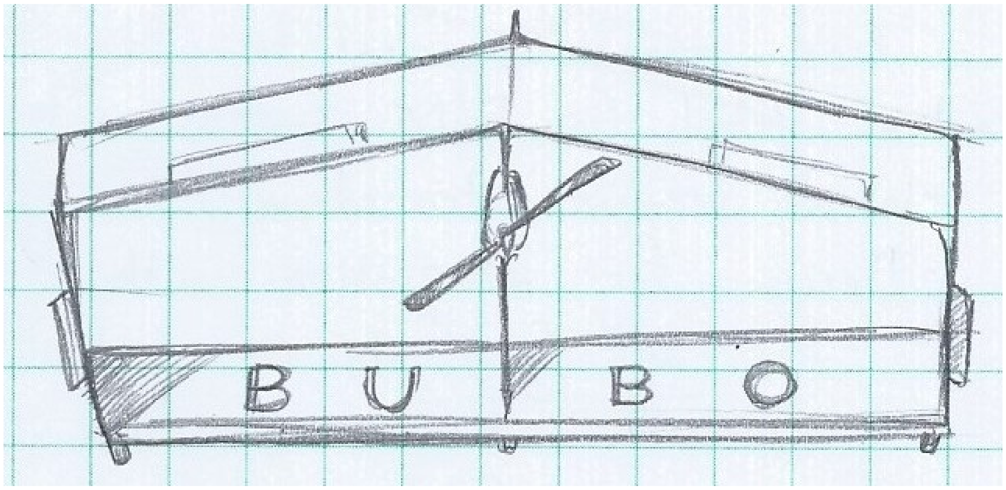

Figure 66. Single Motor Pusher, Top View

Table 78. Single Pusher/ Centered Pros and Cons

Pros	Cons
- Less mass - No interference in wing structure - Stable flight at a range of speeds - No reflexed airfoil - Cheaper	- Less thrust compared to a twin system - No thrust differential possible - Disruption of airflow - Structural concerns

Double Pusher / Centered (No Reflex)

The double centered pusher system is a very reliable and well-tested design. This setup, pictured in Figure **??** allows for the maximum amount of thrust to be delivered while still maintaining the negligible internal moments and protecting the motors from potential impacts. This system allows for the implementation of differential thrust to aid with yaw control. Nevertheless, this method also introduces additional weight and undesired noise in the data collected in the FADS system due to the location of the propellers and size of their influence. Pros and cons of such a setup can be seen in Table 9.

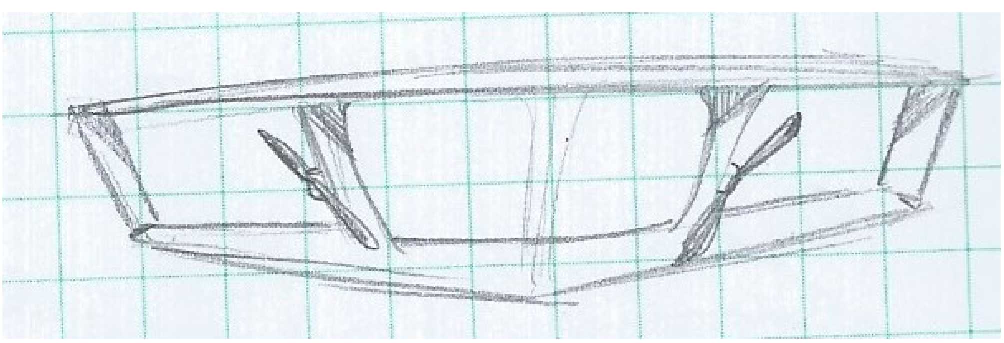

Figure 67. Centered Double Pusher, Front View

Table 79. Double Pusher / Centered Pros and Cons

Pros	Cons
- Propellers allow for rapid acceleration - Simple manufacturing and integration - Better structural support	- Integration of other systems is compromised - Splits fuselage section in two - Disrupts airflow - Noisy data - Extra mass

Multiple Engine

The multi-engine setup presents a simple and intuitive solution to the propulsion configuration, and can be seen in Figure 68. Nevertheless, it presents significant drawbacks. The implementation of the multiple motors presents a substantial increase in both the mass and power required in the system. Furthermore, it is known that the vast majority of the autopilot boards are not able to integrate this multi-engine setup. Additionally, the structural and electrical integration of this setup would be an extremely challenging design. A multi-engine setup's pros and cons can be found in Table 9.

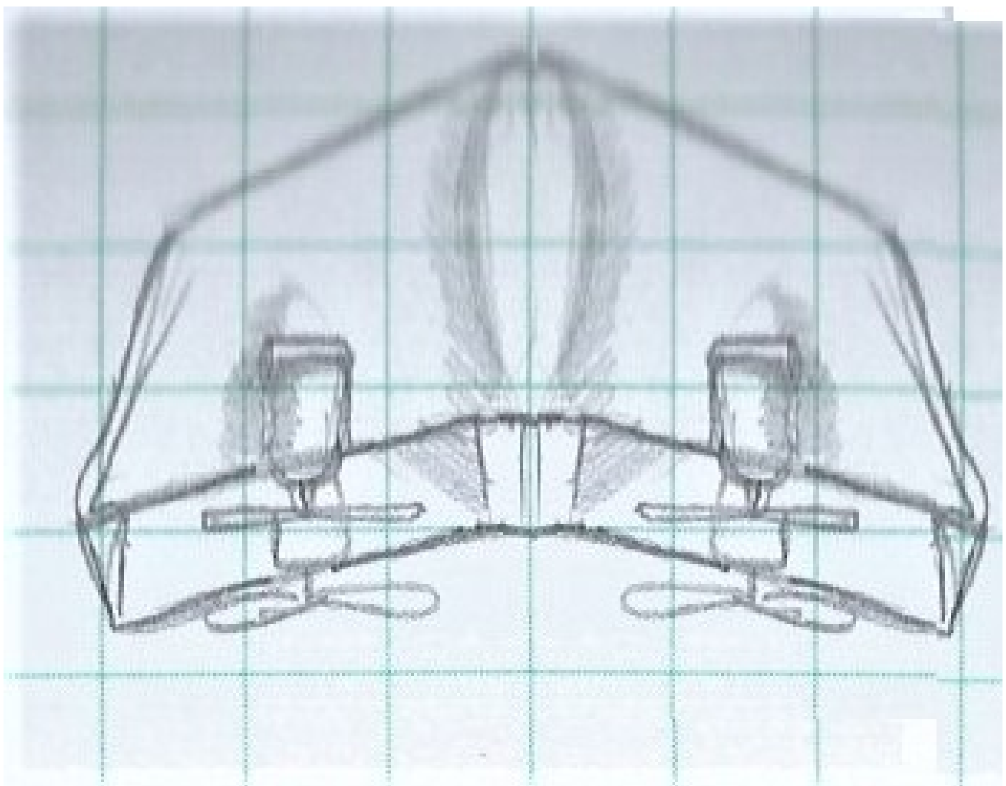

Figure 68. Multi-Engine Configuration, Top View

Table 80. Multiple Engine Pros and Cons

Pros	Cons
- Distributed Structural loading - Better maneuverability - No reflexed airfoil - Redundancy - Reliable	- Manufacturing and integration difficulties - Not protected from crash landing - Significantly more expensive - More power required - More mass

Propulsion Configuration Trade Study

Criteria

The selection criteria were divided into three degrees of importance. Higher tiers represented more critical elements for mission success. Accordingly, the first level consisted of survivability and implementation of the setup. Survivability is directly related to the required 10 flight cycles. The propulsive system should be able to withstand all cycles without major damages. The implementation criterion ensures that the selected setup presents negligible interference in the performance of all remaining onboard systems and airflow. The second tier incorporates weight and manufacturing of each setup. The weight criterion accounts for all the mass necessary for the setup to function. Manufacturing accounts for housing integration, wiring, and autopilot integration. Lastly, due to the limited budget, pricing was considered. These criteria and their weights can be seen in Table 81.

Criterion:	*Survivability*	*Implementation*	*Reliability*	*Manufacturing*	*Price*
Weight:	0.25	0.25	0.20	0.20	0.10

Table 81. Weighting of Propulsion Trade Criteria

Survivability - The survivability is directly related to the location of the motors. The system should be protected from a possible crash. Therefore, the safest location is at the center of the airframe, where structural components can provide physical shielding. This is followed by the trailing edge of the top wing. This position allows the propulsive units to be as far from the ground as possible. Finally, the least desirable positions are along the front of the aircraft, as the aircraft is expected to tip forward on landing, almost certainly damaging the propulsive elements. This translated into the following scoring system seen in Table 82.

Table 82. *Survivability* Scoring Definition

Survivability:	*Bottom Front*	*Top Front*	*Bottom Back*	*Top Back*	*Middle*
Score:	1	2	3	4	5

Implementation - The implementation criterion is intimately related to the utilized number of motors. As shown in Table 83, a greater number of motors can cause challenges in the installation process, as well as introduce flow disturbances, which add noise in the collected data.

Table 83. *Implementation* Scoring Definition

Implementation:	*Five Motors*	*Four Motors*	*Triple Motor*	*Twin Motor*	*Single Motor*
Score:	1	2	3	4	5

Weight - As is the case with all aerospace projects, weight is a critical factor to keep under consideration. In the interest of extending the flight duration and maneuverability of the aircraft, the design should seek to reduce weight as much as possible. Nonetheless, due to the added thrust force imparted by more powerful propulsion systems, one could also expect to achieve some advantages by using a more substantial propulsive unit. The resulting scoring system is given in Table 84.

Table 84. *Weight* Scoring Definition

Weight:	*Five Motors*	*Four Motors*	*Triple Motor*	*Twin Motor*	*Single Motor*
Score:	1	2	3	4	5

Manufacturing - Based on previous experience building remote control model planes, the team was able to estimate an approximate time frame for assembling each propulsive setup. Front-mounting engines takes approximately 2 hours, back-mounting engines take 4 hours, and middle-mounted engines approximately take 3 hours. These times were then propagated by the number of motors each setup uses, and resulted in the scoring system laid out by Table 85.

Table 85. ***Manufacturing*** **Scoring Definition**

Manufacturing (Hours):	*20*	*16*	*10*	*8*	*<5*
Score:	1	2	3	4	5

Price - The propulsion system tends to be one of the more expensive components in a remote-controlled model along with the batteries. Therefore, the price was taken into consideration. The cost will vary with both the quantity and size of the motors. Nevertheless, this criterion will focus only on the number of motors, since sizing can only be determined at later stages of the design process. This is reflected in the scoring system shown in Table 86.

Table 86. ***Price*** **Scoring Definition**

Price:	*Five Motors*	*Four Motors*	*Triple Motor*	*Twin Motor*	*Single Motor*
Score:	1	2	3	4	5

Double Pusher / Reflexed Wing Scores

Survivability: **4** - Position at the top and back of the aircraft will distance the motor units from the ground on landing.

Implementation: **4** - Motor casing will alter airfoil somewhat, though FADS will be almost free of disturbance.

Weight: **2** - Two motors and casings will be heavier than one.

Manufacturing: **2** - Implementing into the wing structure could present a technical challenged, though this heavily depends on the design chosen for the wing.

Price: **4** - Two motors and casings represent a middle-ground between single motor configurations and more complex ones.

Puller Configuration + Reflexed Wing Scores

Survivability: **2** - Propellers will likely be damaged when the aircraft tips over, though sweep may prevent this if the landing is slow enough.

Implementation: **3** - Similar to the other wing-mounted configurations, though FADS will be heavily impacted

Weight: **3** - Similar to other double-wing mounted configurations

Manufacturing: **2** - Similar to other double-wing mounted configurations

Price: **5** - Similar to other double-wing mounted configurations, though the likelihood of propellers breaking must also be considered.

Single Pusher / Centered (No Reflex) Scores

Survivability: **4** - Structure shields the motor and propellers against all but the most severe landings, but fewer structural components weakens the frame as a whole.

Implementation: **4** - Motor casing can be readily implemented into strut, with wiring running through the structural component. No thrust differential, but limited disruption of airflow for FADS.

Weight: **5** - Only one motor, with a lightweight plastic casing.

Manufacturing: **5** - Casing can be 3D printed without much technical challenge.

Price: **5** - Again, only one engine with a simple, cheap casing.

Double Pusher / Centered (No Reflex) Scores

Survivability: **5** - Structure protects propeller units

Implementation: **4** - Can be readily implemented into a double-strut structural configuration. Also allows for thrust differential control if need be.

Weight: **2** - Added weight from both the structural components and the propulsive units.

Manufacturing: **4** - Relatively simple to integrate into vertical struts.

Price: **4** - Two motors is twice as much as one. The additional structural component may add to price.

Multiple Engine Scores

Survivability: **2** - More chances for crippling damage, but shielded by the wing surfaces.

Implementation: **3** - Wiring and integration will extend to every wing surface and modify the aerodynamic properties of the aircraft significantly. However, decentralizing propulsion limits the structural impact, as well as the magnitude of airflow disturbances.

Weight: **2** - Potentially quadruple the weight of a single-engine configuration, though smaller engines will likely be used.

Manufacturing: **1** - Requires more manufacturing time than any other configuration.

Price: **1** - More engines means more money.

Scoring Summary

The scoring summary in Table 87 presents an overview of each configuration. As a general trend, all multi-motor setups suffered under the criteria of implementation, weight, and price. Conversely, all single-engine designs excelled in these same criteria. The center placement of the motors also presented a definite advantage. Finally, the single centered pusher achieved high scores in all categories and was the clear winner by a significant margin, and will be what conceptual design goes forward with.

Table 87. ***Propulsion Configuration*** **Trade Study Matrix**

		2 Pusher	**Puller**	**1 Pusher / Centered**	**2 Pusher / Centered**	**Multiple**
Evaluation Criteria	**Weighting**	**Score**	**Score**	**Score**	**Score**	**Score**
Survivability	0.25	4	2	4	5	2
Implementation	0.25	4	3	4	4	3
Weight	0.20	2	3	5	2	2
Manufacturing	0.20	2	2	5	4	1
Price	0.10	4	5	5	4	1
Total Score (Normalized to 5)		**3.2**	**2.75**	**4.5**	**3.85**	**1.95**

Structures

Wing Span

One Meter Span

A one meter span is the smaller of the two choices. This aircraft would measure one meter from wingtip to wingtip. A smaller wingspan requires less resources from a logistics standpoint, with less mass and material, a lower overall prototype cost, and easier transport; however, it may require more inventive solutions than a larger wing for integration of systems into the wing. A smaller span experiences less severe moments at the wingtips, meaning it has a better chance of survival on a rough landing. The pros and cons of a one meter wingspan are listed in Table 88.

Table 88. One meter wingspan Pros and Cons

Pros	**Cons**
- Less mass and structure - Lower material cost - Easier to manufacture - Greater chance for multiple prototypes - Handles launch and landing stresses better - More compatible with available launch methods - Easier to transport - Greater maneuverability in flight	- Requires larger control surfaces - More susceptible to wind and turbulence - Less wing space to integrate payload and electronics - Integration of sensors will have a greater impact on the coefficient of lift because it will deform a larger portion of the wing surface

Two Meter Span

A two meter span is the larger of the two choices. This aircraft would measure two meters from wingtip to wingtip. A larger wingspan is less susceptible to wind and turbulence in flight as it is heavier and has the potential for more robust control surfaces. Additionally, a larger planform allows for more flexibility with placement of subsystems, electronics, and sensors, and the aerodynamics of the wing will be less affected by the integration of those sensors since less of the wing surface is being deformed. The pros and cons of a two meter wingspan are listed in Table 89.

Table 89. Two meter wingspan Pros and Cons

Pros	**Cons**
- Requires smaller control surfaces - Less susceptible to wind and turbulence - More wing space to integrate payload and electronics - Integration of sensors will have a smaller impact on the coefficient of lift because it will deform a smaller portion of the wing surface	- More mass and structure - Greater material cost - Harder to manufacture - Smaller chance for multiple prototypes - Handles launch and landing stresses worse - Less compatible with available launch methods - Harder to transport - Less maneuverability in flight

Wing Span Trade Study

Criteria

The criteria for this trade study include launch methods, survivability, system integration, manufacturability, sensor integration, and mass. The launch methods that are compatible with the different spans is a hugely important consideration. The ability to safely and consistently launch the aircraft is paramount to the success of the mission, and the size of the airframe can be a limiting factor with some of the launching methods being investigated. Survivability is also an extremely important consideration. The aircraft must be able to make ten consecutive flights so the effect of the size of the airframe on that ability is a major consideration. Since these two metrics are the most important and the most limiting, they are weighted the highest at 0.25.

The second tier of criteria consists of the compatibility of system integration. The ability to include all necessary systems on the plane must be considered, however is less limiting than survivability and launch method because there is a greater potential for creative solutions. Since system integration is of nearly the same importance as survibability and launch methods, it is weighted at 0.20.

The final tier of criteria consists of manufacturability, mass, and system integration effect. Manufacturability and mass can be more easily accommodated for and have a plethora of potential viable solutions to mitigate their effects, however they should still be considered so as not to unnecessarily increase the complexity of the design. The effect of the sensor integration should be small since the sensors will be flush with the wingform, however it is a significant requirement and should therefore be considered. These criteria are weighted the lowest at 0.10.

The weighting of these criteria has been compiled in the following Table 90 for convenience.

Table 90. Weighting of Trade Criteria

Criterion:	*Launch Systems*	*Survivability*	*System Integration*	*Manufacturability*	*Mass*	*Sensor Integration*
Weight:	0.25	0.25	0.20	0.10	0.10	0.10

Launch Systems - The scoring for launch system compatibility, given in Table 91, is dependent on the number of considered launch systems the airframe is compatible with. Compatibility with a launch method requires the launch method be able to interface with the airframe given it's wingspan with no major modifications needing to be made to the launch system.

Table 91. *Launch Systems* Scoring Definition

Launch Systems:	*Zero Compatible Methods*	*One Method*	*Two Methods*	*Three Methods*	*Four to Five*
Score:	1	2	3	4	5

Survivability - The scoring for survivability is dependent on how the wingspan affects the ability of the airframe to complete takeoff, flight, and landing with no major damage. This takes into account how much the airframe will be affected by an impact during a hard landing or takeoff, as well as how the airframe will react to forces in flight. "Low" survivability means the aircraft would be drastically affected by the impact in launch, landing, and flight due to the wingspan, imposing severe limitations on the flight envelope of the aircraft and requiring rigorous reinforcement for launch and landing. "High" survivability means the aircraft would be unaffected by the impact of launch, landing, and flight due to the wingspan, imposing no limitations on the flight envelope of the aircraft and requiring no reinforcements for launch and landing. This is reflected in the scoring system shown in Table 92.

Table 92. *Survivability* Scoring Definition

Survivability:	*Low*		*Moderate*		*High*
Score:	1	2	3	4	5

System Integration - The scoring for system integration is dependent on how easily storage space for the different systems can be found or created in the airframe and how much variation there can be in this placement. The placement of systems will have an immediate impact on the aircraft's center of gravity and thus the airframe must be able to support a subsystem configuration which will allow for a centerline center of gravity for stability. A larger and thicker wing will provide the greatest opportunity for variation in placement. "Low" system integration means there are no possible configurations in the given wingspan which would allow for a centerline center of gravity and protection of these systems. "High" system integration means there are many possible configurations which would allow for a centerline center of gravity and several which allow for full protection of all subsystems. This relative scale can be seen in Table 93.

Table 93. *System Integration* Scoring Definition

System Integration:	*Low*		*Moderate*		*High*
Score:	1	2	3	4	5

Manufacturability - The scoring for manufacturability, shown in Table 94, will consider the time, complexity, tooling, and material needs for the given wingspan. The time it takes to build a single prototype from start to finish will be a factor, with a shorter build time receiving a better score. The techniques required for construction of a larger member may be more complicated to provide the same level of structural integrity as a smaller member. The complexity of the techniques required to maintain the needed strength will be a factor, with more complex techniques scoring lower. The availability and cost of tooling required to build a given wingspan is a consideration, with more expensive and difficult to access tooling scoring lower. Finally, the material needs for a given design will be considered, including the quantity, price, and availability of those materials. A "Low" score for manufacturability takes the longest time, is the most complex, requires the most expensive\difficult to access tooling, and has the highest material needs. A "High" score for manufacturability takes the shortest amount of time, is the simplest, requires the least expensive\easiest to find materials, and has the lowest material needs.

Table 94. *Manufacturability* Scoring Definition

Manufacturability:	*Low*		*Neutral*		*High*
Score:	1	2	3	4	5

Mass - The scoring for mass is dependent on the mass of the airframe. "Heavy" means the mass of the airframe due to the size of the wingspan is a burden on the design and would require extensive mitigation to achieve flight. "Light" means the mass of the airframe due to the size of the wingspan is very easy to accommodate. This resulted in the scoring system shown in the following Table 95.

Table 95. *Mass* Scoring Definition

Mass:	*Heavy*		*Neutral*		*Light*
Score:	1	2	3	4	5

Sensor Integration - The scoring for sensor integration will consider the variation capability of sensor placement and the effect the integration will have on the aerodynamic performance of the aircraft. This effect on the aerodynamic performance will be considered based on the effect on the coefficient of lift due to the percentage of the wingform that must be deformed to fully integrate the sensors. A "Large" effect for senor integration means an array of sensors would be difficult to place in locations on the wing to experience different aspects of flow over the wing and the sensors would encompass a large portion of the wing surface. A "Small" effect for sensor integration means an array of sensors would be extremely easy to place in various ways to measure the flow and encompass an extremely small percentage of the wing surface. The scoring scale derived from these determinations is given in Table 96.

Table 96. *Sensor Integration* Scoring Definition

Sensor Integration:	*Large*		*Moderate*		*Small*
Score:	1	2	3	4	5

One Meter Span

Launch System: **5** - All the launch systems investigated are able to be used with the one meter wingspan based solely on the wingspan constraint.

Survivabiltiy: **4** - The smaller airframe of the one meter wing span means forces applied at the ends of the wings create smaller moments than those which would be created on a larger airframe. This implies the one meter span would handle launch and landing forces with relatively little re-enforcement compared to the two meter span. The shorter wing would also require a higher force to break it at the center, meaning the aerodynamic forces the one meter span could handle in flight would exceed those of the two meter. However, the smaller wingspan would have a lower wing loading, making the aircraft more susceptible to turbulence and wind and therefore more likely to crash.

System Integration: **3** - The smaller and thinner wing of the one meter is more difficult to arrange the subsystems in than the larger and thicker wing of the two meter, but it is still possible to configure the subsystems in a way to produce a center-line center of gravity. However, it is probable that not all of these configurations would be able to fully protect each of the subsystems.

Manufacturability: **5** - The one meter span aircraft will take less time to construct and fewer materials. Many materials are sold in one meter sections and would therefore be easily obtainable. The majority of the tooling available to the team can be used on this scale and the manufacturing techniques of aircraft at a one meter span are well documented and easy to comprehend.

Mass: **5** - The mass of the one meter airframe will be considerable less due to having less material in the wing. This will be much easier to accommodate in the subsystems (such as needing smaller propulsive elements) than the two meter span.

Sensor Integration: **2** - The much smaller wing area of the one meter span limits sensor placement options and makes the effect on the coefficient of lift of the aircraft of the sensors being integrated much more pronounced than that of the two meter aircraft. It would be much more difficult to produce a sensor array placement that would be exposed to many elements of the flow without interference from each other with the one meter span aircraft.

Two Meter Span

Launch System: **2** - The two meter span is only compatible with the table-bungee and the rail-bungee system. The other three launch systems would require extensive modification to use.

Survivabiltiy: **2** - The two meter wingspan has more to be damaged in the event of a rough landing. Additionally, the larger wingspan creates a longer moment arm so equal forces at the wingtips will be more severe for the two meter than the one meter.

System Integration: **5** - The larger and thicker wing of the two meter is easier to arrange the subsystems in than the smaller and thinner wing of the one meter. There are also many configurations which the subsystems would be fully protected due to the increased volume of the two meter wing and the ability to nest subsystems safely inside the wing.

Manufacturability: **2** - The two meter span aircraft will take more time to construct and more materials. The necessary materials may be difficult to find and expensive to obtain in such large pieces. More complex structural components and higher quality materials may need to be used to compensate for the decreased rigidity of the larger members, adding unneeded burden to the manufacturing process.

Mass: **3** - The mass of the two meter airframe will be considerably more due to having more material in the wing. This will be much harder to accommodate in the subsystems (such as needing larger propulsive elements) than the one meter span, but is not so burdensome as to prevent a feasible design.

Sensor Integration: **5** - The much larger wing area of the two meter span allows for various sensor arrangements and makes the area of the wing deformed by the sensors a smaller percentage of the total wing area than the one meter span, improving the aerodynamic performance of the two meter aircraft compared to the one meter.

Scoring Summary

The results of the wing size trade study are given in Table 97. The trade shows the one meter span is better than the two meter for the purposes of this project. The consideration of the available launch systems and the survivability had a huge influence on the decision, with the one meter span being decisively better in both of these categories. While the two meter span had better scores in system and sensor integration, the potential for creative solutions for these two categories allows this disadvantage to be disregarded and the one meter span to be selected.

Table 97. *Wing Size* Trade Study Matrix

		One Meter Span	**Two Meter Span**
Evaluation Criteria	**Weighting**	**Score**	**Score**
Launch Systems	0.25	5	2
Survivability	0.25	4	2
System Integration	0.20	3	5
Manufacturability	0.20	5	2
Mass	0.10	5	3
Sensor Integration	0.10	2	5
Total Score (Normalized to 5)		**4.55**	**3.20**

Landing Method

Landing safely is critical to ensuring the survivability of the aircraft. For the aircraft to be able to survive 10 flight cycles, it must be able to land without taking damage that would be detrimental to future flights. A successful landing method is one that prioritizes safety and minimizes damage. Complexity, additional weight/drag, and reliability must also be considered when choosing a landing method.

Skid/Hard Landing

This landing would have skids attached to the bottom of the aircraft so that it could slide along the ground. Some additional bracing on the nose of the aircraft would protect the airframe from damage if/when it tips over as well as prevent it from rolling over. The pros and cons for a skid landing are listed in Table 98.

Table 98. Skid Landing Pros and Cons

Pros	**Cons**
- Minimal cost/time to develop	- Risk of damage to all parts of aircraft
- Land almost anywhere	- Landings must be precise
- Low additional mass	- May not scale to larger aircraft

Landing Gear

Landing gear is a very safe method of landing, but requires significant efforts to develop. Landing locations are also significantly limited with landing gear - even gravel roads may be too uneven. While the additional mass added by the landing gear is small, additional drag is significant. The pros and cons for landing gear are listed in Table 99.

Table 99. Landing Gear Pros and Cons

Pros	Cons
- Lowest risk of damage - Low additional mass	- Requires very precise landing - Significant additional drag - Requires smooth terrain for landing - Mechanical/structural complexity - Requires redesign for scaling

Net

A net is a method which requires minimal additional mass (if any) to the aircraft for system interface; all the mass that goes into ensuring a safe landing would be on the ground. The net also scales well because forces are distributed throughout the wing. A major downside is that damage could occur, especially if the propulsion system were to get tangled in the net or if the aircraft misses the net entirely. The pros and cons for a net landing are listed in Table 100.

Table 100. Net Landing Pros and Cons

Pros	Cons
- Land anywhere net can be deployed - No/minimal additional mass/drag - Distributed forces - Scales well	- Requires precise landing - Possible damage to/from propulsion getting tangled

"Catch"/Moving Landing

This landing would involve a moving vehicle matching speeds with the aircraft, allowing it to softly touch down either on the roof or in a trailer behind the vehicle. While this could theoretically provide the softest landing for the aircraft, safety is a serious issue with this landing. The aircraft and moving vehicle would be a serious risk to those overseeing the landing and the added complexity of two moving pieces would increase the difficulty of the landing. The pros and cons for a skid landing are listed in Table 101.

Table 101. "Catch"/Moving Landing Pros and Cons

Pros	Cons
- No/minimal additional mass - Low risk of damage - Low additional mass	- Limited landing locations (on roads) - Landings must be precise - Possibly not safe

Parachute

A parachute is a common method of retrieval for many light aircraft. It allows for a controlled descent and reduces damage, especially in the case of stall or emergencies. However, there are many issues with parachutes, especially with this size of aircraft. The significant mass of a parachute and delicate positioning on the aircraft's body make it very undesirable for aircraft this light. Furthermore, windy conditions could significantly impact the performance of a parachute. It also must be repacked between flights, which adds to the difficulty of achieving a re-flight within 15 minutes. The pros and cons for a skid landing are listed in Table 102.

Table 102. Parachute Landing Pros and Cons

Pros	Cons
- Land almost anywhere - Usable in emergency/stall - Soft landings minimize damage	- Requires very careful placement on aircraft body - May drift to undesirable locations - Heavy - Requires repacking - Subject to damage - Redesign for scaling

Landing Method Trade Study

Criteria

The landing is the most important aspect of the survivability of the aircraft. Here the aircraft is closest to the ground and has the highest risk of damage. For this reason, the risk of damage to the aircraft is the second highest-weighted criteria, behind the safety of the group members. After damage and safety are considered, the rest of the criteria are roughly equally important. The complexity determines how much resources must be devoted to the landing method; a slightly safer landing method may not be favored if it becomes an entire subsystem on its own. The burden that the method has on the aircraft in flight is also important to consider; will the additional mass or drag be detrimental to the aircraft flying? Finally, the landing must not be too difficult that it cannot be repeated 10 times as required. The easier it is to land safely, the better the survivability of the aircraft. These weights are compiled in Table 103.

Table 103. Weighting of Landing Method Trade Criteria

Criterion:	*Complexity*	*Aircraft Risk*	*Safety*	*Aircraft Burden*	*Reliability*
Weight:	0.15	0.25	0.30	0.15	0.15

Complexity - This describes the structures and mechanisms involved with the landing, and how much of a time/resource commitment would be required to build this landing method, with scores assigned as shown in Table 104.

Table 104. *Complexity* Scoring Definition

Complexity	Complex Subsystem	Significant Effort	Moderate	Minimal	Not Significant
Score:	1	2	3	4	5

Risk to Aircraft - The chance of major damage occurring to the airframe or subsystems, with scores assigned as shown in Table 105.

Table 105. *Risk to Aircraft* Scoring Definition

Risk to Aircraft	Very High	High	Moderate	Low	Minimal
Score:	1	2	3	4	5

Safety - Chance of unsafe incidents occurring, with scores assigned as shown in Table 106.

Table 106. *Safety* Scoring Definition

Safety	Unsafe Landing	High risk of incident	Moderate	Very low	Zero risk
Score:	1	2	3	4	5

Burden to Aircraft - Additional drag/mass due to landing method, with scores assigned as shown in Table 107.

Table 107. ***Burden to Aircraft*** **Scoring Definition**

Aircraft Burden	**Large**	**Moderate**	**Small**	**Minimal**	**None**
Score:	1	2	3	4	5

Reliability - Ease or repeatability of landing, with scores assigned as shown in Table 108.

Table 108. ***Reliability*** **Scoring Definition**

Reliability	**Very Difficult**		**Challenging**		**Easy**
Score:	1	2	3	4	5

Skid/Hard Landing Scores

Complexity: **4** - Some resources would go to the design of the skid and/or hardening the aircraft for impacts, but this will not be a difficult endeavor.

Risk to Aircraft: **3** - Forces, while among the highest of the landing methods, are predictable and the aircraft can be strengthened in those key areas.

Safety: **5** - Landing can occur a safe distance from the group.

Burden to Aircraft: **4** - Skid/structural support may add some mass, minimal drag.

Reliability: **3** - Landings will be fairly easy to repeat, but certain situations may cause extra damage to airframe.

Landing Gear Scores

Complexity: **1** - Likely a subsystem in itself, significant resources will have to go to the structure of a landing gear set-up.

Risk to Aircraft: **3** - Dependent on structure and placement of landing gear it could be much better, but due to the difficulty of landing there is moderate risk.

Safety: **5** - Landing can occur a safe distance from the group.

Burden to Aircraft: **2** - Landing gear would add a moderate amount of mass and a significant amount of drag.

Reliability: **2** - Landing would require a straight, flat stretch of road; even gravel may make this method nearly impossible.

Net Landing Scores

Complexity: **4** - Quite simple, some work would go into finding the right size and tension of the net and some resources may be necessary to strengthen the aircraft.

Risk to Aircraft: **2** - Net may damage the aircraft, especially the propulsion systems. Reliability also poses a risk if the aircraft misses the net.

Safety: **5** - Landing can occur a safe distance from the group.

Burden to Aircraft: **5** - Very little to no mass or drag would be added to the aircraft.

Reliability: **3** - Depending on the size of the net, landing could be very difficult or easy; moderate is chosen as the in-between case.

"Catch"/Moving Landing Scores

Complexity: **3** - Moderate efforts to integrate vehicle and landing system, as well as minimizing the risk to the aircraft.

Risk to Aircraft: **2** - Reliability of landing poses serious risk to aircraft, good landings pose little/no risk to aircraft.

Safety: **2** - Landing would have to occur near one or several group members while at speed.

Burden to Aircraft: **5** - Little/no additional mass would be added to the aircraft.

Reliability: **2** - Landing in a small area while matching the speed of the catch vehicle would be very difficult.

Parachute Landing Scores

Complexity: **3** - Moderate efforts to ensure the right size/placement of parachute to minimize risk to aircraft.
Risk to Aircraft: **4** - Generally low risk, but vulnerable in windy conditions.
Safety: **4** - Generally safe, but windy conditions could be unsafe to group.
Burden to Aircraft: **1** - Would add significant mass and drag to the aircraft.
Reliability: **3** - Landing is generally easy/safe, but windy conditions impact reliability. Repacking parachute would also impact reflight times/capabilities.

Scoring Summary

Table 109 displays the results of the landing method trade study. Skid/Hard Landing is the best choice, slightly better than the net landing due to the lower risk to the aircraft.

Table 109. *Landing Method* Trade Study Matrix

		Skid/Hard Landing	Landing Gear	Net	Moving Landing	Parachute
Evaluation Criteria	**Weighting**	**Score**	**Score**	**Score**	**Score**	**Score**
Complexity	0.15	4	1	4	3	3
Risk to Aircraft	0.25	3	3	2	2	4
Safety	0.30	5	5	5	2	4
Burden to Aircraft	0.15	4	2	5	5	1
Reliability	0.15	3	2	3	2	3
Total Score (Normalized to 5)		**3.90**	**3.00**	**3.80**	**2.60**	**3.25**

Launch Method

The launching method for previous iterations of the Eagle-Owl system proved to be unsuccessful and ultimately were a large contributing factor in the hindrance of sustained powered flight. For this reason, the team is only considering launch systems previously used and verified by CU Boulder RC teams, specifically by the IRISS and RECUV groups on campus.

IRISS Table-Bungee Method

This method of launch involves the use of a folding card table, a bungee cord, a stake, and a quick release mechanism. The bungee cord is pulled back, with the tension in the cord measured using a simple force gauge accurate to about 0.5 lbf. Once the tension is at the desired value, the cord is run through a quick release mechanism and staked down to the ground. The aircraft is then attached to the bungee using a hook, and placed on the card table that has been set up with a roughly 15°inclination. The team then moves away from the set up, and pulls a string attached to the quick release mechanism. This releases the bungee, and propels the vehicle forward along the table and into the air. This process can be seen in Figure 69, while pros and cons of the table-bungee method are listed in Table 110.

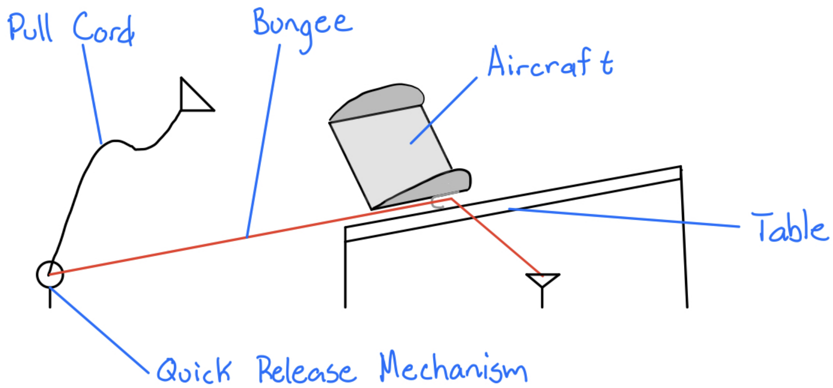

Figure 69. IRISS Table-Bungee Diagram

Table 110. IRISS Table-Bungee Pros and Cons

Pros	**Cons**
- Reliable - Accurate force measurements - Appropriate forces for aircraft - No team members immediately present - Simple mechanical design	- Hook must be integrated into airframe - Relatively high set up time

IRISS Hand-Bungee Method

This method is very similar to the Table-Bungee launch in that the bungee is pulled back to the desired, measured tension and then staked down through a quick release mechanism. The cord is again attached to the aircraft using an integrated hook, but instead of being placed on a table, the aircraft is placed in the hands of a designated team member. This member is not throwing the aircraft into the air, but instead is simply guiding the vehicle as the bungee propels it forward. An illustration of this launch method can be found in Figure 70, while pros and cons of the hand-bungee method are listed in Table 111.

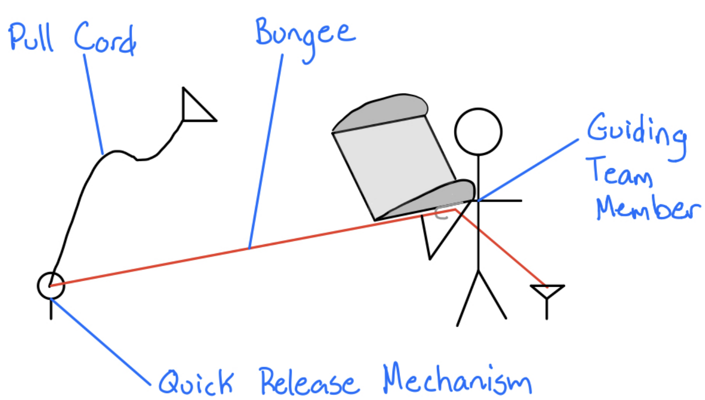

Figure 70. IRISS Hand-Bungee Diagram

Table 111. IRISS Hand-Bungee Pros and Cons

Pros	Cons
- Reliable - Accurate force measurements - Appropriate forces for aircraft - Simple Mechanical Design	- Team member must be immediately present - Hook must be integrated into airframe

RECUV Rail-Bungee Method

The RECUV team at CU Boulder uses a similar method to the two described previously. For this type of launch, a bungee cord is also used, although the tension in this cord is measured simply by feel. The bungee is then placed through an integrated hook on the airframe, and the aircraft is placed on a set of inclined rails. A team member holds the vehicle on the rails and then lets go, which allows the bungee to propel the aircraft up the rails and into the air. Figure 71 shows a visual representation of this system, while Table 112 shows the pros and cons.

Figure 71. RECUV Rail-Bungee Diagram

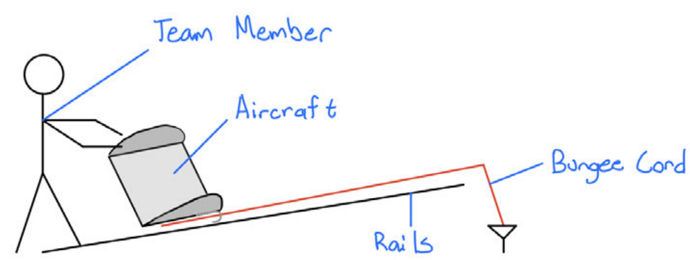

Table 112. RECUV Rail-Bungee Pros and Cons

Pros	Cons
- Reliable launches - Simple mechanical design	- Team member must be immediately present - No exact force measurement method - Lower force range than needed for aircraft - Hook must be integrated into airframe

Pneumatic Launcher Method

The existing pneumatic launching system used by CU Boulder teams is mounted on the roof of an SUV. Air is kept in a pressurized tank and slowly allowed into a secondary chamber where pressure builds until it reaches an appropriate value. Once this value is reached, the incoming flow of air is cut off, and the pressure in the chamber is then released in order to propel the aircraft up the launch rail. While the aircraft sits on this rail, it is supported by a simple L-shaped stand that works to keep it upright as it travels down the rail. A simplified diagram of such a system, along with a table of pros and cons, can be seen in Figure 72 and Table 113

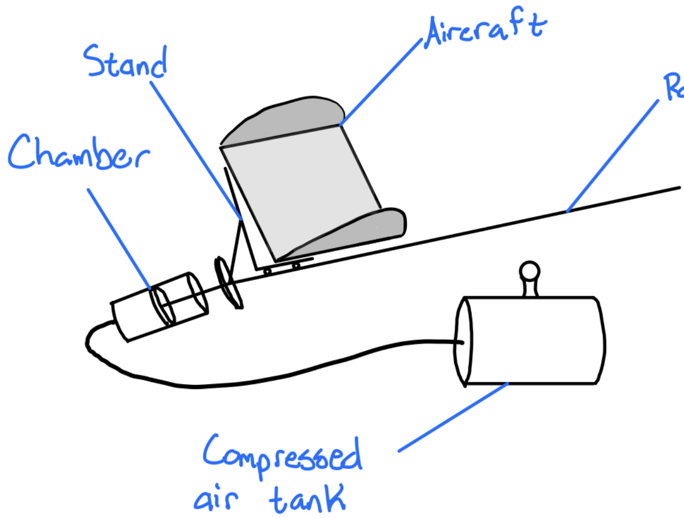

Figure 72. Pneumatic System Diagram

Table 113. Pneumatic System Pros and Cons

Pros	**Cons**
- Reliable launch speeds - Little modification needed to airframe	- Much higher forces than needed by aircraft - High mechanical complexity - Team member must be immediately present - Customer prefers not to use this method

Car Roof Method

This method is very straight forward. As the name implies, the aircraft is simply secured to the roof of a car. The car then drives down a straight road at the appropriate speed, and the clamps securing the aircraft to the car's roof are opened. The aircraft is then propelled into the air by its own motor and lift production. Once again, a diagram (Figure 73) and table of pros and cons (Table 114) is given for the car launch method.

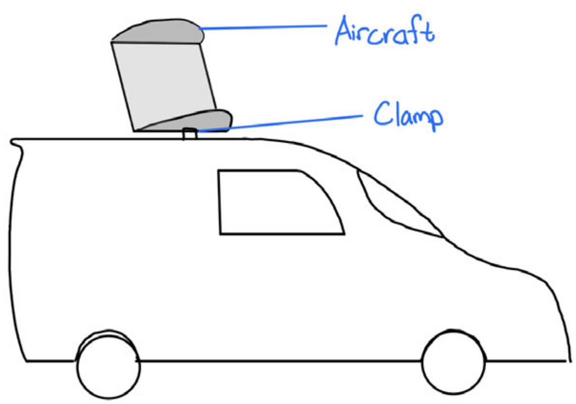

Figure 73. Car Roof System Diagram

Table 114. Car Roof System Pros and Cons

Pros	Cons
- Reliable launch speeds	- High stress on airframe - Unknown forces acting on aircraft - Restricted to launch only roads - Customer prefers not to use this method

Launching Method Trade Study

Criteria

Seven different criteria, shown in Table 115, were evaluated when considering different launching methods for the BUBO. These criteria were broken up into tiers based on importance, with these tiers then used to determine the respective weighting.

Table 115. Launch Method Criteria Weighting

Criterion:	*Launch Speed Reliability*	*Force Range*	*System Interference*	*Stress on Airframe*	*Number of Components*	*Cost of Replacements*	*Team Safety*
Weighting:	0.20	0.10	0.15	0.15	0.10	0.10	0.20

Launch Speed Reliability - The scoring for launch speed reliability is meant to encapsulate the accuracy and repeatability of the aircraft's speed at launch. This is closely related to how accurately the propelling forces can be measured, and how accurate of a model there is for determining the launch speed from these forces. The lowest expected score for this criterion corresponds to only knowing a rough order of magnitude estimate for launch speed (within 10 m/s), while the highest score corresponds to being able to predict launch speed to within 1 m/s. The ranges of certain launch speed reliability's were estimated using input from experienced RECUV and IRISS pilots who have previously operated the systems. These scores are shown in the following Table 116.

Table 116. *Launch Speed Reliability* Scoring Definition

Launch Speed Deviation (m/s):	*> 10*	*7.5-10*	*5-7.5*	*2.5-5*	*0-2.5*
Score :	1	2	3	4	5

Force Range - The scoring for force range of each launch system considered was based on how close the normal operating force of launch is to the estimated force needed to propel the aircraft into the air. After discussions with various experienced RC pilots, it was estimated that this vehicle will require approximately 40-50 lbf during launch. This was the value used in scoring as the baseline, "target" range, with deviations from this range assigned scores as laid out in Table 117.

Table 117. *Force Range* Scoring Definition

Force Range Deviation from Target (lbf):	*> 15*	*11-15*	*6-10*	*1-5*	*0 (force inside target range)*
Score :	1	2	3	4	5

System Interference - System interference scores were determined based on how many modifications had to be made to the airframe in order to accommodate the launch system, and if these modifications were fixed in position or could be placed in multiple locations on the airframe. This is reflected in the following scoring system shown in Table 118.

Table 118. *System Interference* Scoring Definition

Modifications Needed:	*3 variable location or 2 fixed location*	*2 variable location*	*1 fixed location*	*1 variable location*	*None*
Score:	1	2	3	4	5

Stress on Airframe - The scores for stress imparted by the launch method on the airframe were developed based on the advice and expertise of Christopher Choate, an experienced RC pilot at CU Boulder. Since extensive stress testing could not be performed for each launch method in the time allotted, the imparted stress was evaluated more qualitatively, with considerations taken as to how violent the launch is, how much force is involved, and what moments are imparted throughout the launch process. These all factor into the relative scoring system shown in Table 119.

Table 119. ***Stress on Airframe*** **Scoring Definition**

Anticipated Stress	*Highest*	*High*	*Moderate*	*Low*	*Lowest*
Score :	1	2	3	4	5

Mechanical Complexity - Mechanical complexity was evaluated by looking at how many moving parts each system uses, as well as how intricately these parts are combined to form the launch system. Without the time to fully examine each and every part of every system, this was evaluated using a relative scale shown in Table 120.

Table 120. ***Mechanical Complexity*** **Scoring Definition**

Mechanical Complexity	*Highest*	*High*	*Moderate*	*Low*	*Lowest*
Score :	1	2	3	4	5

Cost of Replacements - In order to score the replacement cost for components of each subsystem, the components with the highest chance of failing first had to be identified. Then, the cost of finding replacements or repairs was considered, and ultimately used to create a relative scale from most expensive system to least expensive, which is given in Table 121.

Table 121. ***Cost of Replacement*** **Scoring Definition**

Cost of Replacement	*Highest*	*High*	*Moderate*	*Low*	*Lowest*
Score :	1	2	3	4	5

Team Safety - One of the most vital aspects of this trade study, team safety scores were based on how many team members must be in the vicinity of the launch as it happens. If team members are needed nearby, the scores were further broken down by how much relative force is present in the launch system, which directly corresponds to how much risk the team member is exposed to. These scores were compiled by discussing the methods and failures with pilots experienced in using each launch system, and the exact scale is given in Table 122.

Table 122. ***Team Safety*** **Scoring Definition**

Team Safety	*2 members present*	*1 member present; high forces*	*1 member present; moderate forces*	*1 member present; low forces*	*No members present*
Score :	1	2	3	4	5

IRISS Table-Bungee Scores

Launch Speed Accuracy: **5** - Use of a force gauge allows for very precise knowledge of bungee tension, and launch speed can be easily obtained from this.

Force Range: **5** - Force range typically around 45-50 lbf, right in the desired range for this aircraft.

System Interference: **4** - Only needs one small hook located along center line of aircraft bottom, can be moved fore and aft to accommodate for other systems.

Stress on Airframe: **5** - Based on Chris Chaote's advice, this method supports aircraft while not overly imparting forces

Mechanical Complexity: **4** - Only quick release mechanism, bungee, pull cord and table needed, all of which are very simple in design.

Cost of Replacements: **4** - All components are fairly cheap to replace, with the table being the main concern should it fail.

Team Safety: **5** - Team members can all stand a safe distance away and simply pull the cord to launch.

IRISS Hand-Bungee Scores

Launch Speed Accuracy: **4** - Force gauge used similar to table-bungee system, but some uncertainty imparted by the use of a human to guide during launch.

Force Range: **3** - Hand-bungee method typically used for forces of roughly 30 lbf.

System Interference: **4** - Only needs one small hook located along center line of aircraft bottom, can be moved fore and aft to accommodate for other systems.

Stress on Airframe: **5** - Similar to table-bungee system, it was advised that this method does not impart a great deal of stress on the airframe.

Mechanical Complexity: **5** - This design is the most simple of all considered, needing only a bungee, quick release mechanism, and a pull cord.

Cost of Replacements: **5** - Due to the very simple design, replacement parts will not be at all expensive.

Team Safety: **3** - Team member must hold aircraft as it is launched, and is subjected to moderate relative forces in doing so.

RECUV Rail-Bungee Scores

Launch Speed Accuracy: **2** - Force in the bungee is simply measured by feel, not with any sort of gauge or other device. This translates to a large unknown when attempting to calculate speed.

Force Range: **2** - This launch system is estimated to usually impart about 20-25 lbf during launch

System Interference: **4** - Only needs one small hook located along center line of aircraft bottom, can be moved fore and aft to accommodate for other systems.

Stress on Airframe: **4** - Low stress imparted on airframe during launch, although having only two rails supporting near wingtips could impart bending moments near the aircraft's center.

Mechanical Complexity: **4** - Fairly simple set up, although rails need some bracing in order to support the load.

Cost of Replacements: **3** - Rail braces are manufactured out of ski poles, and rails themselves are fairly large and could be expensive to replace should they fail.

Team Safety: **4** - Team member must be present but is exposed to very little tension and therefore very little risk; teams have experienced failure with all members present and no injuries or concerns reported.

Pneumatic System Scores

Launch Speed Accuracy: **5** - Pressure gauge reading allows for accurate knowledge of forces being imparted, which can then be used to calculate launch speed.

Force Range: **1** - Forces typically used with pneumatic system are in the 350-400 lbf range, which is far above the desired range.

System Interference: **5** - Use of an L-shaped stand in theory should result in no modifications to be made to airframe.

Stress on Airframe: **1** - High forces and launch speed would impart entirely too much stress on airframe designed for low speed flights.

Mechanical Complexity: **1** - System is very complex with many components inside and outside of the car it is housed in.

Cost of Replacements: **1** - Pressure valves and tanks are expensive to replace, and rail system is custom built and fitted to the car used to deploy.

Team Safety: **2** - Team member must be on hand to flip switch, very close to components moving with high forces.

Car Roof System Scores

Launch Speed Accuracy: **5** - Car's speedometer should be accurate enough for desired launch speeds.

Force Range: **3** - Forces imparted by launching are hard to model and understand, but should be somewhat close to desired range.

System Interference: **2** - System requires something to clamp onto on either side of aircraft, which can be moved fore and aft.

Stress on Airframe: **1** - Aircraft sitting on top of car is subject to turbulent flow coming off of car's hood. Due to the large height of the aircraft, this would impart large moments on the sidewalls of the box-wing.

Mechanical Complexity: **3** - Must fit a clamps and supports to a car and design them to be operated from inside the vehicle.

Cost of Replacements: **2** - Design components wouldn't be extremely expensive, but there is the risk of crashing the car used which could significantly increase cost.

Team Safety: **4** - Team member must be present, but they are inside of the car and therefore are only subjected to the normal risks of driving.

Scoring Summary

Table 123 shows the scoring results for all 5 launch system options considered. As can be seen, the IRISS Table-Bungee system Scored the highest, and offers the best overall option when all criteria are considered. This method scored the highest in the two Tier 1 categories of launch speed accuracy, which were determined to be the two most important criteria in selecting a launching method for this project.

Table 123. *Launching Method* Trade Study Matrix

		IRISS Table-Bungee	**IRISS Hand-Bungee**	**RECUV Rail-Bungee**	**Pneumatic System**	**Car-Roof System**
Evaluation Criteria	**Weighting**	Score	Score	Score	Score	Score
Launch Speed Accuracy	0.2	5	4	2	5	5
Force Range	0.1	5	3	2	1	3
System Interference	0.15	4	4	4	5	2
Stress on Airframe	0.15	5	5	4	1	1
Number of Moving Parts	0.1	4	5	4	1	1
Cost of Replacements	0.1	4	5	3	1	2
Team Safety	0.2	5	3	4	2	4
Total Score (Normalized to 5)		**4.65**	**4.05**	**3.30**	**2.60**	**2.85**

Appendix B: Risk Matrix

Failure Mode	Severity (1-5)	Likelihood (1-5)	Risk (1-25)	Mitigated Risk (date)
Structural				
Damage on landing	3	2	6	
Damage on takeoff	3	4	12	9 (12/2)
Damage in cruise	5	1	5	
Spiral stability	4	1	4	
Dutch roll stability	4	3.25	13	8 (12/2)
Roll stability	4	1	4	
Tumble stability	4	4	16	8 (12/2)
Electronic				
component overheat	3	2	6	
LiPo puncture	4	2	8	4 (1/20)
Radio glitch (connection failure)	2	3.5	7	
Surge cascade	5	1	5	
GPS lock loss	4	2	8	
IMU drift leading to autopilot loss of control	5	1	5	

Figure 74. Risk Matrix

Failure Mode	Severity (1-5)	Likelihood (1-5)	Risk (1-25)	Mitigated Risk (date)
Manufacturing				
Repairs > 15 minutes	3.5	2	7	
Personnel injury	5	1	5	
Improper securing	3	2	6	
Tolerancing error	3	3	9	
Quality of building	3	2	6	
Takes a lot longer than expected	3	2	6	
Machinery unavailable	3	2	6	
Propulsion				
Motor failure	5	1	5	
Propeller failure	5	1	5	
Software/Controls				
Data collection doesn't start	2	2	4	
Control gains are very wrong	4	2.5	10	
Data doesn't save	2	2	4	
Data overwrite	2	2	4	
Coding software takes longer than expectec	3	2.5	7.5	

Figure 75. Risk Matrix continued

Failure Mode	Severity (1-5)	Likelihood (1-5)	Risk (1-25)	Mitigated Risk (date)
Logistics/Procurement				
Parts cannot get here in time	4	2	8	
Parts we get are not what we want	4	1	4	
Don't get EEF funding	3	1.5	4.5	
Stuff we need is too expensive	3.5	2	7	
Needing to replace damaged equipment/pa	3	2	6	
Parts dead on arrival	3	1.5	4.5	
Parts out of stock/on backorder	3	2	6	
CAD design pushes back manufacturing	3	2	6	
Wind tunnel not available for testing	2	2.5	5	
and car tests not approved	5	2	10	6 (3/1)
Propulsion testing issues	3	2	6	4 (3/1)

Figure 76. Risk Matrix continued