University of Colorado
Department of Aerospace Engineering Sciences
Senior Projects - ASEN 4018

Project Final Report Report

(NESSIE)

Neutrally-buoyant Elevated System for Satellite Imaging and Evaluation

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Project Customers

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1. Project Purpose

Author 1: Paul McClernan, Author 2: José Cardenas Abedrop

Space Domain Awareness, SDA, (formerly Space Situational Awareness, SSA[2]) is an increasingly important field to enable continuing satellite operations. As the number of new satellites and debris from launches and collisions increase with time, tracking these objects becomes more important to allow continued access to space, providing the benefits of modern lifestyle. This essential task requires a large network of sensors which currently consists of ground-based radar stations and telescopes. These sensors constantly take data of the sky, detect both known and unknown objects, catalog them, and update the estimation of the object's orbit for future position propagation[3]. To meet the growing demands, SDA networks need to increase their sensor capability as much as possible[1]. This is where Dr. Holzinger's MANTA concept fits in.

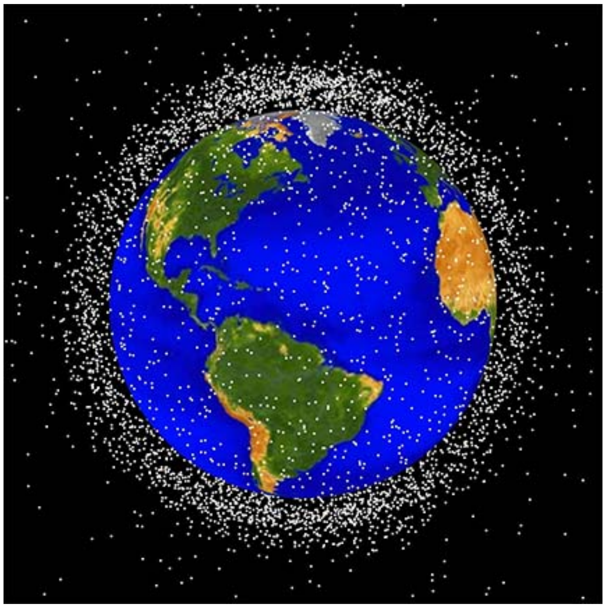

Fig. 1 Nasa estimates there being over 500,000 objects in orbit around Earth[1]. Image from www.nasa.gov

MANTA is a small scale telescope platform for SDA with one novel characteristic, it is placed on a lighter-than-air vehicle with the capability to ascend to approximately 18,000 ft. This gives two distinct advantages: First, MANTA takes an SDA sensor above the most optically detrimental cumulus and stratus clouds in the lower atmosphere[4]. Since normal telescopes rely on clear weather to operate to full capacity, this means that MANTA could either be deployed when a main telescope station is occluded by clouds to reduce the influence of weather, or flown as additional independent SDA sensor. The second advantage is the flight altitude inherently removes 18,000 ft of atmospheric distortion, which places MANTA's telescope higher than any ground-based telescope in the world[5]. As a first step to achieve MANTA's goals, NESSIE (Neutrally-buoyant Elevated System for Satellite Imaging and Evaluation) is a student-built 1:2.5 scale model of MANTA which strives to prove the feasibility of the vehicle's design and quantify the expected vibrational environment that MANTA's stability system needs to compensate for to allow useful images to be taken. NESSIE is an exotic airship that mostly consists of a 20 ft, outer diameter, and 10 ft inner diameter, torus-shaped gas envelope. This unique shape allows a minimum 100°field of regard (FOR)* of the sky to be visible to the payload. NESSIE does not carry a telescope or a stability system, but allocates a defined payload capability for a scaled telescope payload.

*Note the differentiation between field of regard (FOR) and field of view (FOV). For the purposes of this document, FOR is used for the angle in which the telescope has the capability to point, and FOV refers to the actual telescope's boresight angle.

2. Project Objectives & Functional Requirements

Author 1: Paul McClernan, Author 2: José Cardenas Abedrop, Author 3: William Newman

In order to define exactly what must be accomplished in this project, several different approaches were used as metrics. Following in this section, these methods will be detailed. First is the project's levels of success. The system was designed around these levels, which were based off the customers requirements, as well as CONOPS diagrams which were developed early on in the design. An explicit list of project deliverables to the customer is presented. Following is a functional block diagram showing where NESSIE fits into the full design, and which components were purchased versus developed by the project team. The section concludes with a list of the formal functional requirements that the team used to design the system.

A. Levels of Success

To quantify the success of the project, the levels of success, following in table 1, were formalized early on in the problem definition phase. They did evolve over time as the problem was better understood, but have largely stayed the same. The process by which each level was written follows the following methodology. Level 1 should give base functionality, level 2 should show full functionality, level 3 should show integrated functionality and prove scalability of NESSIE to the full scale MANTA project where applicable.

	Level 1	Level 2	Level 3
Flight	Design and build an FAA-compliant vehicle for an airworthiness test by takeoff, fly at 10 ft AGL† and land.	Build an FAA-compliant vehicle, takeoff, fly at 400 ft AGL, and land.	Build an FAA-compliant vehicle, takeoff to 400 ft AGL and land within a radius of 300ft of takeoff location.
Controls	Stay within 100 ft of target altitude, prove ability to correct vertical position within 10 ft in under 200s	Stay within 80 ft of target altitude, prove ability to correct vertical position within 10 ft in under 150s. The aircraft is stable under 5mph gusts	Vertically stay within 50 ft of target altitude, prove ability to correct vertical position within 10 ft in under 80s. Fly at 400 ft, then prove analytically it could be stable at 18,000 ft.
Landing	Land with no damage that hinders the operation of the craft after flying at 10 ft AGL	Land with no damage that hinders the operation of the craft and within communication range of ground-station after a >100 ft AGL flight	Land with no damage that hinders the operation of the craft within 300 ft of ground station after a >300 ft AGL flight.
Observation Uptime	The vehicle is capable of providing power and system operations allowing 20 minutes uptime	The vehicle is capable of proving power and system operations allowing 35 minutes uptime	The vehicle is capable of providing power for 55 minutes uptime proving minimal power consumption at target altitude and the benefit of lighter-than-air vehicle.
Telemetery	Establish a link between the groundstation and the vehicle on the ground that allows for vehicle control and guidance	Establish a link between the groundstation and the vehicle at 400 ft that allows for vehicle control and guidance	Use the established link to transfer >2KB/s of customer data

Table 1 Levels of success were developed in 5 different areas of NESSIE. The minimum requirement for project success is meeting the first level in each category.

B. Concept of Operation Diagrams

The concept of operations, otherwise known as CONOPS, breaks down what a successful mission looks like, visually and graphically, in an easy manner. We first gathered the requirements from Professor Holzinger, then designed the CONOPS for the original project, MANTA. As can be seen in figure 2, the mission begins with no more than three personnel, who can load the craft up and bring to a launch location. These personnel will then assemble and launch the craft, which will ascend to 18,000 ft MSL and conduct SDA operations. This involves measuring the angular locations of satellites (Right ascension and declination) within 10 arcsecond accuracy, 3 σ precision. The optical system should be capable of detecting objects at an apparent magnitude of +13 (very dim). This information is sent back to the ground station by radio, along with mission telemetry. The craft will remain operational from dusk to dawn with a 14 hour max flight time, staying within a 30 mile range of base operations. Once the night is over, it descends back to the launch location, where all onboard copies of the data will be collected and stored for post-processing. The vehicle is disassembled, repacked, and transferred to its storage location.

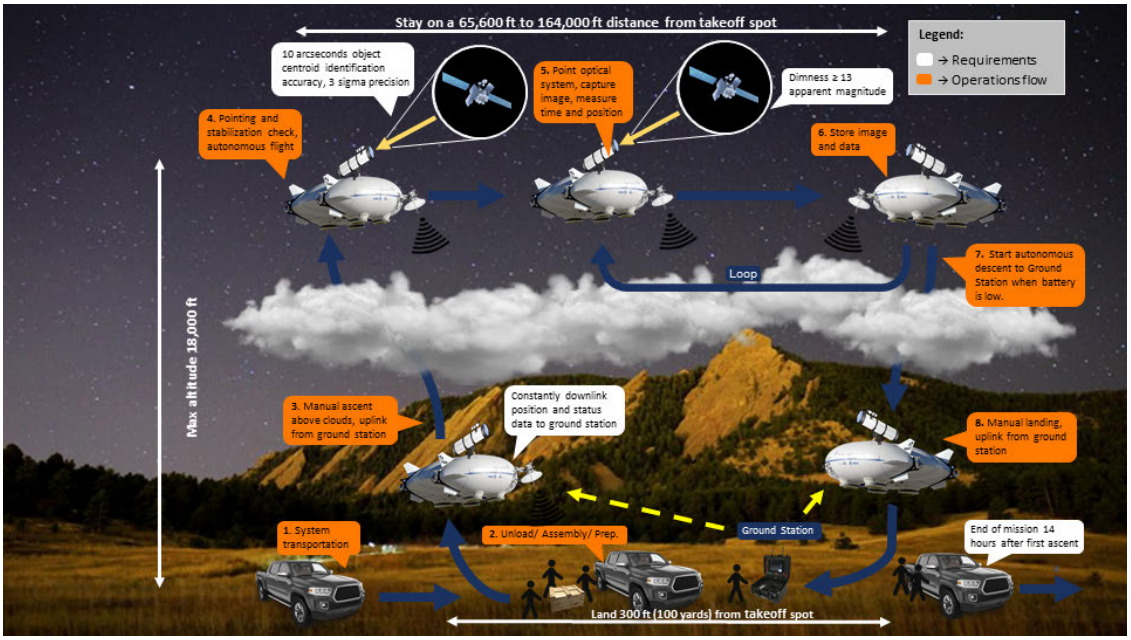

Fig. 2 MANTA's Concept of Operations. This includes travel to takeoff location, takeoff, a full SDA mission, landing, and aircraft retrieval.

After the project was descoped to be more accomplishable in a student project budget and time frame, the resulting project focused on designing and building the aircraft, which will be a platform with the capability to carry an optical system. NESSIE is a 1:2.5 scaled version of the craft MANTA will use, and demonstrate the vehicle's design usability for the MANTA. As shown in figure 3, NESSIE's mission begins by driving the craft to a launch facility, where the airship is assembled and launched. The craft will ascend up to 400 ft AGL, while testing and validating controllability and telemetry transmission/receiving. Once at 400 ft, the craft will then collect data from its on-board inertial measurement unit, or IMU. This data is transmitted along with telemetry to the ground station continuously. Once the battery gets low (40 min) the craft will then descend back down to the launch location, where the data will be downloaded and saved for post-processing. The planned margin on battery is 20%.

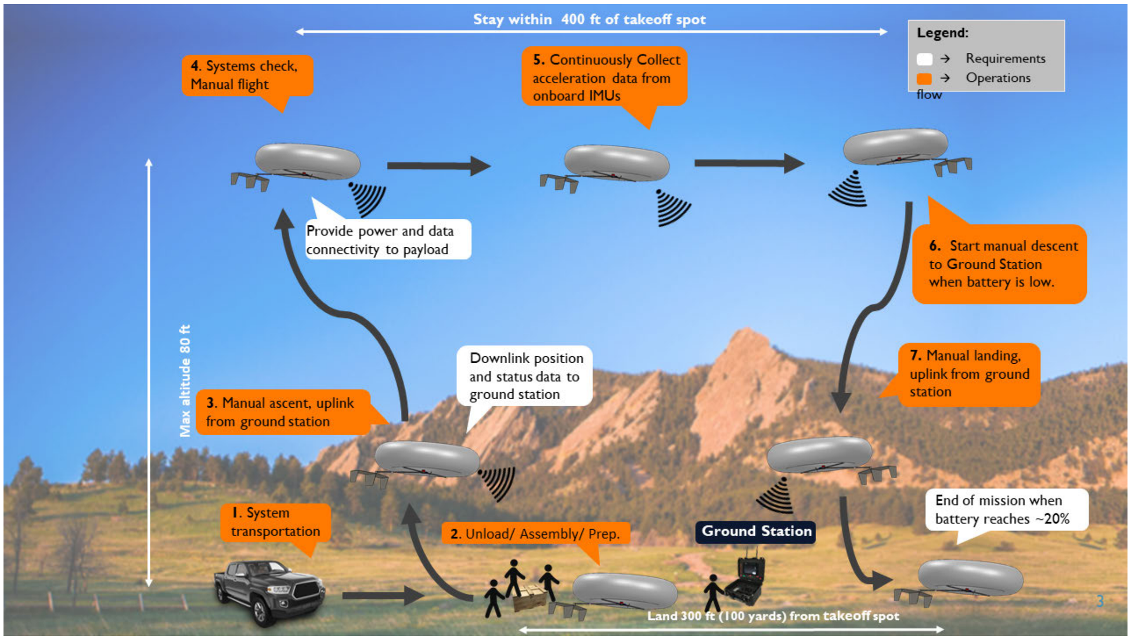

Fig. 3 NESSIE's Concept of Operations. This includes travel to takeoff location, takeoff, landing, and aircraft retrieval. NESSIE's CONOPS differs from MANTA's in the range of flight and the activities preformed while airborne.

C. Project Deliverables

The project had the following deliverables for the class and to the customer. Note that the customer deliverables were unfinished due to COVID-19 closures. Each of the reports generated for the class sought to develop the design and to demonstrate the current state of the project. The customer deliverables: the airship is self-explanatory. The "Path forward to full-scale document" was developed so that the path was clear from NESSIE to MANTA. This would have detailed the legal necessities to fly, including the necessary legal regulations of the FAA and the waivers that would need to be secured(flying unmanned at night, out of line of sight, etc). This document would also have included the needed design scaling, and the potential recommended design changes for full scale (including using internal gas cells instead of a simple balloon, among others)

1. Class Deliverables

- Problem Definition Document
- Conceptual Design Document
- Preliminary Design Review
- Critical Design Review
- Fall Final Report
- Manufacturing Status Review
- Test Readiness Review
- Final Oral Report
- Project Final Report

2. Customer Deliverables

- NESSIE Airship‡
- Path forward to full-scale document‡

D. Functional Block Diagrams

The next figure displays NESSIE's functional block diagram, which is split into the aircraft and the groundstation diagrams. The limits of NESSIE's scope are shown with dotted lines. The aircraft block begins with the radio connection to the groundstation. This link enables a telemetry downlink which gives the vehicle's current position and payload data to reach the groundstation. The uplink allows commands to be sent to the aircraft. The radio and antenna are connected to the command and control block which is composed of a Pixhawk 4 Mini flight controller, and its GPS unit. The vehicle is moved by the vehicle atmospheric control block, which contains the servos that deflect NESSIE's tail elevators, and the ESC's that control the propulsion motors. The entire system is controlled by the Power supply block which has a LiPo battery and a low voltage power distribution board, which gives 5V power for other smaller components. The out of scope section is the stabilized telescope system.

The groundstation block can also be described starting with the uplink and downlink radio block. This serves the purpose discussed above. The uplink sends commands to the aircraft, and the downlink receives telemetry and payload data. These commands originate from a handheld RC controller and are processed through Mission Planner on the ground station computer. This is also where the telemetry is displayed to the pilot, and where the payload data is decoded and stored. The out of scope section of this half excludes the telescope tasks that would have been sent to the optical payload.

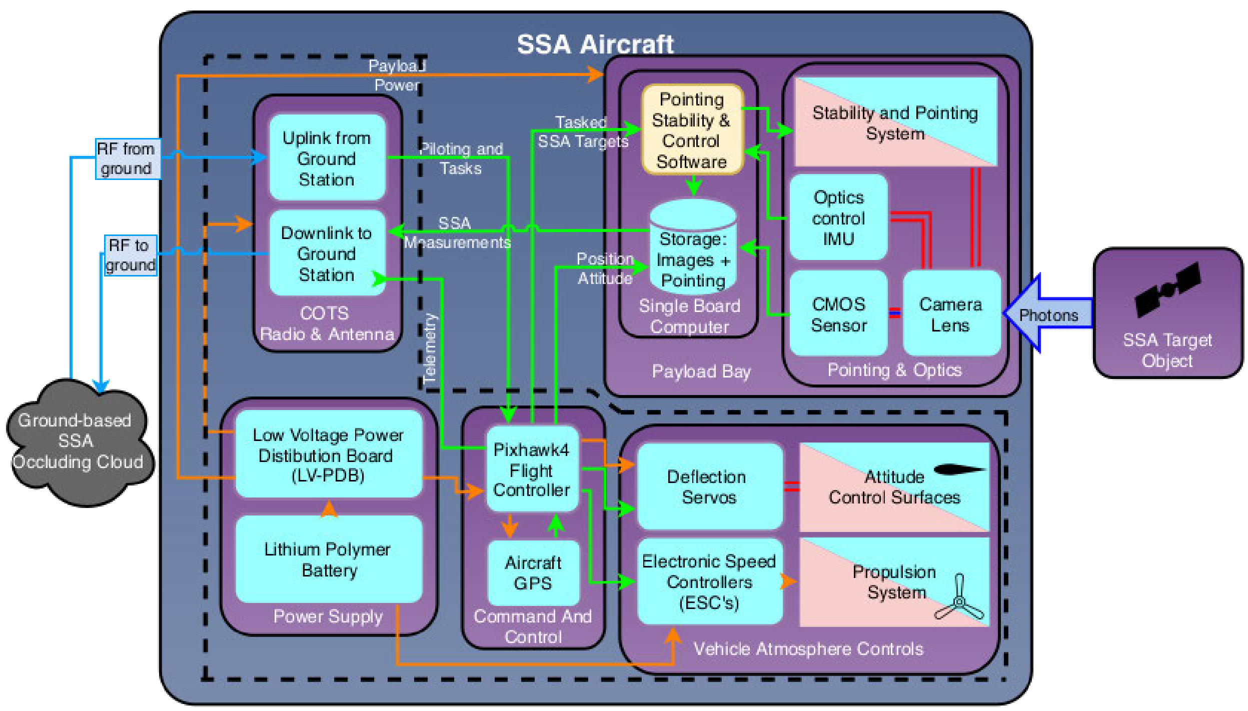

Fig. 4 Functional block diagram for MANTA. NESSIE will not have any components besides an IMU and SD card in the payload bay, and will not be imaging any targets. Otherwise they have identical FBDs.

‡Unfinished due to COVID-19 closures

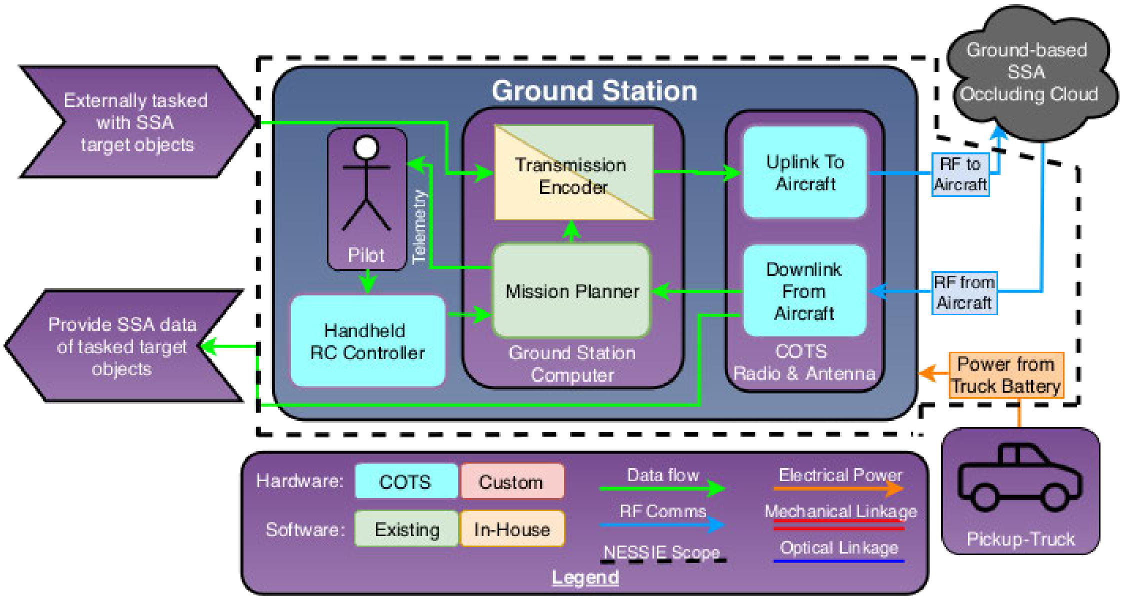

Fig. 5 Functional block diagram for the ground station that will be used for communicating with NESSIE.

E. Functional Requirements

Following are the functional requirements developed for the project. Each had several design requirements associated.

FR 1: System shall be capable of supporting a scaled payload that could collect the necessary image data to allow for initial orbit determination.

Motivation: In order for a full scale payload to take measurements with 10 arcsecond object centroid accuracy and to capture objects with 13 apparent magnitude[§], the system must provide the payload with enough angular stability for the image to be captured within the given requirements. In addition to stability performance, the payload must also be provided with enough power and space, as well as sufficient weight and communication capabilities.
Validation: The following payload specs are met: DR 1.1: System shall minimize vibration frequencies greater than 6.7Hz for the payload. DR 1.2: System shall dedicate 1 lbs to the payload DR 1.3: System shall provide 5.57 W to the payload. DR 1.4: System shall provide a cubic shaped payload bay with 4.87" length sides to house the optical system during operation.DR 1.5: Payload space shall provide a housing location where an optical system would have a field of view (FOV) over 100 degrees.

FR 2: System shall be capable of operating at 400 ft

Motivation: The system needs to to fly at a height that it can test the capabilities of the controls, station keeping, and vibration mitigation systems. 400 ft is the maximum height we are allowed to fly according to FAA regulations.
Validation: Demonstration: The system will be flown at 400 ft.

FR 3: System shall be capable of attaining a specified altitude and station keeping, within a certain range, at that altitude.

[§]These are the levels of accuracy requested by the customer in order to capture useful data.

Motivation: The aircraft should be capable of reaching an altitude of 400 ft. When the desired altitude is reached, it needs to be able to maintain its location within a specified range so it can simulate collecting several images in a single flight and remain in communications range with the ground station.

Validation: Demonstration: A test launch will be performed in Spring 2020 to an altitude of 400 ft. The aircraft will constantly log its location data during this test flight. During post-processing this data will be compared to the desired altitude and location expected by the flight team.

FR 4: System shall transmit status and location data to the ground station and also receive control instructions from the ground station.

Motivation: The aircraft and the ground station need to be able to communicate to enable vehicle and data recovery.

Validation: Test: Before any test launches the team will attempt to communicate with the aircraft from the ground station. The aircraft will transmit location and status updates to the ground station. The ground station will transmit flight instructions to the aircraft. If the data received by one system is the same as the data transmitted by the other system, then the systems are properly transmitting and receiving data from each other.

3. Design Process and Outcome

Author 1: Evan Vavpetic, Author 2: Cavan Roe, Author 3: Paul McClernan, Author 4: Richard Weir

When given a problem it is the engineers job to meet or exceed all requirements given by the customer or provide substantial engineering reasoning as to why they cannot be met. The following subsections will walk through how the final design was chosen. Explaining important choices and design parameters. This section will also explain how the requirements satisfied by the design choices were selected.

A. Conceptual Design Alternatives

Given the complexity and novelty of the solution required for this design problem, many conceptual design alternatives were considered. The methodology for trade studies completed for each aspect of the baseline design are summarized below. The actual trade studies can be found in the appendix.

1. Vehicle Type

Vehicle type was one of the most significant design decisions made for this project, as this decision affected other design areas significantly. After descoping the mission from MANTA to NESSIE early in the design process, three alternatives were considered for the vehicle type, those three being: fixed-wing, blimp, and dynastat. The fixed-wing and blimp designs are relatively straightforward, while the dynastat is slightly more complex as it is a hybrid airship with fixed wings that generates some lift from use of a lifting gas and some from aerodynamic lift. The metrics and weights used to perform this trade study are shown in Table 2.

Metric	Stability	Weight	Flight Time	Ease of Integration	Design Complexity	Cruise Speed	Cost	Controllability
Weight	0.18	0.18	0.12	0.12	0.12	0.1	0.1	0.08

Table 2 Metrics and associated weights for vehicle type trade study

Stability and weight were the two most important metrics for this design choice. As such, the blimp scored highest in this trade study as the weight would be able to be reduced significantly by utilizing a lighter-than-air airship design and having the gondola located underneath the lifting gas made the design inherently more stable than a fixed-wing aircraft. Specifically, it was decided that a toroidal envelope would be used for the blimp so that FOR for an optical payload mounted in the gondola would be optimized.

2. Propulsion Type

The type of propulsion system the vehicle would make use of was the next most crucial design decision, as many of the alternatives were complex. The different design alternatives considered were: a pressurized balloon with a pressure regulator, rigid vertical rotors, a combination of a pressurized balloon and vertical rotors, and standard fixed wing propulsion. The metrics and weights used to perform this trade study are shown in Table 3.

Metric	Power/Fuel Consumption	Controllability	Risk	Weight	Ease of Integration	Design Complexity	Cost
Weight	0.2	0.2	0.15	0.15	0.1	0.1	0.1

Table 3 Metrics and associated weights for propulsion type trade study

A combination of a pressurized balloon and vertical rotors scored highest in this trade study, as the vertical rotors provided sufficient attitude control, while the use of the lighter-than-air envelope minimized weight. This trade study initially assessed a tilt rotor option, back in the Fall. It was thrown out even though it had a high score for feasibility, because the team did not believe it would be possible to integrate. This Idea came back in the spring semester when the need for a horizontal force was required. A tilt rotor and a pressurized balloon provided the perfect control both vertically and horizontally. The team reached out to several professors to ensure this was a possibility as well as several models proving it was would provide the level of control required.

3. Control Input Type

The vehicle needed to have control inputs so that it could take off and land in a specified area, as well as fight against wind gusts. Only three design alternatives were considered for a method of inputting controls to the vehicle. Those alternatives were: manual control, autonomous control, and a hybrid of manual and automatic control. The metrics and weights used to perform the trade study for this design element are listed in Table 4.

Metric	Assembly Complexity	Availability	Controllability	Cost	Risk
Weight	0.3	0.25	0.2	0.15	0.1

Table 4 Metrics and associated weights for vehicle control input trade study

A manual controller scored highest in this trade study as manual controllers are widely available as COTS kits and are low-risk due to how often they are used in industry and hobbyist projects. Ideally, the vehicle would have some form of autopilot to decrease pilot workload, but designing an in-house autopilot was deemed out of the scope of this project.

4. Flight Controller

While a wide variety of flight controllers are available for purchase directly off the shelf, processing capability and power requirements were especially important for this design due to the need to minize weight. Thus, only the three most applicable flight controllers were considered, those being: the Pixhawk 2 Cube, the Ppz Chimera, and the Pixhawk 4. The metrics and weights used for the flight controller trade study are shown in Table 5.

Metric	MCU Processing Speed	Input Voltage	Software Availability	Reliability	Weight	Cost
Weight	0.3	0.3	0.2	0.1	0.05	0.05

Table 5 Metrics and associated weights for flight controller trade study

Originally, the Pixhawk 4 scored highest in this trade study due to relatively low input voltage requirement and its class-leading MCU processing speed. However, the descope that took place after PDR there was even less space to mount the flight controller in the gondola. Consequently, the Pixhawk 4 Mini was selected as the flight controller for this project as it had all of the same capabilities that were required but can in a smaller form factor than the Pixhawk 4.

5. Power Supply

Everything onboard the vehicle was to be powered by a battery, so selecting the best alternative was of extreme importance. A unique constraint was that the selected battery needed to perform well in cold temperatures, as the operational environment of the vehicle often included night flying at high altitudes. Three battery types were considered: lead acid, lithium ion, and nickel. The metrics and weights used for this trade study are listed in Table 6.

Metric	Weight	Maintenance	Cost	Volume	Capacity at Low Temperatures
Weight	0.3	0.2	0.2	0.15	0.15

Table 6 Metrics and associated weights for battery trade study

The lithium battery scored highest in this trade study due to their relatively low weight, their minimal requirement for maintenance, and most of all they have the highest percentage of available capacity at low temperatures.

6. Other Aspects of the Baseline Design

Aside from these design alternatives that were traded on, there were a few aspects of the baseline design that were simple enough that no trade studies were necessary. For example, inertial position determination was a key part of the design, but it was clear that using a COTS GPS device was the best choice due to their proven capability and common application. Additionally, attitude determination and control was also a key element of the baseline design. The Pixhawk 4 Mini flight controller came with onboard gyroscopes, so it made the most sense to use them as they were already accounted for in the mass budget.

B. Requirements Flow-Down

1) **Functional Requirement 1: System shall be capable of supporting a scaled payload that can collect the necessary image data to allow for initial orbit determination.**

The final MANTA product needs to be capable of supporting a telescope capable of SSA. To ensure this being a possibility, preliminary research was done on possible options for the optics system. It needed to be both lightweight and powerful enough for seeing orbiting objects with an apparent magnitude of at least 13 with 3-sigma precision. Equations from *Astronomical Optics* were used to get lower and upper bounds on an equation for apparent magnitude:

$$m_{upper} = -2.5log\left[\frac{SNR^2}{0.7N_0\kappa\tau\Delta\gamma D^2Qt}\right] \tag{1}$$

$$m_{lower} = 0.5m' - 2.5log\left[\frac{SNR^2\phi^2}{0.7N_0\kappa\tau\Delta\gamma D^2Qt}\right] \tag{2}$$

In these equations, m is apparent magnitude, SNR is the optic sensor's signal-to-noise ratio, N_0 is constant equivalent to the measure of photons per second per square centimeter, κ is a transmittance modifier, τ is the system transmittance through the atmosphere, $\Delta\gamma$ is the bandpass of the sensor, D is the lens diameter, Q is a measure of quantum efficiency, t is the capture time, and m' is the sky's apparent magnitude. Using the assumptions and constant values from *Astronomical Optics*, a range of ideal optics parameters were created. Using the final results from this analysis, three viable telescoping lenses were found. ¶

Fig. 6 Sigma - Art 85mm F1.4 DG HSM | A Standard Prime Lens for Nikon DSLRs

Fig. 7 Sigma - 60-600mm f/4.5-6.3 DG OS HSM I S Optical Telephoto Zoom Lens for Nikon F

Fig. 8 Orion SkyScanner 100mm TableTop Reflector Telescope

The cameras weighted up to 6 lbs and the largest was 8 inches long.
Next the team examined a plethora of optics sensors of various sizes and capabilities. The sensors all were quite small; all of them weighed below 2 lbs and none exceeded 2 inches.
Finally the team had to look at slewing capabilities for a mounted camera system. Due to the small yet constant perturbations expected at 18,000 ft AGL, a gimbal system was likely the best solution for this problem. The team recommends creating a 3 axis gimbal from scratch in order to meet the required precision and fit in a small area. Gimbal motors can weight up to 1.1 lbs each, giving a combined weight of 3.3 lbs when working with 3-axes.

¶Lenses found at https://www.bestbuy.com/site/sigma-art-85mm-f1-4-dg-hsm–a-standard-prime-lens-for-nikon-dslrs-black/6000901.p?skuId=6000901, https://www.bestbuy.com/site/sigma-60-600mm-f-4-5-6-3-dg-os-hsm-i-s-optical-telephoto-zoom-lens-for-nikon-f-black/6339428.p?skuId=6339428, and https://www.telescope.com/Orion-SkyScanner-100mm-TableTop-Reflector-Telescope/p/102007.uts

Using the specs found for these three components and adding an additional 15% margin to any final values, parameters for a payload bay capable of housing the optics system were derived.
Lastly these parameters had to be scaled down in order for our model to be a reasonable approximation of the full-scaled system. Since weight is the largest limiting factor on the scale model, this was the initial parameter to be scaled down. The scaling was done using a method outlined in the report "About The Size of It" by Bradford W. Powers. In this report a number of possibly scale-able items are given corresponding scale factors in the format K^x, where K is the scale factor and x is based on the exact item being scaled. This method is able to scale model aircraft such that they remain dynamically identical at scaled sizes. This process resulted in a scaling factor of 2.4662, which was used to scale down any full-scale payload parameters.

Design requirements for FR 1

1) DR 1.1: System shall minimize vibration frequencies greater than 6.7Hz for the payload.
   Motivation: In order to allow the payload to effectively capture images, vibration of the optical system must be minimized. In particular, high frequency vibrations need to be minimized to allow the optical system to effectively capture images.
   Verification: *Test* - The system shall minimize frequencies greater than 6.7 Hz during image capture mode.

This requirement was derived based on a simulation of an ideal exposure of an object. The object image was varied in angular position on a simulated sensor to approximate vibration. The different positions of the object during the collection led to different outputs once digitized. The discrepancy between the ideal centroid at the center and the derived centroid based on a weighted average of the pixels is calculated for various frequencies. The object image size was assumed to be the minimum angular size of an object as given by the diffraction limit. This is defined by the following equation.

$$\theta = 1.22\lambda/D \tag{3}$$

Where λ is the wavelength of light, D is the aperture diameter, and θ is the minimum angular *radius* of the object on the sensor. These values were assumed to be λ = 650nm, D =10cm, and resulted in θ = 1.664 arc-seconds. This wavelength corresponds to the peak of the solar spectrum, which is the spectrum that is reflected off of satellites for the purposes of SSA. The aperture diameter is derived in a requirement below. The simulated sensor was 5x5 pixels, with square pixels measuring 10 arc-seconds on a side. This is a slight underestimation of typical sensor angular resolution (typically it is $\tilde{3}$-5 arc-seconds). Most real sensors found were 12 bit or higher, 12 bit pixels were used (i.e. each pixel had a value in the range of $\in \{0, 2^{12} - 1\}$). As for the vibration simulation, the x and y angular positions were varied from the center of the sensor according to a circular vibration given by

$$\delta x = K \cos 2\pi f + \phi \quad \delta y = K \sin 2\pi f + \phi \tag{4}$$

Where K is the amplitude of vibration, which was taken to be 10 arc-seconds (derived from customer requirement), f is the frequency of oscillation in Hz, which was varied from 0.1 to 5Hz, and ϕ is the phase offset. Two simulations were done, one in-phase(ϕ = 0) and one out-of-phase ($\phi = \pi/2$). Each simlation was iterated for the exposure time of 1 second, which is derived below. To better illustrate the simulated sensor, two plots highlighting the path of the object are shown below. The first is at a higher frequency, and the second is at a lower frequency.

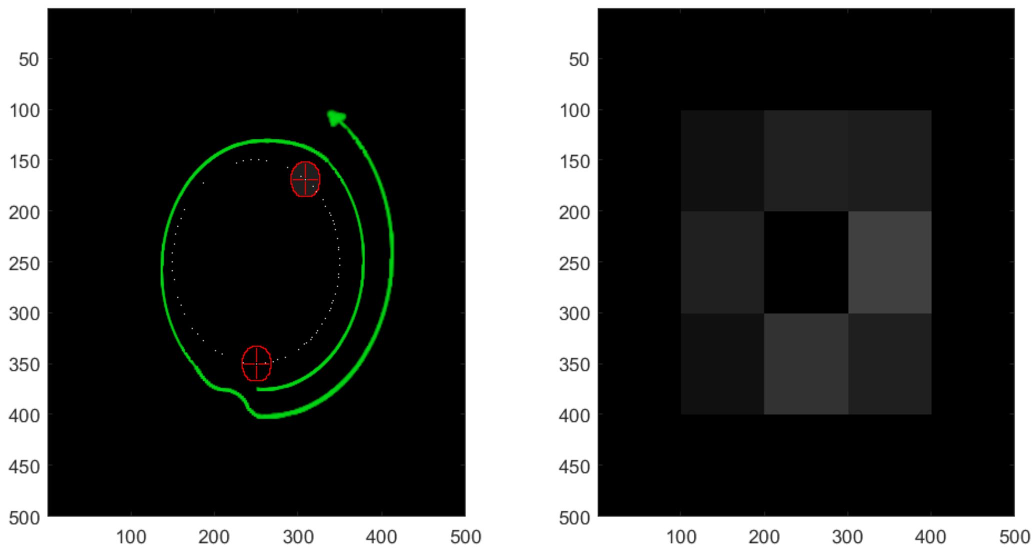

Fig. 9 Representative simulated pixel map with high frequency circular vibration

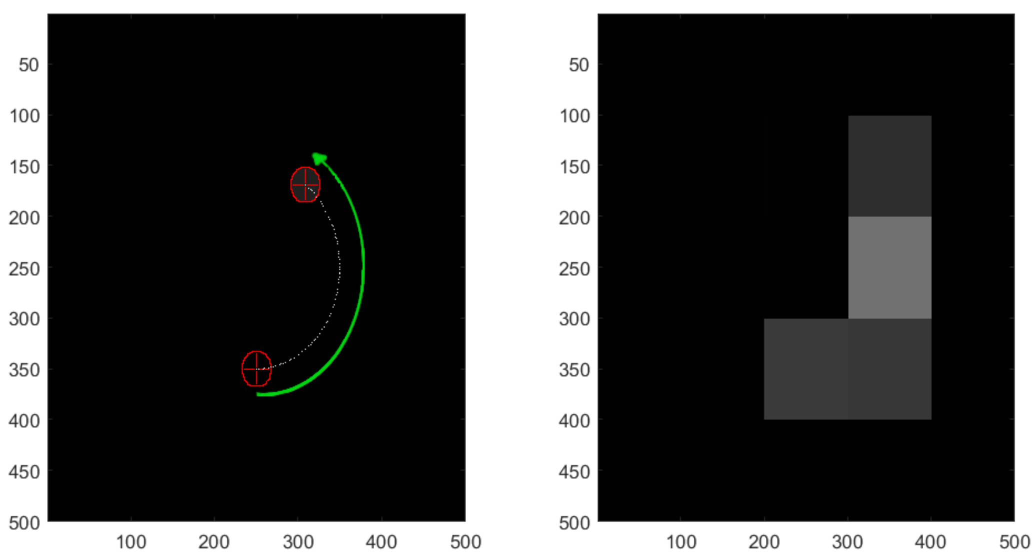

Fig. 10 Representative simulated pixel map with low frequency circular vibration

Note that in these images, the ideal centroid is in the center of the image. It can be easily seen that a lower frequency path inherently adds more error to the centroid estimation. Even though the first figure has some error associated, it is mitigated by the fact that it has completed at least one full cycle. A full accounting of the errors by frequency is shown below. This is compared with the customer requirement of 10 arc-second 3σ centroid determination.

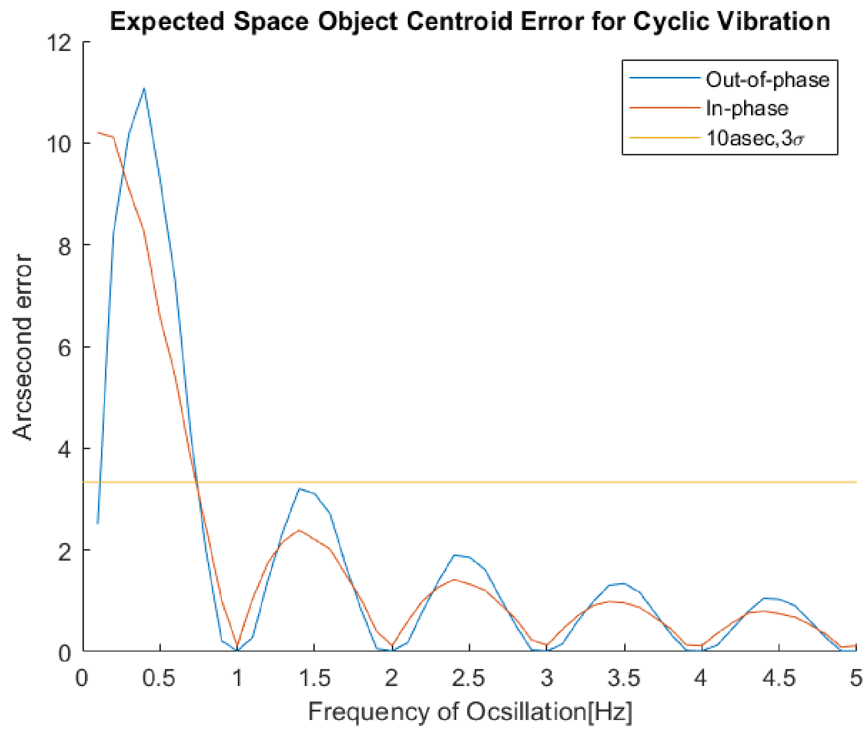

Fig. 11 Representative simulated pixel map with high frequency period

Based on this plot, the only vibrations that need to be removed are those below 1 Hz. Everything else is an acceptable amount of error. Based on the capabilities of typical gimbal motors (high end motors can operate in the range of 300-400 rpm (5-6.6 Hz)) this 1 Hz requirement is reasonable. Since the 1 second exposure time and corresponding 1 Hz vibration requirement was derived for the full scale MANTA vehicle, for NESSIE, it must be scaled down. NESSIE utilizes a linear scaling factor of K=2.446. Given that time scales with $K^0.5$, this means that the error frequency scales with the inverse of that. Carrying this out gives the result of 6.7 Hz.

2) *DR 1.2: System shall dedicate 1 lbs to the payload

Motivation: In order for the full scale system to be able to have a sufficiently accurate payload, it must dedicate 15 lbs of the takeoff weight towards the payload. For the scale model, this can be linearly scaled down to 1 lbs to represent the system carrying a standard payload.

Validation: *Test* - The system shall carry a 1 lb weighted object during test flights.

Telescope	6 lbs
Optical Sensor	2 lbs
Gimbal Motor (x3)	3.3 lbs
Additional Electronics	1.7 lbs
15 % Margin	2 lbs
Total	**15 lbs**

Table 7 Summation of optical components' weights

15 lbs is too heavy for this senior project because:

- The FAA currently only allows UAVs with a gross take-of weight below 55 lbs
- You would need about 240 liters of helium to just lift 15 lbs, even thought this weight doesn't include that of the gondala, control devices, electronics, and the balloon envelope. This much helium alone would cost approximately $1200.

The weight was lowered to 1 lb because 1 lb is fairly easy to lift using helium, and an integer valued weight is easy to understand and covey to others.
This scaling from 15 lbs to 1 lb is how the scaling factor of 2.446 was derived

$$K^3 = \frac{15}{1}$$
$$K = 2.446$$

3) DR 1.3: System shall provide 5.57 W to the payload.
   Motivation: In order for the optical payload to function it needs power. Since the aircraft itself already has power of its own and will have power distribution boards, it is more convenient for the aircraft to supply power to the optical payload to reduce weight and complexity of the system.
   Verification: *Demonstration* - The aircraft shall be capable of providing 5.57 W to the optical payload during the image capture mode.

A telescope capable of satisfying the full-scale system's optical requirements is estimated to draw 131.21 W of power. This was scaled down using the scaling factor method described by Powers:

$$131.21W/K^{3.5} = 5.57W$$

4) DR 1.4: System shall provide a cubic shaped payload bay with 4.87" length sides to house the optical system during operation.
   Motivation: The optical payload needs to not only fit onto the payload, but also be able to move during its expected tracking tasks. Therefore, enough space for the expected optical payload to be able to move freely shall be provided from the aircraft. The final optical system is estimated to need a 12" payload area, so scaled it will be a 4.87" payload bay.
   Verification: *Inspection* - The aircraft shall be measured and have a payload space of a 4.87 in cube.

The two largest components of the optics system are the telescope and the sensor. The largest telescope found was 8 inches long, and the largest sensor was 2 inches long, giving a maximum length of 10 inches. With a margin added the size comes out to 12 inches long. A cube was chosen to ensure a full range of motion of the telescope was hypothetically possible.
Length is scaled linearly, so using Power's scaling:

$$\frac{12in}{K} = 4.87in$$

5) DR 1.5: Payload space shall provide a housing location where an optical system would have a field of view (FOV) over 100 degrees.
   Motivation: The theoretical optical system will need direct line of sight to space objects. The larger the FOV, the easier it will be to track these objects. It also increases the number of possible objects in view that can be pointed at over one mission.
   Verification: *Inspection* - The payload space will be measured to see how many degrees an optical system would be able to slew across.

This requirement was derived using two different lines of thinking: How large of a FOV would allow for a viable time frame for an image to be taken, and how low on the horizon do atmospheric effects have a major impact on the image quality.
A MATLAB script was developed to simulate the ISS in orbit around earth. The ISS is in a low orbit and is therefore traveling very fast relative to objects on the ground. a simulated camera was pointed directly up at the sky and the amount of time the ISS was in frame for three passes was recorded. This experiment was done for FOVs ranging from 180 degrees to 1 degree.

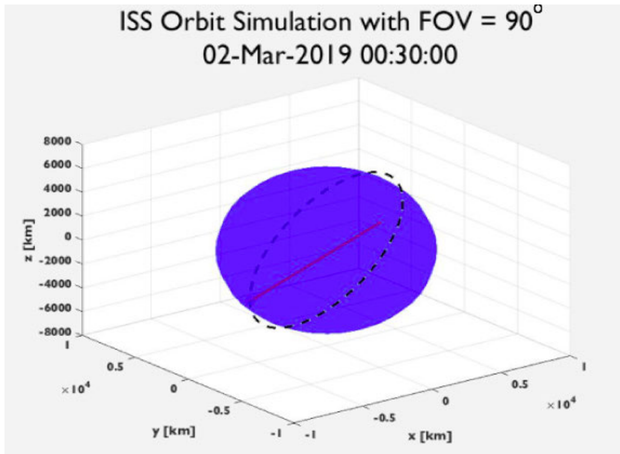

Fig. 12 Screenshot from a simulation of the ISS above boulder. The dotted line is the orbit of the ISS, and the red line connects a location 400 ft above boulder (on the right side) to the ISS's current location (on the bottom left).

This experiment showed that in order to get the 1 second capture time for an object going as fast as the ISS, the FOV needed to be at least 94 degrees. A FOV of 94 degrees gives a 24 second imaging window.
The next test was concerned with how apparent magnitude would be limited as the angle above the horizon was lowered, and the optics had to look through more atmosphere. The effect would be on atmospheric transmittance, τ, which varies based on the distance through which a telescope much look through the atmosphere.

$$\tau = e^{-lc} \tag{5}$$

where l is the length of atmosphere the telescope must look through, and c is a series of atmospheric constants. The derivation would then be based on this distance l vs the angle above the horizontal, θ.
In this graphic, h is the altitude of aircraft, R_e is Earth's radius, and R_a is the distance from Earth's center to edge of the atmosphere[‖] From trigonometric properties, an equation for l vs θ

[‖]The atmosphere around earth is actually much larger than the value used in these equations, but this is the length to the point in the atmosphere that is no longer dense enough to have an effect on imaging.

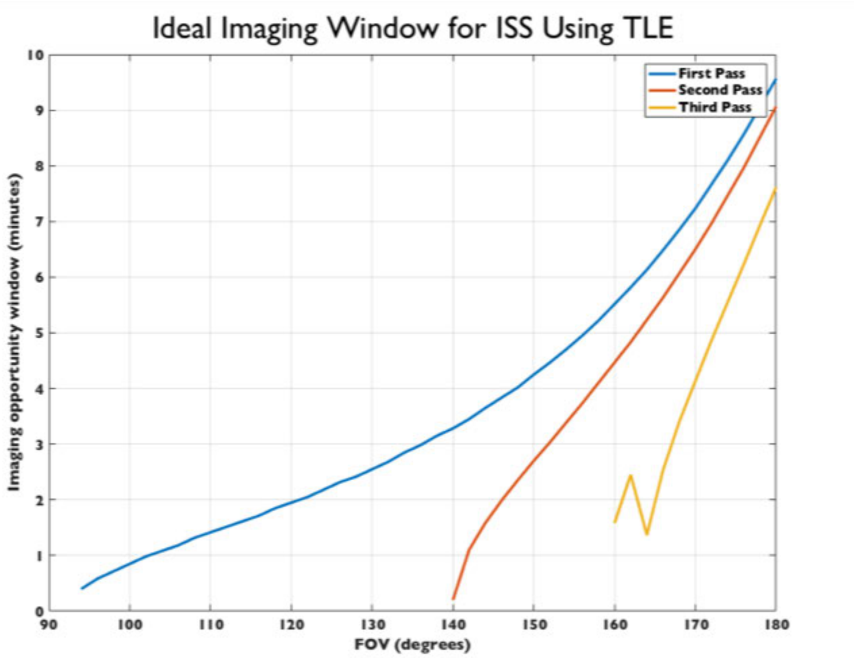

Fig. 13 Resulting plot from the ISS simulation experiment. The three different lines signify the three passes the ISS take over Boulder before the Earth's rotation makes it no longer be overhead.

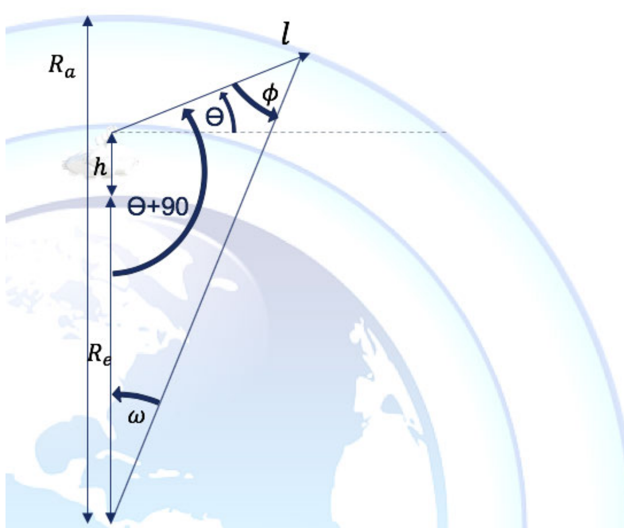

Fig. 14 Figure of the geometry used for determining τ, the transmittance through the atmosphere, based on the viewing angle above the horizon

was derived.

$$\phi = sin^{-}1\left(\frac{(-R_e + h) * cos(\theta)}{R_a}\right)$$

$$\omega = 180 - \phi - (\theta + 90)$$

$$l = \frac{sin(omega) * R_a}{-cos(\theta)}$$

This equation for l was then plugged into eq 5, and that equation for tau was used in eq 2. This equation was then put into MATLAB using the general variables and assumptions made in *Astronomical Optics*.

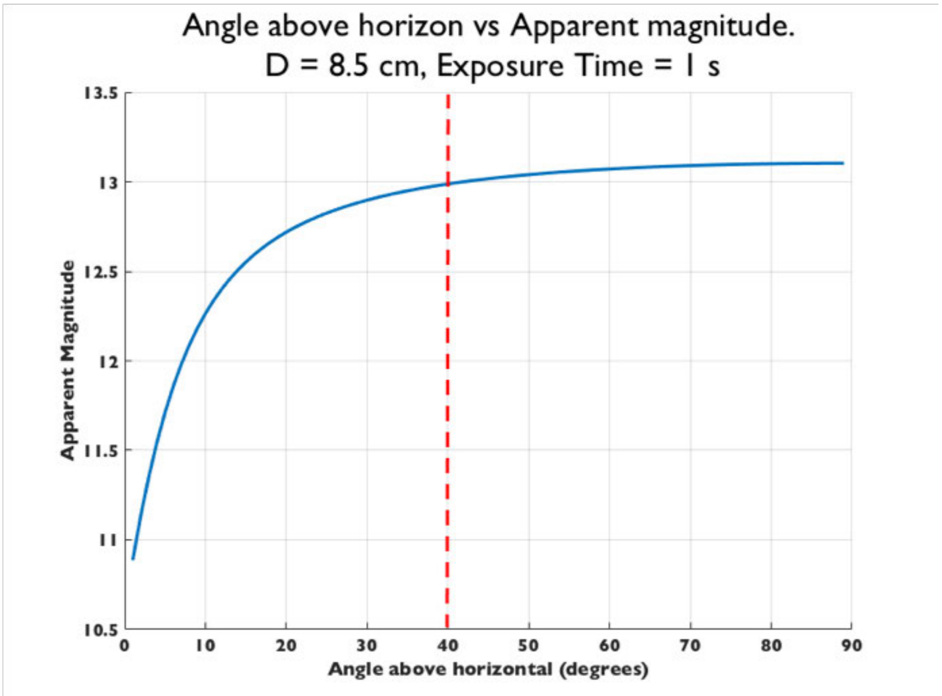

Fig. 15 Plot of apparent magnitude vs angle above the horizon. 13 was the minimum apparent magnitude requested by the client.

From this plot you can see that as the angle above the horizon gets lower, the apparent magnitude begins to drop significantly. At an angle of 40 degrees the minimum apparent magnitude of 13 is reached.

From these two tests the team found that:

A) The FOV needed to be at least 94 degrees in order to get a picture of fast-moving satellites

B) an angle above the horizontal below 40 degrees (relating to a FOV of 100 degrees) gives increasingly worse images in respect to apparent magnitude.

It is worth noting that objects in LEO will likely not be dimmer than an apparent magnitude of 13, and objects in orbits higher than the ISS will be moving much slower and will be more likely to remain above the aircraft for enough time for a picture to be taken. A final choice was made to have a FOV of 100 degrees, as that is long enough to image the ISS (with some added margin). If the FOV was any larger it would result in some dimmer images due to the atmospheric transmittance when looking at the edges of the FOV.

FOV is a geometric property and as such does not need to be scaled.

2) **Functional Requirement 2: System shall be capable of operating at 400 ft AGL.**

The full-scale MANTA project relies on reaching an altitude of 18,000 ft, above most cloud coverage. Due to CU and FAA restrictions, the maximum height our airship will be able to fly is only 400 ft. This is far from the end-goal of 18,000 ft, but the team wants to get as high as possible as to prove the stability of the craft at high altitudes.

At 400 ft in altitude there are conditions not found at ground level. The team must ensure prior to this test that the aircraft will be able to survive these harsher conditions.

Design requirements for FR 2

1) DR 2.1: System shall maintain the necessary thermal environment of no lower than 32 °F
Motivation: The power system is the most susceptible low temperatures and will therefore be the leading cause of maintaining a certain thermal environment. As the temperature decreases, the available capacity of the battery goes down. In order to minimize battery capacity loss due to low temperatures, the system should maintain a temperature of 32 °F which preserves at least 75% of the battery's maximum capacity at 68°F.
Verification: *Test* – The thermal control system will operate at conditions representative of those at 400 ft and subjected to temperatures ranging from 23-48 °F and maintain an operating temperature of at least 32 °F.
Of all of the components on the full-scale aircraft, the lenses are most prone to changes due to lower temperatures. For this reason the full scale model will need to implement some sort of heating system on the telescope itself to ensure no warping or shrinking of the lenses occurs. This thermal consideration is outside of NESSIE's scope, because the small-scale airship will not have a real camera on board needing thermal control.
On the small-scale model, the electronic component most prone to damage at low temperatures is the battery.

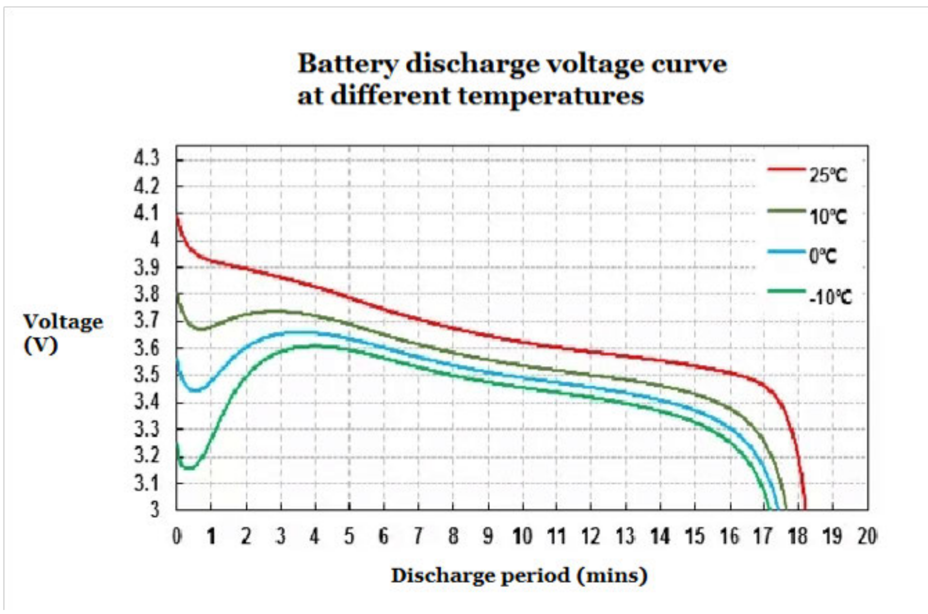

Fig. 16 Plot of Voltage vs Discharge time for lithium ion batteries at different temperatures.

Data sheets for lithium ion batteries recommend maintaining temperatures above 0 degrees Celsius or 32 degrees Fahrenheit. Most likely the temperatures the aircraft are going to be subjected to are higher than this limit, but the battery will still be placed in proximity of the ESCs. They release a lot of heat and will be able to maintain a non-freezing thermal environment around the battery.

2) DR 2.2: System shall be capable of surviving gusts up to 5 mph.
Motivation:On a calm day at 400 ft there can be wind blowing up to 5 mph. This wind stream can heavily influence the system's ability to operate, or could cause catastrophic damage to the system.
Verification: *Demonstration* - The system will be subjected to simulated 5 mph gusts by pushing or dragging the system with a tether and its response will be recorded.

The aircraft will only be flown on an extremely calm day based on CU guidelines as well as a general rule for airships. Knowing the wind-speed at high altitudes is not an exact science, but can be estimated using a wind gradient equation for wind turbines.

$$v_w(h) = v_1 0 * \left(\frac{h}{h_1 0}\right)^{\alpha} \quad (6)$$

The value we want to know is the wind-speed at 400 ft, $v_w(400)$. This will be based on v_{10}, the velocity of wind 10 feet above ground level, and α, the Hellman exponent. This exponent will be approximately 0.4 on a stable day above flat ground. This means that any wind-speed below 1.3 mph at ground level will likely be below 5mph at 400 ft.
It is worth noting that this requirement only considers constant wind speeds. Gusts are expected and will be dealt with based on the dynamics of the balloon.

3) DR 2.3: System shall shall comply with FAA hobbyist regulations.
Motivation: The FAA requires hobbyist aircraft be below 55 lbs at launch. Visual line of sight with the aircraft must be maintained at all times as part of the hobbyist designation.
Verification: *Inspection* - The aircraft will be weighed prior to any flights. Visual line of sight will be maintained throughout all flights.
In order to fly a UAV normally, the FAA has a series of forms that must be submitted and approved, taking around 180 days. In order to circumvent this, NESSIE will be flying under the *hobbyist* restrictions. By following the FAA hobbyist guidelines the team will be able to fly NESSIE without filing any paperwork at all.
4) DR 2.4: A path to flight at 18,000 ft shall be outlined.
Motivation: The aircraft being designed by our team is a proof-of-concept of a final, larger, aircraft which will fly at 18,000 ft. The team plans on providing to the customer a document containing a path towards getting the final aircraft to 18,000 ft legally. This document will also include scaling factors that should be used to turn the proof-of-concept aircraft into the final version.
Validation: *Demonstration* - An informal report will be given to the client to outline a path to getting a flight at 18,000 ft one day. Both legal and scaling capabilities will be discussed and presented in these findings.
This is a requirement directly requested by the customer. Due to the final full-scale MANTA project being reliant on reaching altitudes far beyond 400 ft, there will be a bureaucratic process necessary to get such a large vehicle to such a high altitude.
In addition the scaling factors used will be provided to the customer so that they may create a full size airship based on the airship created in this project.
These steps will allow the customer to utilize the information from our 400 ft flight to reach a much higher altitude down the line.

3) **Functional Requirement 3: System shall be capable of attaining a specified altitude and station keeping at that altitude.** One of the customer-defined requirements for MANTA was station-keeping. The vehicle must be capable of being flown to a certain horizontal and vertical position, and needed to maintain them within a certain margin. When scaling these requirements down for NESSIE, a linear scale did not make sense in this case. Since NESSIE is required to meet much more stringent station-keeping requirements, when scaling back up MANTA will be able to meet its requirements.
Design requirements for FR 3
1) DR 3.1: The system shall provide sufficient net lifting force to attain desired altitudes.
Motivation: The aircraft needs the ability to provide enough lifting force throughout the ascension in order to reach a desired altitude.
Verification: *Analysis & Test* - The aircraft will be flown to a height of 10 ft. A force spring scale

will be attached to the underside of the aircraft. The aircraft will then be instructed to reach the desired altitude. The data from the forces being exerted in the z direction will be used to extrapolate whether the aircraft would reach the desired altitude.

This requirement is fairly self-explanatory when it comes to making an remotely controlled aerial vehicle. Whatever the method, a sufficient amount of lifting force needs to be generated in order to fly.

2) DR 3.2: The system shall provide sufficient net lifting force to maintain target altitude within 50 ft.
   Motivation: The aircraft needs the ability to control its lifting force to maintain the desired altitude for a sufficient amount of time to image orbiting objects.
   Verification: *Analysis & Test* - The aircraft will be flown to a height of 10 ft. A force spring scale will be attached to the underside of the aircraft. The data from the forces being exerted in the z direction will be used to extrapolate whether the aircraft could hover at the desired altitude.
   This requirement is derived from a customer requirement to provide station-keeping. Originally for MANTA, this requirement had a much larger margin, however since NESSIE is a scaled down model, this was changed to be more stringent. The FAA specified max altitude for our flight is 400 ft AGL, and this is the metric that we have designed NESSIE to operate at. The FAA does allow some margin for perturbations and uncertainty of measurement, however anything more than 25 ft would be untenable.
3) DR 3.3: The aircraft shall be controllable by manual RC controller
   Motivation: The aircraft needs the ability to reach an altitude chosen by the pilot in order to begin image collection.
   Verification: *Demonstration* - The aircraft will be tested at low-altitude flight (10 feet) and will be subjected to commands from the ground station. This test will consider motion laterally, longitudinally, vertically, and angularly. The aircraft shall remain stable after the ground station's input.
   This requirement falls out of the trade studies as a part of the CDD document. NESSIE is a manually flown vehicle as a proof of concept for MANTA, which we expect to be have manual take off and landing, with an autonomous flight mode during the night for SSA data collections.

4) **Functional Requirement 4: System shall be capable of attaining a specified altitude and station keeping at that altitude**
   System must be able to stay within range of communications in order to be control-able. This implies being able to survive wind-gusts and being able to return to desired position without drifting out of communications' range. Furthermore, losing the craft can potentially lead to harming civilians and legal issues.
   Design Requirements for FR 4
   1) DR 4.1: The system shall maintain a link margin of 0 dB or greater throughout the duration of its flight.
      Motivation: A link margin greater than or equal to 0 dB indicates a viable communication link between the vehicle and the ground station. Having a link margin of 0 dB or greater throughout the duration of the flight guarantees that the ground station can always communicate with the payload and vice versa. The link budget will account for non-negligible attenuation due to the atmosphere, cloud cover, space/path losses, and noise from the antennae. The link budget will also include a required design margin.
      Verification: *Analysis & Test* - The aircraft communications system shall be placed 500 feet downrange of the ground station and an attempt to establish a viable communication link will be made. The strength of the resulting communication link will be recorded. This information will then be extrapolated from to confirm MANTA's communications system can analytically

communicate at 30.1 miles (50 km) during 18,000 ft conditions. This is the maximum distance the craft is expected to travel from the ground station.

Similar to the FR requirement, this is fairly self-explanatory in its derivation. NESSIE will be flying at 400 ft, at a max distance of 200 ft, so it must be able to communicate at that distance (the total distance is 447 ft), so if 500 ft is met in testing, the communications system will be sufficient to fly.

2) DR 4.2: The ground station shall have the ability to transmit to the aircraft.
   Motivation: If the ground station cannot talk with the aircraft, the aircraft cannot be controlled.
   Verification: *Test* - same as top level requirement This requirement is fairly self explanatory, if we cannot command the aircraft remotely, it cannot be controlled.
3) DR 4.3: The aircraft shall have the ability to transmit to the ground station.
   Motivation: If the aircraft cannot talk with the ground station, the aircraft can not be monitored during flights to confirm its location and functionality.
   Verification: *Test* - same as top level requirement
   This requirement is crucial for the proof of concept to succeed. The airship must be able to stay within range to avoid loosing the craft, and potential damages to others. In addition, the large scale model is required to send telemetry data and position to ground station since it will be out of sight. Communications is a crucial element that must be proven to succeed in order to make the full-scale model feasible.

C. Final Design

While the key parameters of the aircraft are broken down by subsystem in the following section, we take a brief look here at some major elements of the final design. Once the trade studies and requirements flow-down was completed, the final design started to take shape. It is important to note that there was no preconceived idea of how this craft should look. The design is entirely novel and its form, seen in Fig. 17, is driven by the design requirements specified above.

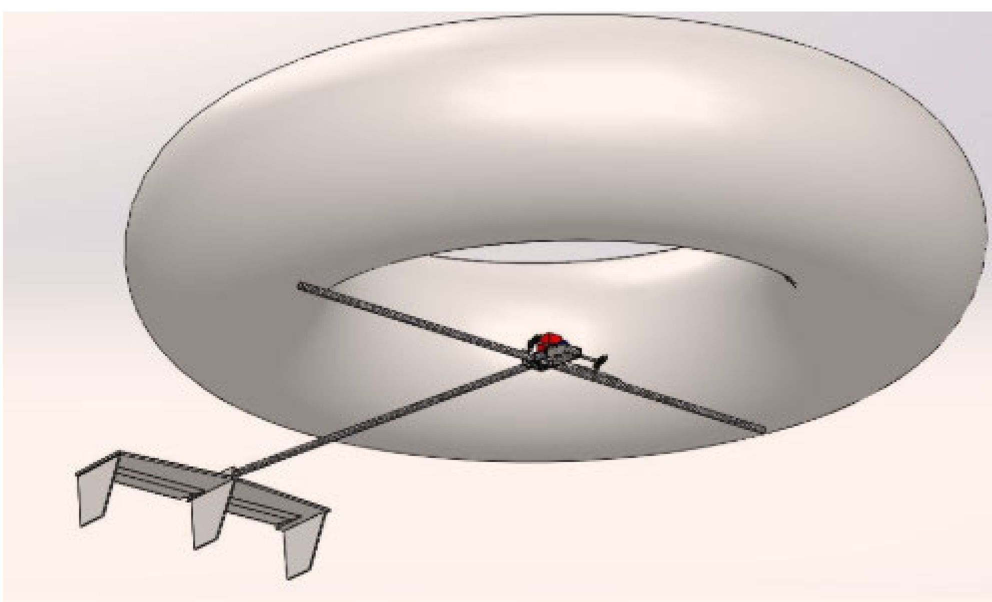

Fig. 17 CAD model of final design.

One of most significant restraints on the design of this system were FAA hobbyist regulations which required the entire craft to weigh 55 lbs or less in order to fly under hobbyist restrictions. Fortunately this constraint was considered from the beginning of the design process, allowing it to be weighed accordingly throughout the trade study process. The final design comes in at an estimated 55 lbs, which is over our initial estimate of 54 lbs. The key here, however, is that the final estimate includes ballast. The envelope was 8.45 lbs lighter than expected, so 8.45 lbs of ballast was added to meet the design weight of 55 lbs.

Another major element that heavily influenced the final design of the aircraft was the decision to use helium as the lifting gas. Both helium and hydrogen gas were considered during the design process, with models and safety proposals being created for system operation in either case. Ultimately, the decision to use helium as opposed to hydrogen was made due to safety concerns expressed by university faculty. The choice of lifting gas had no influence on size of the system, but did affect its performance and weight. Namely, less ballast was required to meet the design weight as helium is a heavier gas than hydrogen.

The last point to keep in mind is that NESSIE is an airborne vehicle designed to create a platform for an optical system. For this reason, the team to formulated functional and design requirements for the vehicle from an optical standpoint. This is most evident NESSIE's shape; the inner diameter allows for adequate viewing capabilities (100°FOR) for whatever optical system is held inside the gondola. Minimizing the drag associated with the design also played a role considering the correlation between drag and vibrational disturbances. Dampening the vibrations in any fashion allows for better quality images as there is less noise being allowed to creep in. In the end, every detail about NESSIE's design along with it's requirements can be traced back to and reasoned from an optical system point of view.

1. Key Parameters by Subsystem

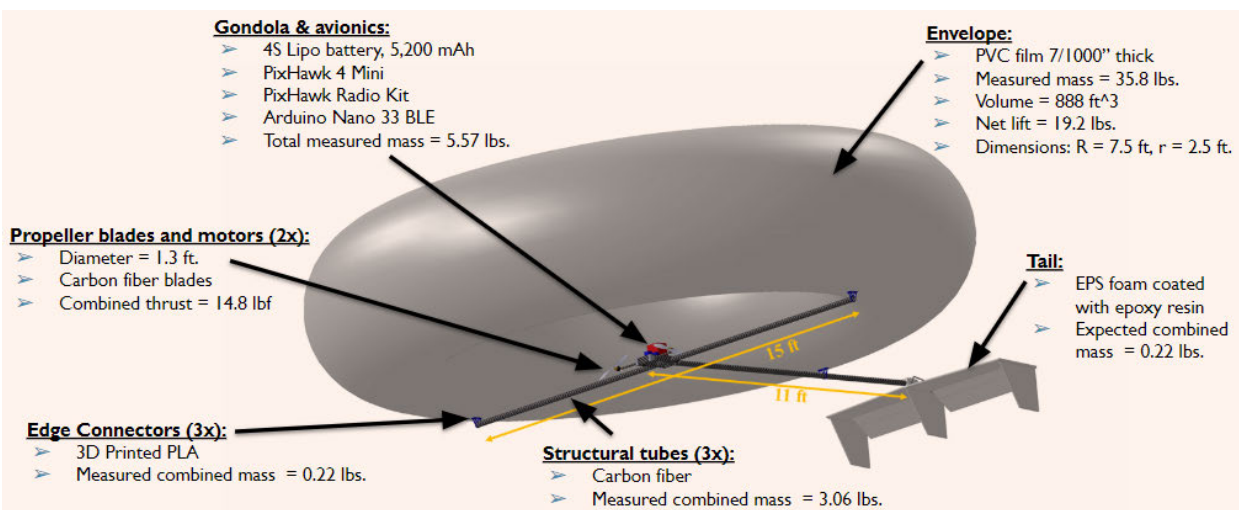

Fig. 18 Final design with relevant parameters listed.

While key parameters are summarized visually in Fig. 18, a more detailed summary is provided by breaking these parameters down by the subsystem. The first subsystem considered is the envelope, as seen in Fig. 19, which is absolutely critical to the operation of the aircraft. The envelope itself, manufactured by Larger Than Life Inflatables out of 7 thou PVC film, has an outer diameter of 19.90 ft and an inner diameter of 10.10 ft. Note that Fig. 18 lists the dimensions of the envelope with respect to the inner and outer radius taken from the center to the middle of the tube. This stays consistent with the math definition of a torus. As mentioned previously, the envelope was underweight by 8.45 lbs, putting it at a measured weight of 35.8 lbs. Given its 888 ft^3 volume and use of helium as a lifting gas, the envelope was designed to generate 19.2 lbs of lift. During descent, a solenoid valve is opened to vent helium and decrease lift. This valve has a minimum flow rate of $0.106\frac{ft^3}{min}$. The envelope is mounted rigidly to the structural tubes, which also run through the gondola that houses all of the avionics.

Fig. 19 Inflated envelope.

The avionics subsystem is what allows the pilot to command and control the craft. All power is supplied by a LiPo battery with a capacity of 5200 mAh that supplies 14.8 V. This battery pack is sufficient to ensure that all components would be powered for 40 minutes of constant use and could maintain power through a mission window of up to 8.9 hours with recharging. Communication is handled by a PixHawk 4 Mini and a PixHawk Radio kit which interface with an external RC controller through ArduPilot Mission Planner. The radio kit specifically operates with a serial connection of 57600 baud, whereas the flight controller makes use of I^2C protocol to communicate with the onboard IMU that collects data, at a bit rate of either 0.1, 0.4, 1.0, 3.4, or 5.0 $\frac{Mbit}{sec}$. All of the onboard avionics are housed inside the gondola, which is made from carbon fiber and provides a 4.87 in^3 open bay for electrical components and a simulated payload. Including the electronics and the gondola structure, the weight for this subsystem was measured at 5.57 lbs. General placement of the avionics in the gondola is seen in Fig. 20.

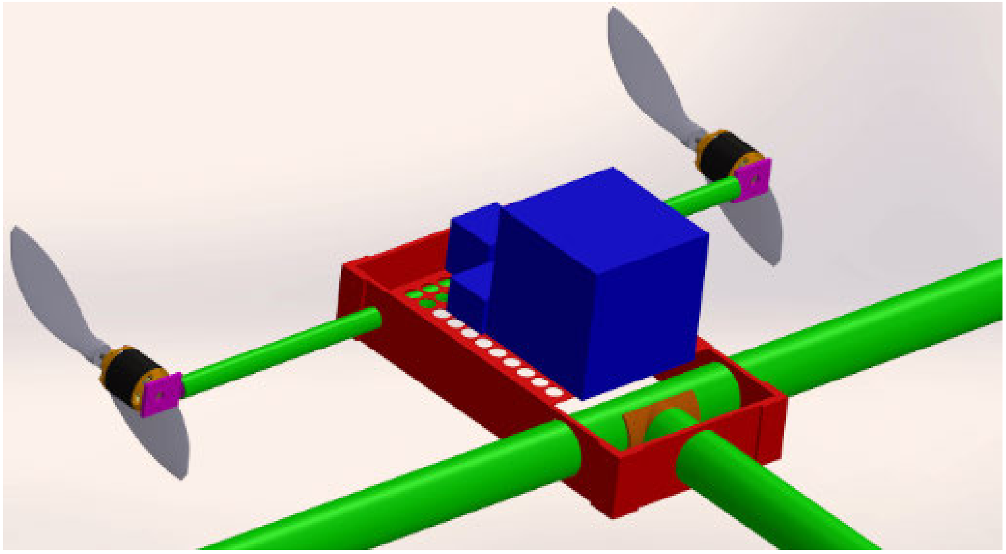

Fig. 20 Gondola with avionics mounted in bay.

The last major element described here is control authority, which is handled by the propulsion and attitude control subsystems. The propulsion subsystem is comprised of two propellers and two motors. The propellers themselves each have a diameter of 15.5 in and when coupled with the motors, which have a maximum power intake of 730 W, are capable of producing a maximum combined thrust of 14.8 lbf. The motors and propellers have a combined measured weight of 0.902 lbs.

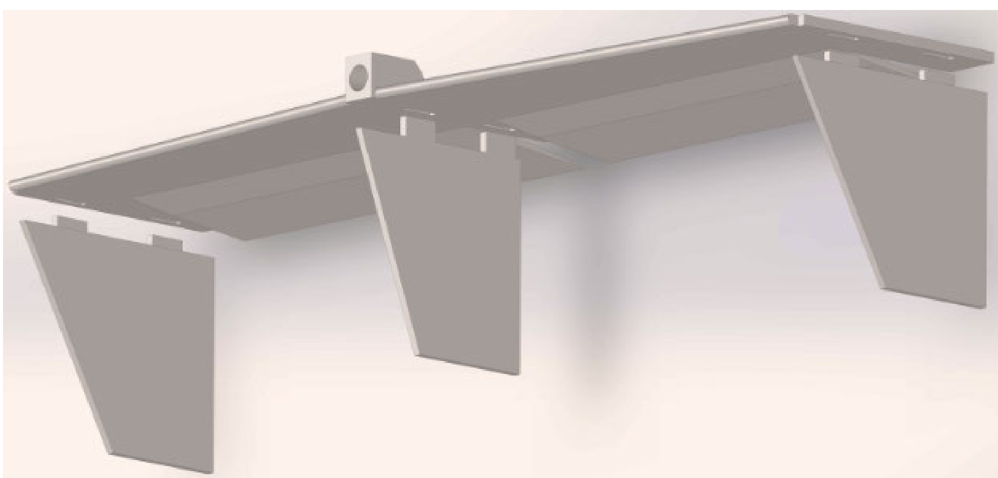

Fig. 21 Tail design.

While the propellers are able to provide some control authority, this is mainly the responsibility of the tail, which is shown in Fig. 21. One of the tail design's most interesting features is the vertical tail fins, which are inverted so as to minimize flow distortion from the envelope. The tail is constructed from 0.59 in thick foam and is coated in an epoxy composite that is 0.01mm thick, weighing in at an estimated total of 0.22 lbs. With a control surface area of 298.7 in^2 and a fixed angle of attack of 5 deg, the tail itself is capable of generating 2.69 lbf entirely separate from the envelope. The tail is connected to the gondola by the tail boom which is a 10.87 ft long, 0.03 in thick, 1.935 in outer diameter carbon fiber tube. The tail boom specifically weighs 1.47 lbs. Nearly identical carbon fiber tubes are used to attach the gondola to the envelope, except that these tubes are 7.5 ft in length and, consequently, weigh 0.83 lbs each. A schematic showing these dimensions is presented in Fig. 22. More in-depth schematics for the tail structure can be found in the appendix.

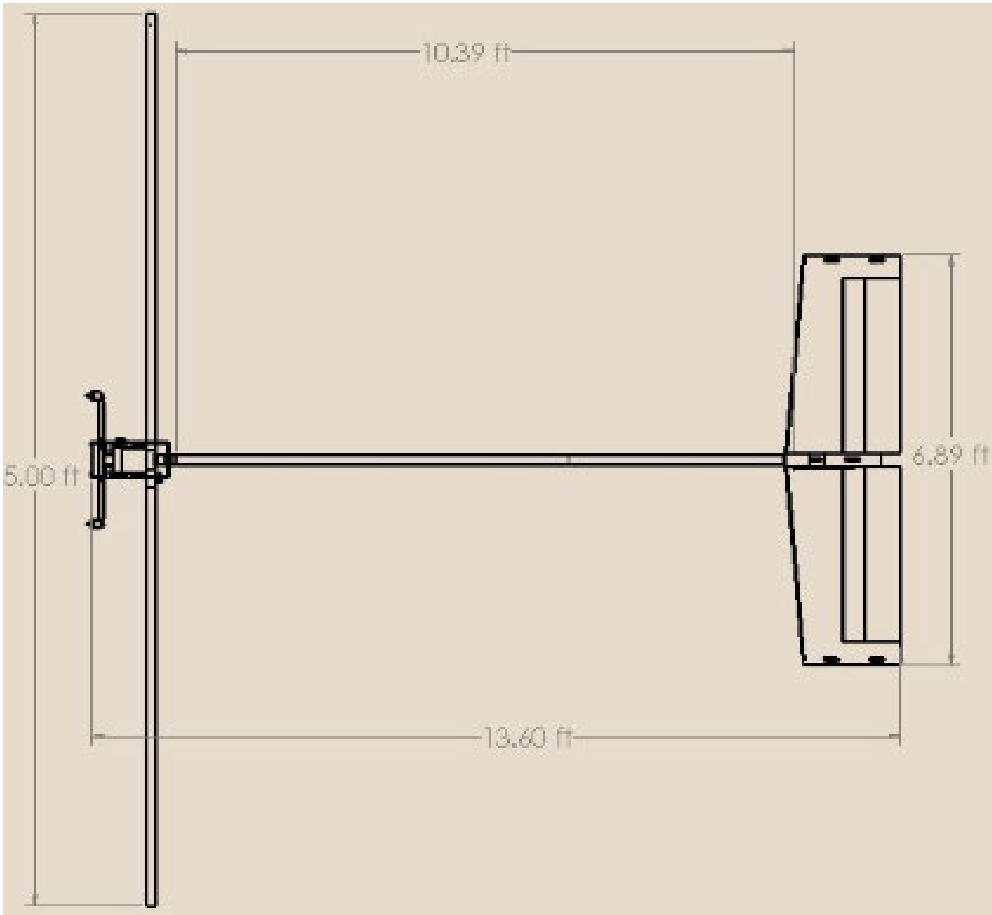

Fig. 22 Engineering drawing showing structural beam dimensions.

2. System Functionality

While the design of this craft was relatively complex, actual operation is surprisingly straightforward. Before liftoff, the craft is staked to the ground so that it is unable to be blown away. While still tethered, the envelope is pumped full of helium gas in order to provide the necessary lift to achieve testing altitude. At this point, ballast is attached at the two free connection points on either side of the edge connector as seen in Fig. 23. As mentioned previously, the craft is controlled remotely by the pilot via a handheld RC controller. The functional block diagram of the craft's power and data connection seen in Fig. 24 shows how the RC controller at the ground station interfaces with the rest of the onboard systems. While ascent would be completely passive under perfect conditions, the pilot has control of the craft during ascent so that they can provide control inputs in case there are weather patterns that require that craft to change its attitude or perform an emergency descent.

In cases where a change in attitude is deemed necessary, the pilot has several options to alter the orientation of the craft. Each motor has its own dedicated electronic speed controller, which allows the propellers to operate at different angular rates so as to control the yaw of the craft. Elevators in the tail can be actuated via servo, thus changing the craft's pitch. It is likely that the common scenario in

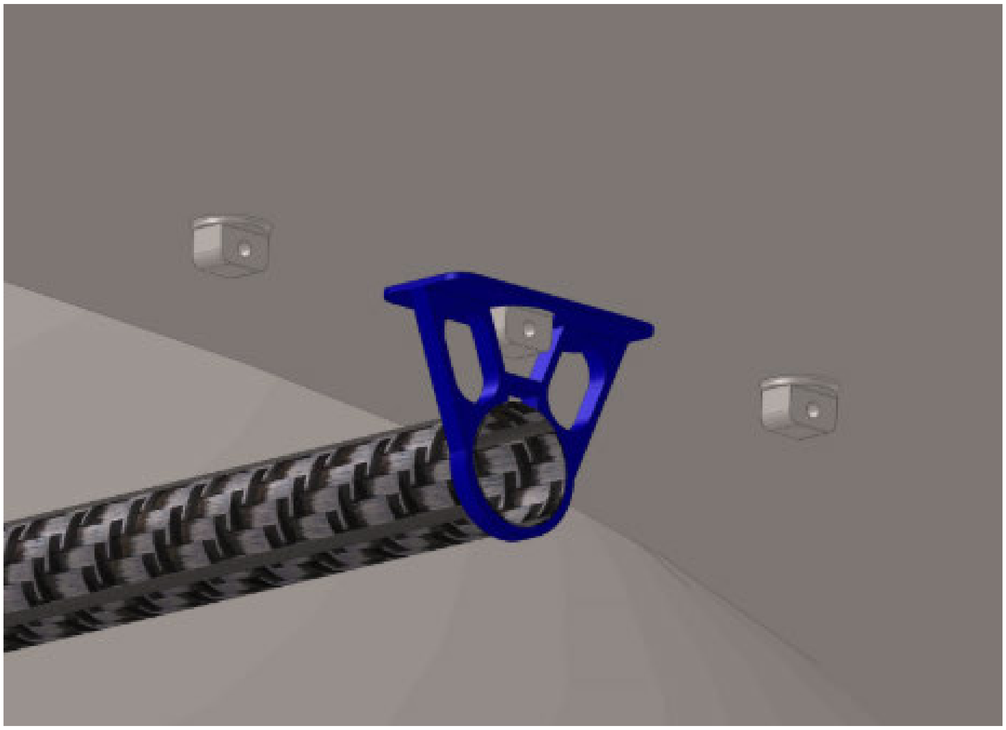

Fig. 23 Close up view of connection points on envelope.

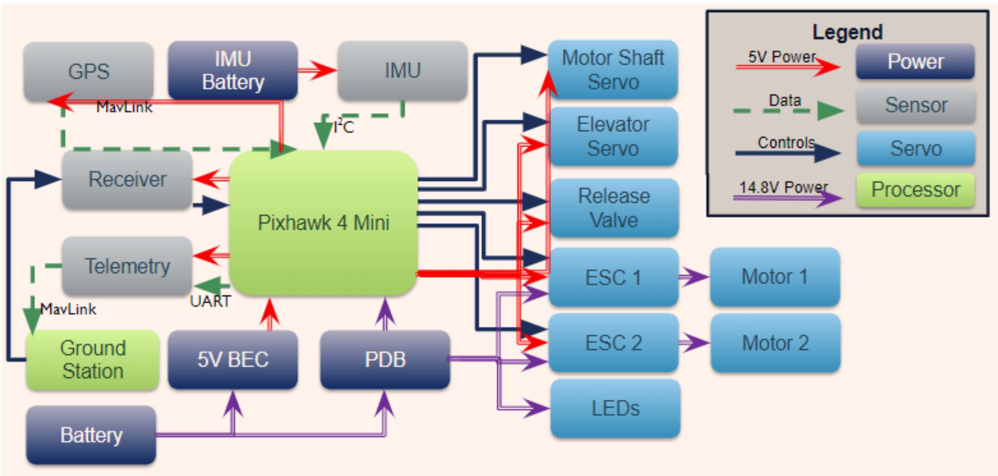

Fig. 24 Aircraft functional block diagram.

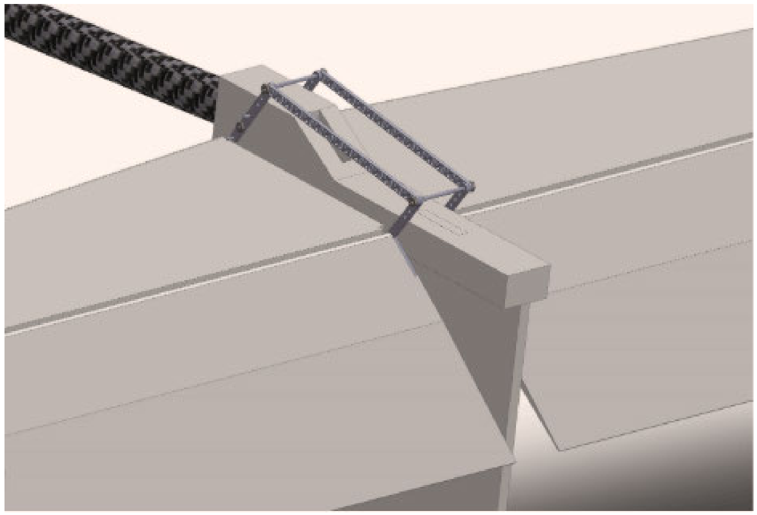

Fig. 25 Servo links permit actuation of the tail's control surfaces.

which these controls would be necessary is to steer the craft into the wind during heavy gusts. The servo links that were to be manufactured to control this action are seen more closely in Fig. 25. In this case, the tail would be able to generate supplemental lift if the lift generate by the helium in the envelope was not sufficient.

Since lift is almost entirely generated by the helium gas, descent is controlled by venting the lifting gas from the envelope to the atmosphere. The primary method for descent is to use the solenoid described previously. the shaft holding the motors is also controlled by a servo, so the propellors can be faced downward to provide thrust to aide in descent. A redundant method was also designed to be used in cases where the craft needed to be brought down faster than the solenoid could permit. This redundant system is comprised mainly of an altimeter, an Arduino Nano, a nichrome wire, and a battery. When the altimeter senses that the craft has reached 450 ft, a 9 V battery puts current through the nichrome wire, heating it to the point where it pops the envelope. A more descriptive functional block diagram is seen in Fig. 26. It should be noted that this is a last-resort method, as this will result in a completely uncontrolled descent and likely destruction of the craft.

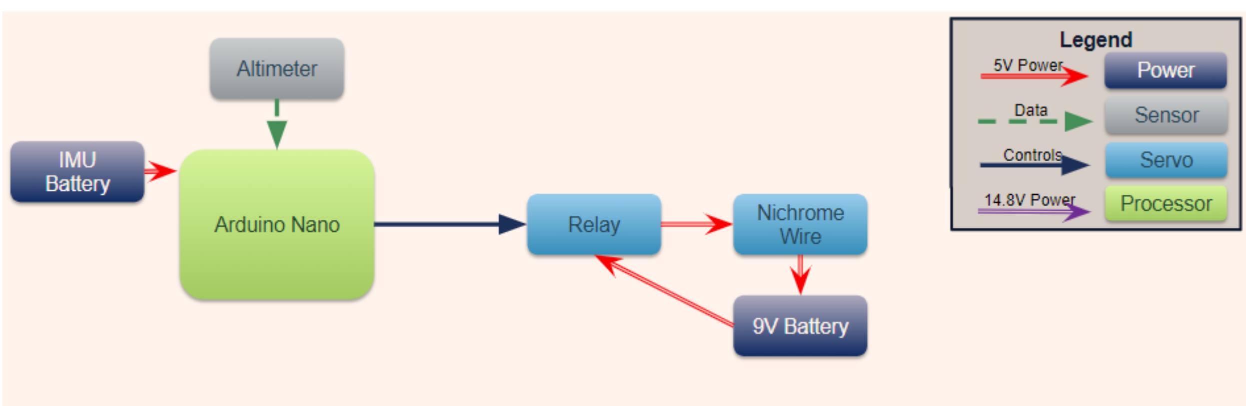

Fig. 26 Functional block diagram of nichrome burn wire system.

4. Manufacturing

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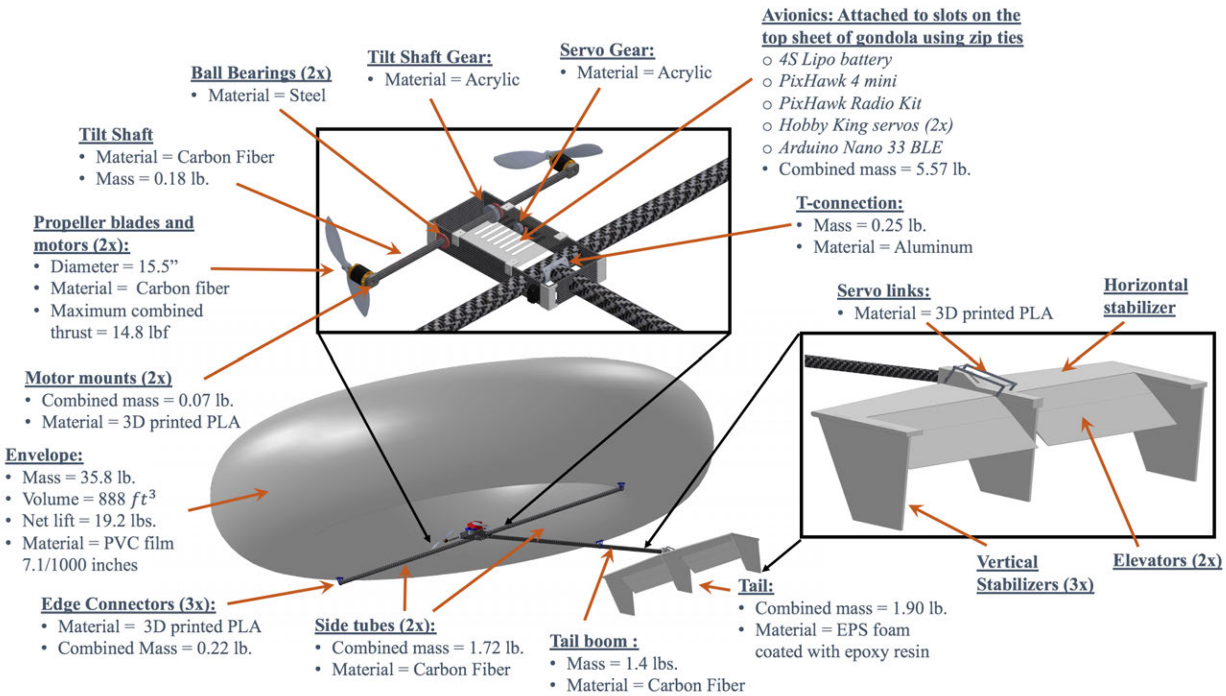


Fig. 27 NESSIE parts breakdown. Not shown in the CAD model is the specific avionics and their locations within the gondola's frame.

A. Manufacturing Tasks

1. Envelope

This part provides most of the lift of the vehicle. The dimensions of the envelope are displayed in figure 28. It is connected to the rest of the structure of the vehicle using the edge connectors. The team purchased this custom part from Larger than Life Inflatables** .The team provided the required geometry, dimensions, number of attachment point and their locations. The vendor engineered a envelope made out of PVC film 3/1000 in thick, with the the dimensions and attachment point locations displayed in figure 28.

**www.inflatables.net

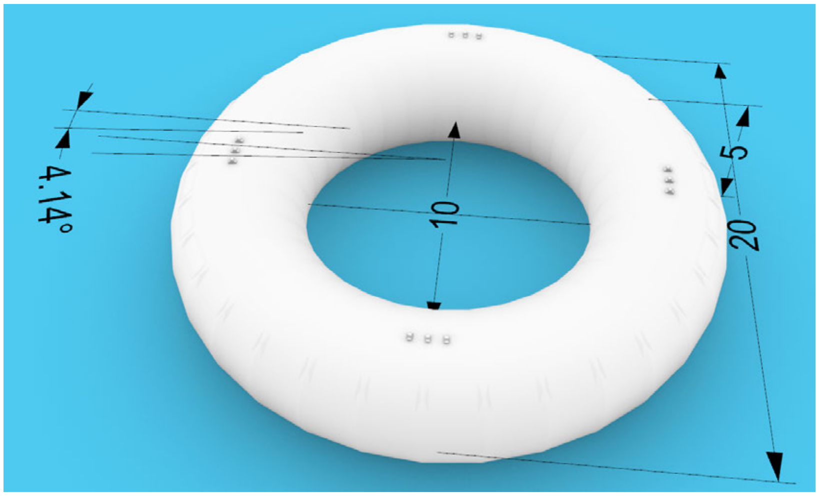
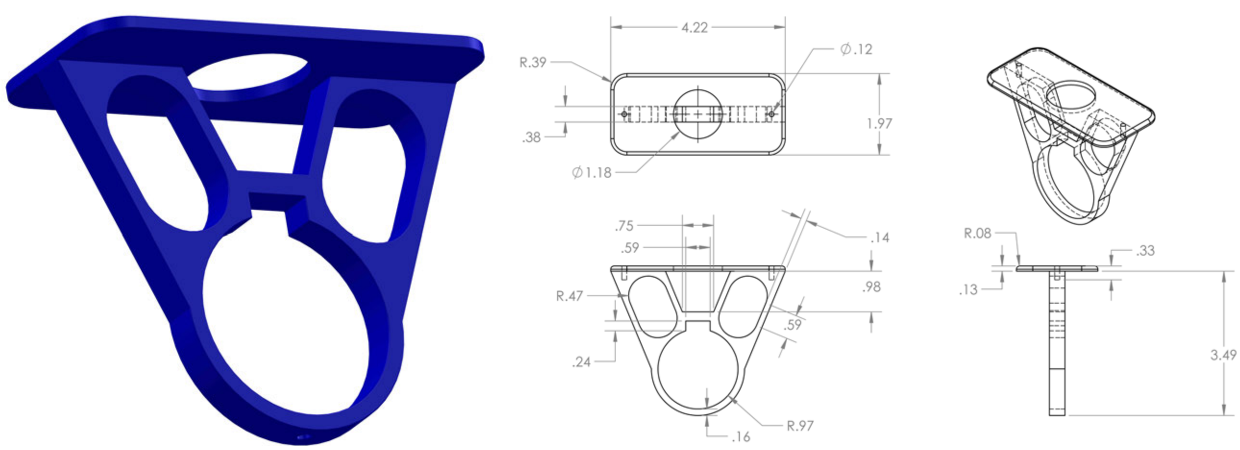


Fig. 28 Dimension of envelope and location of connections

2. Edge Connectors

The edge connectors are the parts that connect the envelope to the structural tubes. There are 3 edge connectors in total. One is at the tail boom 80.9 in away from the gondola. This part is fixed to the structural tubes using epoxy adhesive, and attached to the envelope using zip ties. The second and third connections are at the ends of the 2 side arms. The 3 parts were 3D printed using PLA, due to the complex geometry of the part. The slots were added to reduce weight, material and printing time. This part was 3D printed in a LulzBot Mini 2 3D printer at the University of Colorado Aerospace Engineering Building.



(a) (b)

Fig. 29 Edge Connector, dimensions in inches

3. Side Tubes

The 2 side tubes are made of carbon fiber Roll Wrapped Twill Tubes 0.03 in thick with an inner diameter of 1.875 in and a length of 96 in. This tubes are connected to the gondola and to the T-connection at the center of the vehicle in one end and also to one edge connector at the other end. This tube did not get manufactured by the team. The team planed to drill M3 bolt holes on one of the ends of both tubes, to provide connection to the T-connection. This task was not performed because it was dependent on the T-connection being finished. We planed to manufacture this part in a drill press at the aerospace manufacturing shop at CU Boulder.

4. T-Connection

The T-connection is the part that connects both of the side arms and the tail boom at the center of the gondola. It was made from 2 aluminum tubes. One was 1/8 in thick with an outer diameter of 2 in and a length of 1 ft. The other was 1/4 in thick with an outer diameter of 2.25 in and a length of 1/2 ft. The thinner and longer tube was manufactured into tubes 1 and 3, since they have the same diameter. The thicker and shorter tube was manufacture into tube 2. First, We adjusted the thickness of the tubes using a lathe. For the thinner tube we reduced the outer thickness of the tube to the inner thickness of the carbon fiber structural tubes, 1.88 in. For the thicker tube we had to reduce the thickness both from the inside and the outside. The inner diameter was increased to the outer diameter of the carbon fiber structural tubes, 1.94 in; and the outer diameter reduced to 2.18 in. Then using a band saw, we cut the 3 tubes to the length of 3 inches, figure 30a.

Tube 1 was machined in a CNC mill to create a fish mouth. The fish mouth has the same diameter as the thicker tube for welding, 2.18 in. This was the point were the manufacturing process got cancelled. The team planed to weld the fish mouth of tube 1 to the outer surface of tube 2, creating the T shape. Lastly, the team planed to use the band saw to do the final angle cut of about 120 deg on tube 2 to remove extra material. All the manufacturing involved on this part was done or was planed to be done at the aerospace manufacturing shop.

(a) (b)

Fig. 30 T-connection

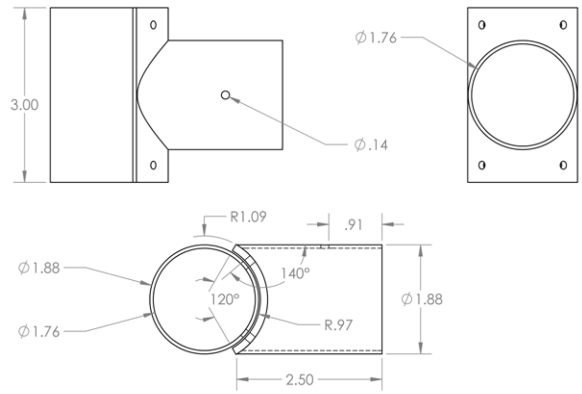


Fig. 31 Dimensions of T-connection, all in inches

5. Tail Boom

The tail boom was made of 2 carbon fiber tubes 0.03in thick with an inner diameter of 1.875in and a length of 96in. We need the total length of the tail boom to be 130in, so we manufactured a inner tube extension. A inner tube extension is another carbon fiber tube with an outer diameter equal to the inner diameter of the 2 tubes. This extension tube goes half way in length inside the 2 tubes larger diameter tubes. This part was manufactured out of a carbon fiber tube 0.0625in thick with an inner diameter of 1.75in and a length of 24in. This tube was first sanded by hand using sandpaper so that it perfectly fit the 2 large diameter tubes, figure 32. Then they were cut to 6in in length using a handsaw. Also, one of the larger diameter tubes was cut using a handsaw to 34in, so that the full extended tail boom has a length of 130in. Holes were drilled on both ends of the tail boom, one for the connection to the T-connection and the other for the tail structure. Finally the inner extension tube was glued inside both tubes using an epoxy adhesive.

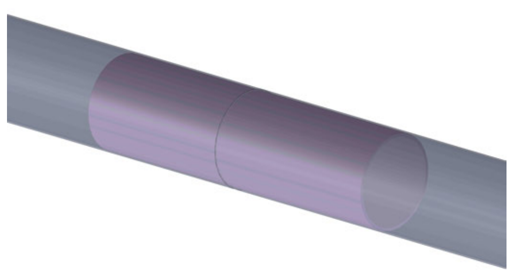


Fig. 32 Inner Tube Extension connection in pink, tail boom show transparent

6. Tail

The tail consists of two main parts, the horizontal section and the vertical tail fins. The horizontal part had 3 components. The main body, the two horizontal stabilizers and a extra piece that was placed exactly in the middle of the wing, where the carbon fiber rod would get attached. All of these parts were made from one 6 ft by 2 ft by 2 in thick F250 EPS foam. A hot wire was used to give it shape and reduce the thickness to 1in. The main body and the stabilizers were 1 inch thick and the center piece was 3.3in, which was manufactured by gluing two 2in pieces on the top of the horizontal stabilizer.

The tail boom hole with an angle of attack of 5 deg was planed to be manufactured using a ramp with 5 deg of inclination and a hole saw drill bit.

To give the tail a more precise and smooth finish a mill was used. The holes where the vertical components would be fitted in were cut using the lathe as well.

The vertical fins were manufactured using the same foam and a hot wire to give them the appropriate shape.

The tail's final dimensions can be seen in 33, 34a, and 34b.

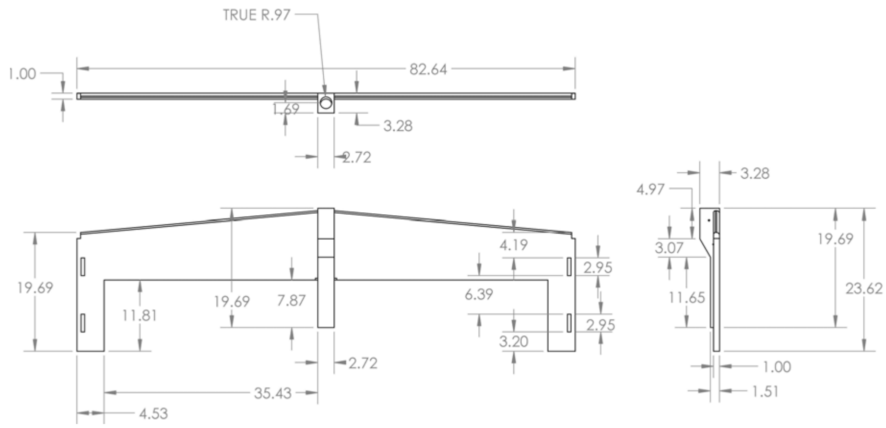
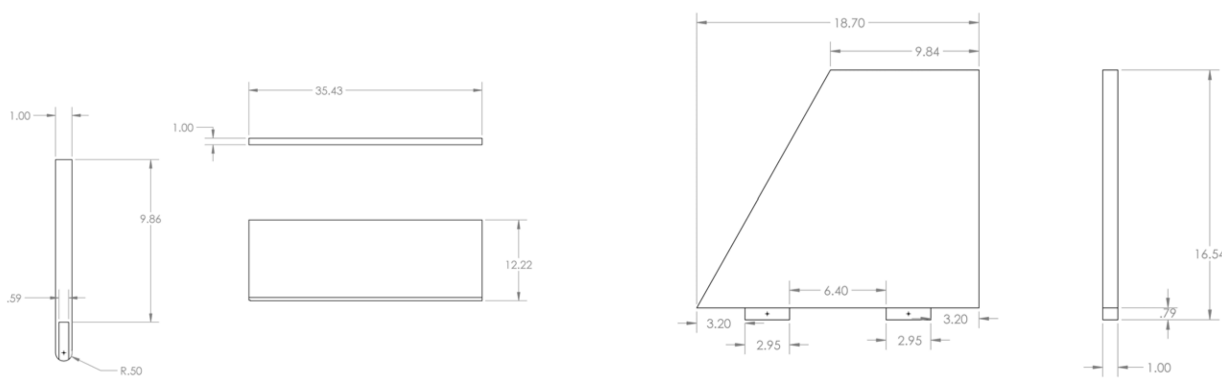


Fig. 33 Horizontal Stabilizer, dimensions in inches

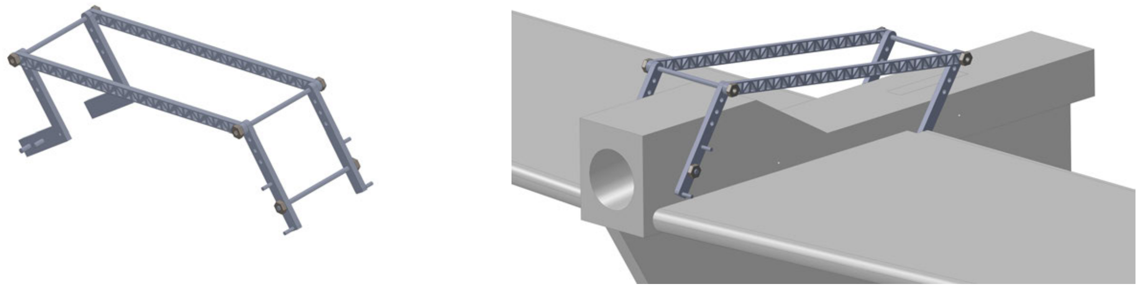


(a) (b)

Fig. 34 Elevator (a) and Vertical Stabilizer (b), dimensions in inches

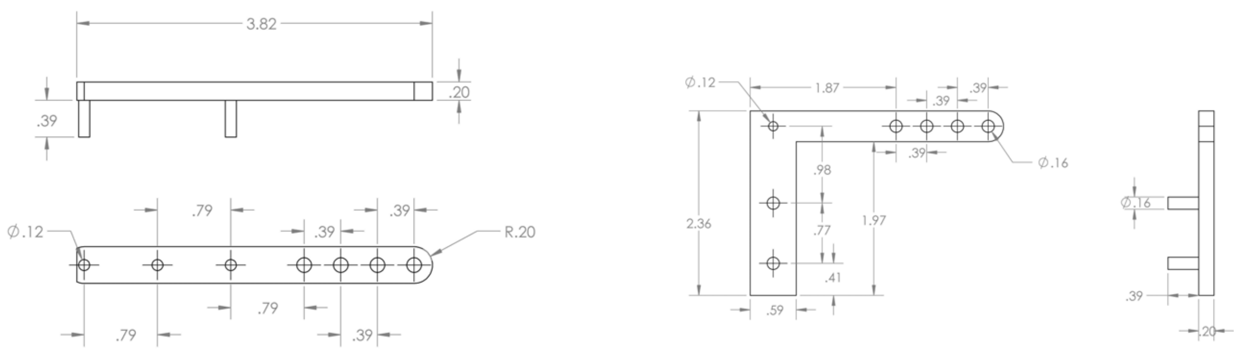
7. Servo Links

The servo links is the mechanical structure on the tail that transfers the torque form the servos to the elevators. This part is connected one of the servos in the gondola structure by two 7/64 inched Kevlar cord with polyester jacket. It is also connected to the elevators using an epoxy adhesive and to the horizontal stabilizer using pins. This part is designed of 3D printed PLA, due to the complexity of the geometry. The 3D printed planed to be used is the Taz 6 Aerostruder located at the Aerospace Building at CU Boulder. The 3D printer used changed so the larger piece fits in the printer space.



(a) (b)

Fig. 35 Servo links for the elevator



(a) (b)

Fig. 36 Servo link 1 (a) and servo link 2 (b), dimensions in inches

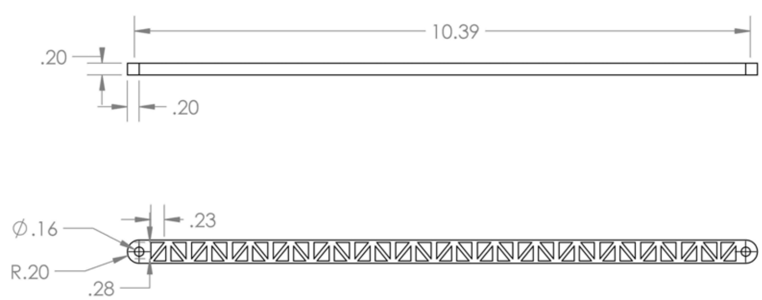
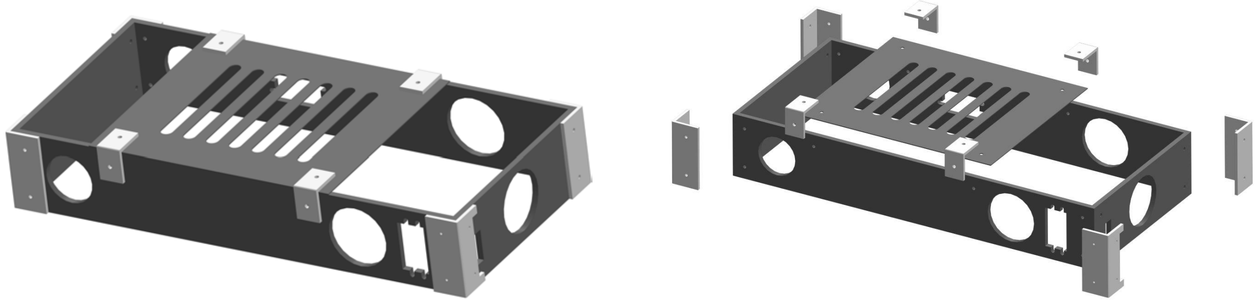


Fig. 37 Servo link 3, dimensions in inches

8. Gondola

In this document we define the gondola to be the assembly of parts show in figure 38. The gondola houses the avionics, the payload and the propulsion system. It is connected to the 2 side tubes and to the tail boom, which provide the connection to the envelope and to the tail. It also has a bearing connection to the tilt shaft.



(a) (b)

Fig. 38 Gondola

The sides of the gondola were made from a 1/5in thick carbon fiber sheet of 12in by 12in. This sheet was milled into the 4 sides of the gondola using a CNC mill in the aerospace machine shop and Solid Cam software (39). Also, slots were milled in the sides for the connection of the 2 servos. Finally the 4 carbon fiber edges were cut to length and bolt holes were drilled to create a rectangular box. We used 6-32 thread 5/8in long blue-anodized aluminum screws and aluminum bolts, with plastic washers on both sides. Thread lock was added to every bolt.

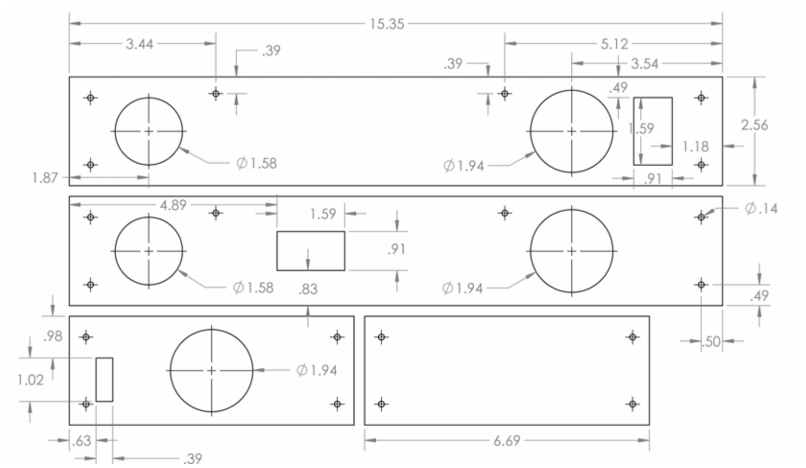


Fig. 39 Side sheet of gondola cut from one large sheet, dimensions in inches

The top sheet of the gondola was done using a carbon fiber sheet of 1/32in thick and 12in by 12in. The design was done in CAD and then transferred to the Wazer software to input the geometry into the water jet cutter. The design had 7 slots to provide housing for the avionics, which are fixed to the top sheet using zip ties. Also, small holes on the corner were drilled for the nut and bolt connection to the gondola box. This connection uses four more carbon fiber edges, which were cut to length using a band saw and drilled using a drill press. All the equipment used in the manufacture of the gondola is located at the aerospace manufacturing shop.

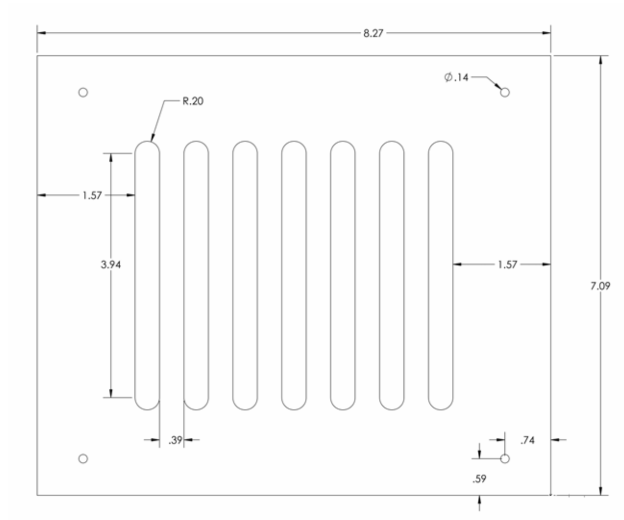
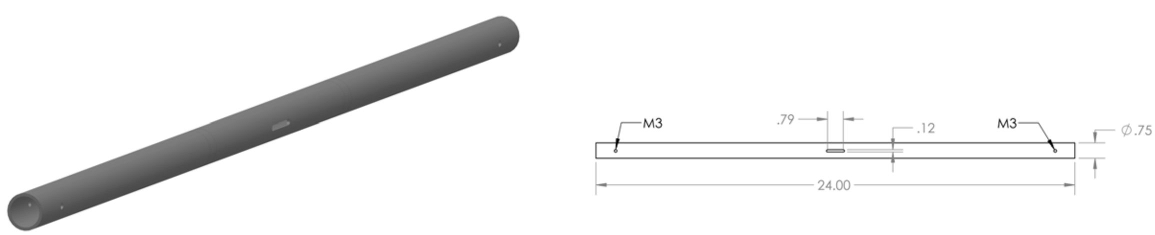


Fig. 40   Top sheet of gondola, dimensions in inches

9. Tilt Shaft

The tilt shaft is the tube that connects both of the motor mounts to the gondola. It is connected to the gondola using 2 bearings, so that the shaft can be rotated with a servo and the direction of the thrust vector can be controlled. For this reason the shaft was designed with a slot in the center, so that the wires can exit at the center of the gondola. The tilt shaft was made of a carbon fiber tube 0.0625in thick with an outer diameter of 0.75in and 24in in length. This tube was bought at the exact length that was needed, 24in. The first task completed was to reduce the thickness of the tube using a lathe, so that the outer diameter is exactly the same as the inner diameter of the bearing, 0.75in. This task was required due to the tolerance of the carbon fiber tube, which was not specified by the vendor. Finally, we drilled the holes for the nut and bolt connection to the motor mounts on both ends of the tube and milled the slot for the motor wires using a CNC mill. All the equipment used in the manufacture of this part is located at the aerospace manufacturing shop

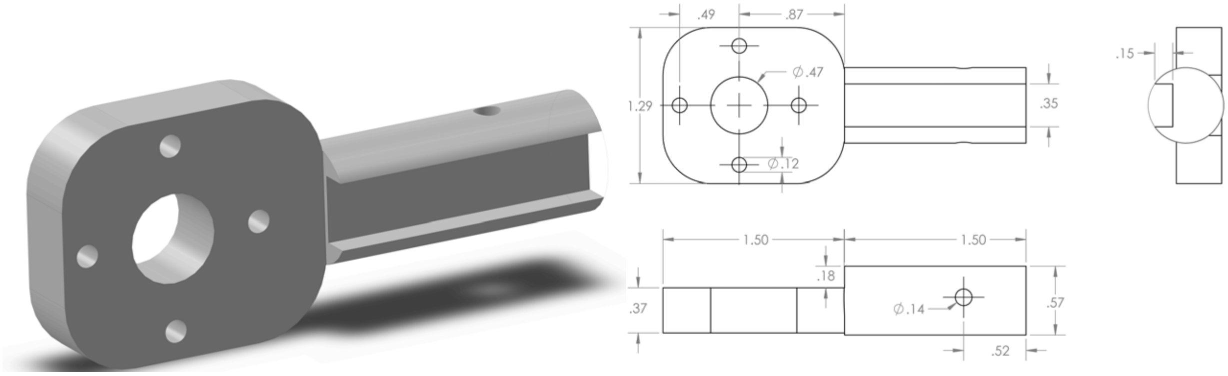


(a) (b)

Fig. 41   Tilt shaft, dimensions in inches

10. Motor Mounts

The motor mount are the 2 parts that support the 2 motors, and also connects them to the tilt shaft. This part was 3D printed using PLA, due to the complex geometry of the part. The motors are fixed to the mount using 4 M3 nuts and bolts at the 4 small diameter holes in the part. The cavity on the circular section of the part is for the 3 motor wires. This cavity was redesign because the motor wires did not fit the cavity. This was due to the larger diameter of the wires close to the motor. The team did not have the opportunity to print the redesigned part.



(a) (b)

Fig. 42 Motor Mount, dimensions in inches

11. Motors and Propellers

These parts were all purchased from a vendor. They were selected based on the efficiency and integration ease. We were able to purchase motors, propellers and ESC from the same manufacturer KDE Direct. The propellers are made of carbon fiber.

12. Tilt Shaft Gear and Servo Gear

The Tilt shaft gear is connected to the tilt shaft and also connected a gear belt. The gear belt is also connected to the servo gear, which provides the torque. The gears were planed to be manufactured out of an acrylic sheet 0.4 inches thick and cut in the laser cuter to the appropriate geometry. The team planed to use the laser cuter at the rapid prototyping room at the aerospace building. The dimensions of the gears are displayed in the following figures:

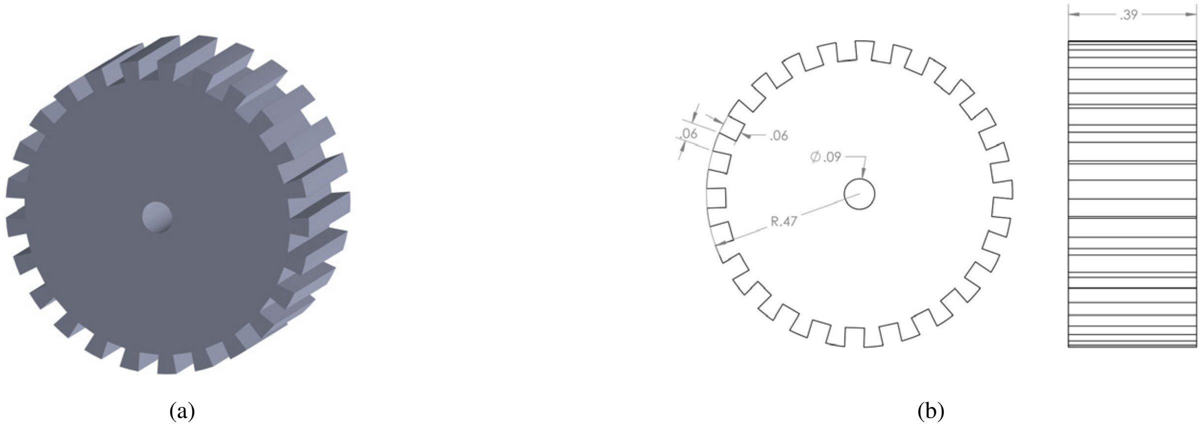


Fig. 43 Servo Gear, dimensions in inches

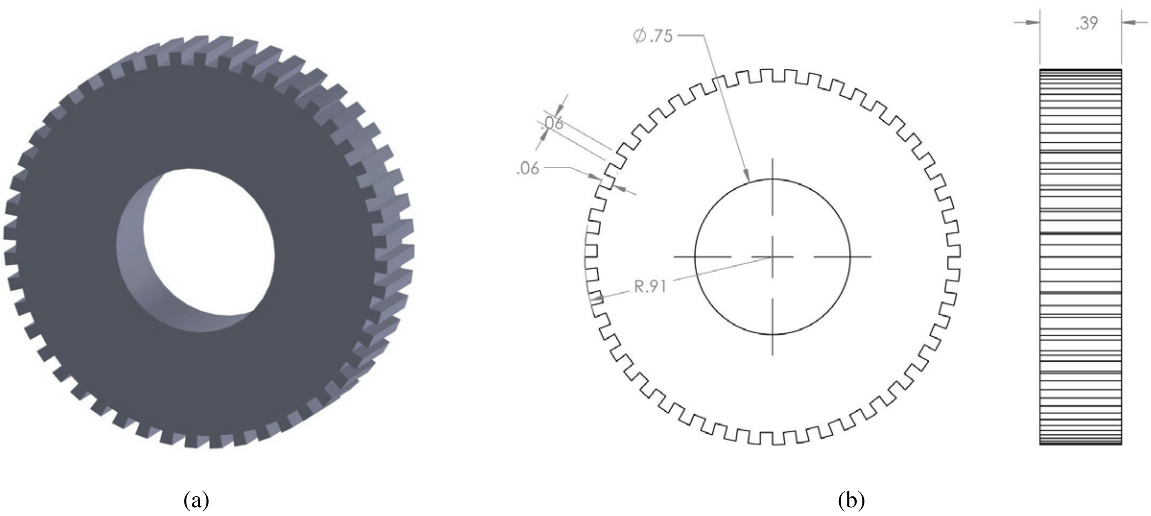


Fig. 44 Shaft Gear, dimensions in inches

13. Avionics and Electronics

As far as our avionics and electronics go everything was off the shelf; the servos, the batteries, all power boards, and the Pix-Hawk 4 Mini were received from external vendors. The connections between all of the electronic components were to be soldered together and then wrapped with electrical tape to ensure no disconnects during flight. The components were to be attached to the gondola frame using a combination of duct-tape and zip ties. The component locations within the gondola frame are depicted in figure 45.

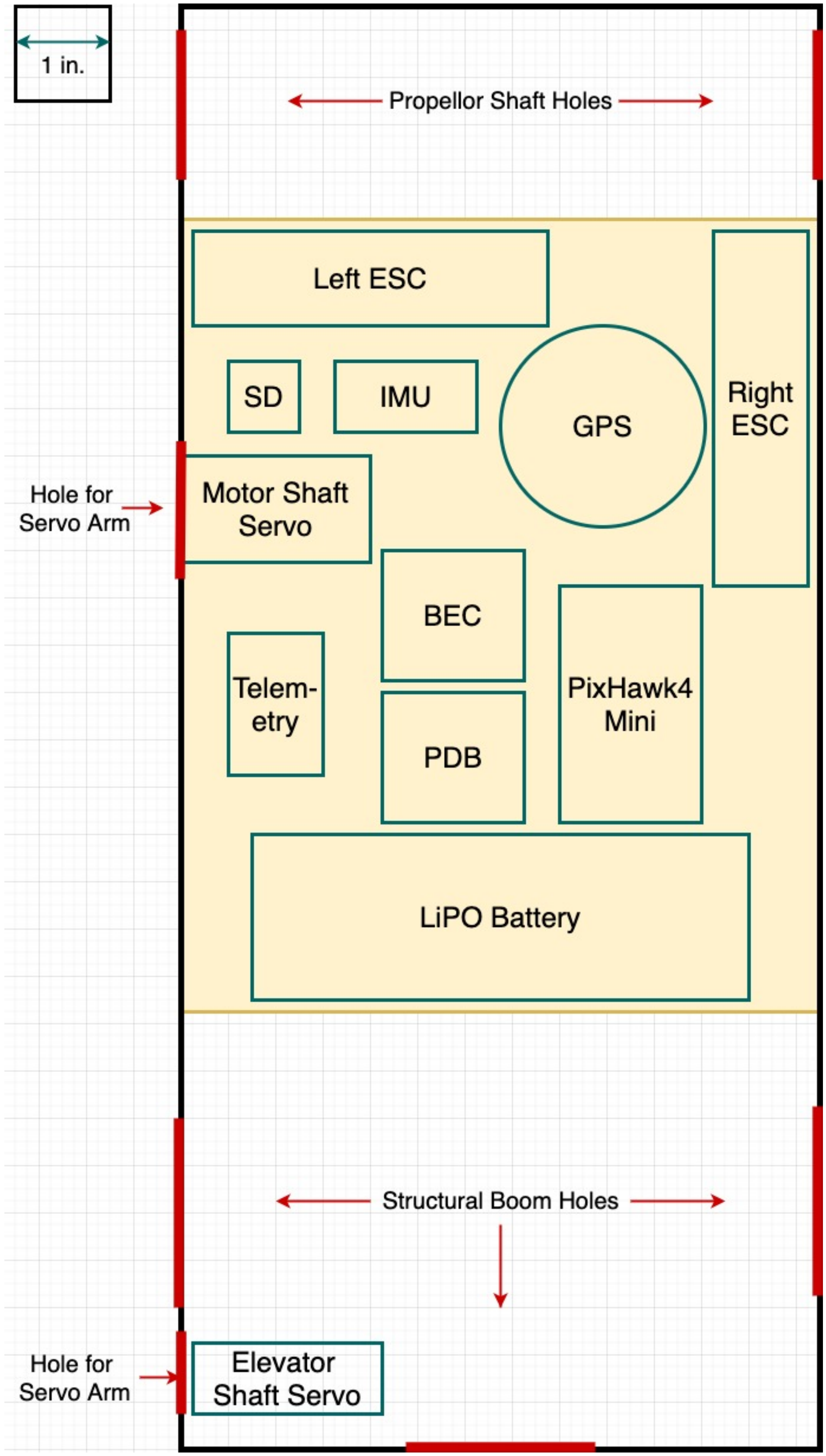


Fig. 45 Component locations within the gondola frame. The yellow box indicates the base plate of the gondola frame and the red lines indicate holes on the side of the frame.

14. Flight Software

The software for controlling the aircraft components during flight was not created by the team. The team opted to used Qgroundcontrol, a free flight software program, for programming the PixHawk4 Mini. This software was configured as a tilt-rotor RC plane as there were no blimp options available. The only adjustments made to the system using this software was setting over 200 parameters[††] This software would also be used to keep track of data incoming from the vehicle throughout the flight.

B. Manufacturing Outcome

The following list defines the manufacturing tasks and their status at the time of halting the project:

- Edge Connectors (3x): 1 left to be 3D printed.
- Side Tubes (2x): Drill M3 bolt holes for T-connection and cut the tubes to length after gluing edge connectors.
- T-Connection: Weld tube 1 to tube 2 and perform the final angled cut on tube 2 using a band saw.
- Tail Boom: Completed.
- Vertical Stabilizers (3x): Completed
- Elevators (2x): Mill holes for servo link connection and for connection to horizontal stabilizer.
- Horizontal Stabilizer: Fixing damage to foam, drilling hole for the tail boom, drilling holes for elevators and servo links, coating surface with epoxy.
- Servo Links (6x): 3D print all the 6 PLA parts.
- Gondola: Completed
- Gondola Components: No components had yet been attached to the frame
- Till Shaft: Completed
- Motor Mounts 2x): 3D print the redesigned model 2x.
- Tilt Shaft Gear and Servo Gear: Laser cut the acrylic sheet.

In the end the team was able to achieve a significant portion of the manufacturing tasks. Pictures of the parts taken when manufacturing stopped are displayed on the appendix.

One of the largest challenges faced by the manufacturing team was the fact that not everything that was ordered got delivered on time, which cause a delay in the manufacturing. In order to minimize the impact of these delays on the schedule, we constantly changed the manufacturing schedule so that time was not wasted and the team is always working. Another challenge faced by the team is that manufacturing a part always takes more time than planed. This is mostly due to equipment setup, parts breaking during manufacturing and ensuring the dimensions are correct. Another reason manufacturing a part took more than expected is because some of the needed machines were under a large demand after the first half of the semester. The team had to find other ways to get the tasks done. A lot of conversation with the experienced machine staff was done in order to obtain the best method to machine each part of our design under each circumstance.

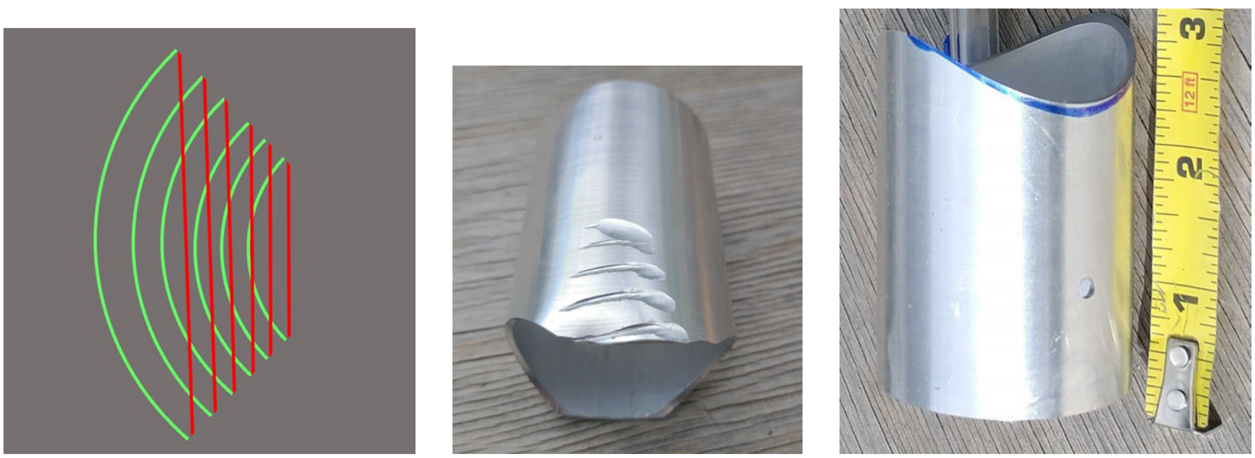
One example was manufacturing the side sheets of the gondola, which were cut from a larger sheet. The first option we considered was using the Wazer water jet abrasive cutter. Due to the thickness of the sheet, 1/5in, the total operation required 90 lbs of abrasive, costing about $150, and had an estimated time of 10 hours. Therefore, the team considered using a 3 axis CNC vertical mill to speed up the process and decrease the cost. When this decision was taken, the 3 axis CNC vertical mills of the aerospace machine had a large demand. Milling carbon fiber releases a residue that can damage the expensive 3 axis machines, so they have to be cleaned after the operation. This usually requires the machine to be closed for approximately one day. For this reason the team changed again the machine to a 2 axis CNC vertical mill that can be cleaned much easier and has a much lower demand. The downside of this change was that the process took about 6 hours, operating the z axis of the

[††]These parameters uploaded to the google drive folder containing all of our teams data.

mill manually. This increased the risk of the operation, since the mill had to be operated with close attention for 6 hours. The repetitive manual operation resulted in one small mistake in an area of the sheet that is not subjected to significant stress. Therefore, the team decided to fill the hole hole with epoxy adhesive and still use the part.

Another significantly challenging part to manufacture was the T-connection. The first challenging task was reducing the thickness of the thin tube in a lathe. Due to the small thickness to diameter ratio of the tube, we had to be careful not to deform it when clamping and machining. The second challenging task was milling the fish mouth on tube 1, figure 46c. This was the most challenging task performed by the manufacturing team on this project. The re son was the same as the previous task, the small thickness to diameter ratio of tube 1. This made fixing this part extremely hard for the milling operation.

The first idea was to use a V-block on a vice to fix one end of the tube, while the mill operates in the other end. Even with the V-block we were not able to apply a significant clamping force on the piece. So we used reduced spindle and feed speeds. This milling was performed according to figure 46a, where the green arcs represent the milling paths and the red lines represent the path of the mill to re position after each pass. Our first try resulted in the piece escaping from the vice fixture and being destroyed, figure 46b.



(a) (b) (c)

Fig. 46 Mill path viewed from above (a), Damaged tube 1 (b), Successful part (c)

To solve this problem, the team milled an aluminum cylinder with an outer diameter equal to the inner diameter of the tube. This cylinder was positioned inside tube 1 when clamping it with a V-block and a vice. This allowed the team to significantly increase the clamping force and achieve a much better quality milling operation. The first passes had no vibration problems and resulted in smooth finish. But once the mill started operating significantly far from the symmetry axis of the tube, a lot of vibrations started to occur. The team was able to minimize the vibrations by reducing the spindle and the feed speeds when operating far from the symmetry axis of the tube, successfully completing the this task, figure 46c.

In addition to the physical manufacturing tasks that the team had difficulty with, there were software tasks that turned out to be unfeasible. Level three of completion for NESSIE included the ability to send IMU data from the ship's payload to the ground station during flight as per request of the customer. Despite having the proper serial bus on both the IMU and the PixHawk4 Mini, the team did not anticipate the difficulty of forwarding this data down to the ground station. PixHawk devices utilize the Mavlink data protocol for communication, and in order to process the IMU data a new driver would have to be developed by the team. In order to still continue the mission despite this problem, a SD card would be attached to the IMU and the data collected would be saved for future processing.

C. Manufacturing Integration

1. Nuts, Bolts Screws and Washers

This project used 3 different screws. The first most used screw is a 6-32 with a length of 5/8in, used 38 times. 24 of these screws are used on the carbon fiber edges of the gondola, 6 for assembling the t-connection to the tubes and 8 for assembling the servos to the gondola. The second most used screw is a M3x0.5mm thread made of steel with a length of 18mm. 8 units of this screw are used to fix the motors to the motor mount. The least used screw is a 6-32 made of steel with a length of 1-1/8in. It is only used 2 times to assemble the motor mounts to the tilt shaft. With the exception of the M3 screws that are screwed to the motors, all the other screws are attached to a 6-32 aluminum hex nut with a width of 7/64in and a height of 5/16in. 6 more of these hex nuts are used on the servo links, summing to 44 nuts. Lastly a nylon washer is placed at every screw and bolt to prevent damage in the parts that they are connecting, summing to 86 washers. The washer have an inner diameter of 0.14in, an outer diameter of 0.32in and a thickness of approximately 0.08in. Thread lock was added to all of the screws that were assembled to prevent them to unscrew with vibrations.

2. Pins

Pins are used only in the connection of the elevators to the vertical stabilizers. 4 pins were planed to be used, one at each end of the two elevators. The pins have a diameter of 3/16in and a length of 2.4in. They were cut on a band saw from a rod with the same diameter and length of 1ft. The pins were planed to be fixed to the elevators first sing epoxy resin. The other end of the pins are connected to holes in the horizontal stabilizer. The pin holes on the horizontal stabilizer are also coated with epoxy resin to prevent damaging the foam..

3. Bearings

Two ball bearings are used to connect the tilt shaft and the gondola part, one at each side of the box. They are ball bearings made out of steel, with a outer diameter of 1.57in, an inner diameter of 0.75in and 0.5in in width. Each bearing weights 0.25 lbs. They are heavy because it was the only non-custom bearing with a larger thickness than the gondola sheet and an inner diameter equal to the outer diameter of the propulsion shaft. Epoxy adhesive was used to assemble the bearing to the gondola and was planed to be used to assemble the bearing to the shaft.

4. Adhesive

The adhesive plays an important roll in the integration of the vehicle. The adhesive that the team used and planned to used was Epoxy, Loctite E-20NS, a structural adhesive. It was intended to be used in several sections of the vehicle. Firstly, it was going to attach the edge connectors to the carbon fiber tubes to avoid any slippage. The adhesive was also used to fix the bearings to the gondola and the Tilt shaft to the bearing. This was decided since a pin was extremely inconvenient, since the holes required would weaken the carbon fiber. The servo links would also be attached to the elevators using the adhesive. The previous is to have a solid connection and avoid any issues when making commands involving the elevators. Lastly, the adhesive would be used to fix the tail boom to the tail, specifically to the inner tube extension connection in the mid-top part of the tail.

5. Kevlar Cord

The cord that got purchased for use was a 7/64in Kevlar cord with polyester. The purpose was to connect the servos in the main gondola to the servo links in the elevators, at the back of the vehicle.

6. Tilt Shaft Timing Belt

The Timing Belt used for the connection between the tilt shaft gear and the servo gear has a outer circle of 285 mm and a width of 10 mm. The pitch of the belt is the same as the pitch of both of the gears, 3 mm.

7. Zip ties

The zip ties had to main purposes as far as the integration of the vehicle goes. The main purpose was to connect the balloon from its attachment points to the edge connectors. This would allow a solid connection between the main body and the balloon. The second purpose was to fix all the avionics to the main gondola to avoid any shift of weight that could cause instability.

5. Verification and Validation

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To verify and validate our design, several different tests were created to ensure NESSIE has a successful maiden flight.

A. Individual Avionic Component Tests

Each component on the aircraft is to be tested individually on the ground prior to any full system tests to ensure that each component will behave as expected during the final flight tests. 24 shows the basic connection setup for each of these components.

1. Electronic Speed Controllers

The two speed controllers power the two motors on the aircraft.These motors are going to be utilized in flight for three purposes, and therefore needed to meet the following three requirements:

- Provide at least 10 N of horizontal thrust to the aircraft during flight
- Generate a yaw moment to turn the aircraft
- Create a downward force of 5 N on the aircraft during descent.

From these requirements we can derive that the maximum amount of forward thrust required will be 10 N, and the maximum amount of reverse thrust required (during any turns) is 2.4 N. Therefore to verify the capabilities of the motors prior to flight the two speed controllers are to be attached to the motors and the maximum force being generated will be compared to the maximum required forces.

2. Motor Shaft Servo

The vehicle has two flight modes that require propulsion: steady level flight and descent. The same two motors are used for both modes and as such they need to be able to switch directions. A servo attached to the motor shaft is being used to direct the motors. This servo needs to be able to switch between the two modes during flight. To validate this component it will be attached to the motor shaft with the motors attached. During transitions he motors will be powered off, so for this test they will be powered off to match realistic flight conditions. The servo will be commanded to switch between the vertical (pointing perpendicular to the gondola frame) and horizontal (pointing parallel to the gondola frame) modes 25 times, and each time it needs to match the desired angle within 2.5 degrees of tolerance. This would be checked using a protractor.

3. Elevator Servo

The elevator on the vehicle's tail (see 25 is designed for small adjustments in the vehicle's pitch during flight. The elevator was designed to cover a range of -15 degrees to +15 degrees in relation to the tail. Once manufacturing of the elevator servo links was completed, the servo would be controlled from the minimum angle of attack to the max in 5 degree increments. The actual measurement needs to be within 2.5 degrees of what the flight software expects for this test to pass. The measurements have a moderately large margin for error so a protractor would be the tool of choice for checking the angle of the elevator at each point.

4. Release Valve

In the case of the vehicle floating above the desired altitude due to buoyancy forces, the first method for decreasing the vehicles altitude would be to release the lifting gas using a solenoid. This solenoid would be attached directly to the balloon envelope and needs to withstand the pressure of the balloon before and during flight. There would have been two tests on the solenoid release valve. The first would be the basic control test where the flight software would be directed to open/close the valve multiple times to ensure control authority. This would be verified visually by a team member. The second test would be to ensure that the valve could withstand the 0.247 psi of pressure expected during flight at 400 ft AGL. This test would be completed by attaching the valve to an air tank with a psi gauge. The air tank would be slowly opened by a team member until the desired pressure of0.247 was reached. If the air pressure gauge reads a constant psi for at least 40 minutes[‡‡] the test the valve would be verified.

B. Balloon Envelope Inflation/Deflation Test

Upon receiving the balloon from our external vendor, we needed to verify that it had no tears/leaks prior to flight. To accomplish this the team filled the balloon up with air in the High Bay within the Aerospace building. Once the balloon was filled with air[§§] the fill valves were shut. Team member first analyzed the entire exterior of the donut-shaped balloon for any obvious leakage. Next the balloon was recorded for 36 hours to see if any deflation occurred.

After the 36 hours were up the footage was analyzed for any noticeable change in shape/deflation. The envelope did not discernibly change shape and no leakage was reported, so the test was considered a pass. This satisfied our 2nd functional requirement and DR 3.1. Since the actual flights would be much shorter than 36 hours, the team was comfortable assuming that the envelope would maintain lift throughout flight.

Following the inflation test, a deflation test was preformed. This test was done to ensure that the craft could descend safely without the aid of the burn wire. The valves on the envelope were opened and the air was allowed to deflate on its own. At varied time intervals a team member measured the height of the torus and calculated its volume using the following equations, where R is the major radius of the torus, r is the minor radius, and h is the height from the floor to the highest point on the surface.

$$\theta = 2cos^{-1}\left(\frac{h-r}{r}\right) \tag{7}$$

$$V = \pi r R(2\pi r - (\theta - sin(\theta))) \tag{8}$$

The measurements for this test were not as precise as other tests, as a team member had to use a tape measure and eyeball the height of the balloon's rounded surface. Despite this, volume estimates were made with a margin of approximately $9.8m^3$. The results of this test can be seen in figure 47. Eventually the valves were pinched shut by the weight of the balloon and the team had to interfere to fully deflate the balloon.

[‡‡]This is derived from the third level of success detailed in 1

[§§]The balloon was considered "filled" when the envelope was sturdy to the touch. It was not created with the intention of expanding greatly during flight, so we were careful to not overfill it.

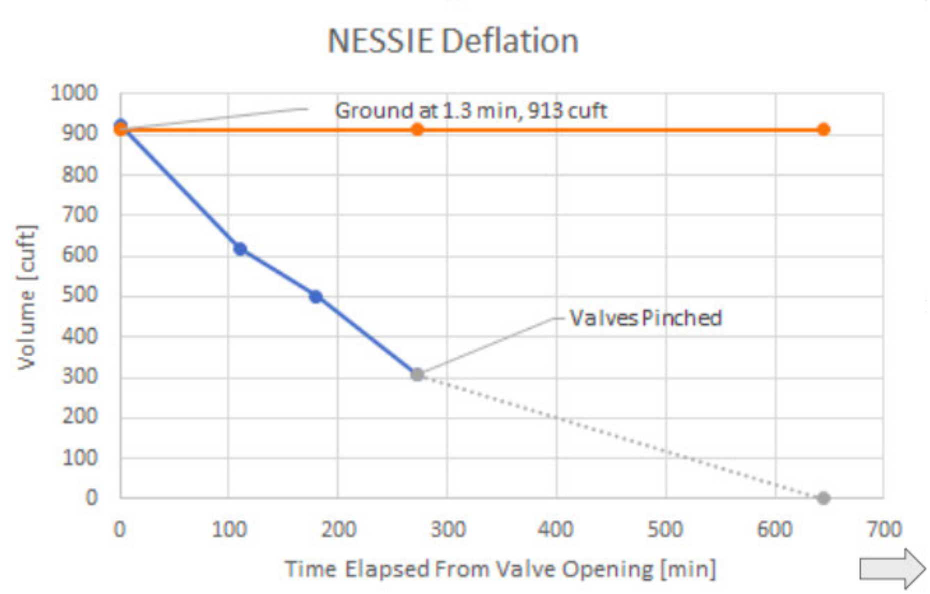

Fig. 47 Plot showing the calculate volume of the flat-bottomed torus throughout deflation. The orange line shows the volume required for a helium-filled craft to be neutrally buoyant and ground level.

The results of this test were mixed. On one hand, the balloon was able to deflate to a volume where the aircraft would be neutrally buoyant at ground level (in Boulder) within 1.3 minutes using air, or 9.7 minutes using helium[¶¶]. This means the aircraft would be able to descend in a reasonable amount of time without use of the burn wire or propellers. However, by extrapolating the results to a full deflation using hydrogen, it would take approximately 6 hours to deflate without human interaction. If hydrogen was the lifting gas in question issue of static discharge need to be considered for the safety of those deflating the envelope.

C. Object Determination Test

The Object Determination Test is designed to provide two sets of results. The first is to verify that the potential motion of the aircraft is low enough that a deconvolution algorithm is capable of backing out any motion from the aircraft due to wind gusts. The second is to provide a baseline set of data that will be used to compare to the fully integrated free-flight test data. The data recovered from the on-board IMU will be compared to the varying frequency motions conducted during this test, to ensure the aircraft moves under the maximum threshold of 6.7 Hz. This test satisfies functional requirement 1, "shall have the ability to take images for orbit determination". Ultimately this test validates that NESSIE provides a suitable platform to capture images of space objects for orbit determination.

This test will undergo 4 separate phases to completion. In the first phase, a RaspberryPi camera will be attached to a mount, along with an IMU sensor. The mount will be attached to a stand, with a central pivot point where the RaspberryPi and IMU are located. This allows the camera system to undergo the best simulated conditions the team expects to encounter as if it were flying with NESSIE. The stand would be placed a specified distance away from a wall where an LED is attached, measured for accuracy, as to simulate what the camera would see when observing a space object. This would take into account the brightness of the LED and the relative size of the "space object". With the LED

[¶¶]this is assuming time-to-deflate and gas density are proportional.

on, the mount would be rotated around, manually by hand, at approximately 0.5 Hz and the camera would capture the image of the LED with a 1-second exposure time. The IMU would then collect motion data. This process would be repeated, varying the frequency all the way up to approximately 6.7 Hz. With the images taken and the data collected and sorted to when the image was taken, the second phase would then commence. From here, the images and data would be passed through a Deconvolution algorithm, which would take the motion captured from the IMU and back it out. Within this deconvolution algorithm is a point spread function, or PSF. The PSF takes in the IMU data that essentially recreates the motion of NESSIE while the image is being taken and uses it to reverse course; allowing for image restoration. Therefore, the more accurate the PSF, the higher quality of the restored image. With the expectation that the algorithm works, the resulting processed image would return the original image of the LED. In the next phase, the image would be passed to a member of the customers graduate team for post-processing, to determine if the centroid of the object could be located with a 10 arc-second/3 sigma precision/accuracy, as demanded by the customer. If the centroid of the "space object" can be determined to within this accuracy then this signifies the images can be restored to the appropriate level, allowing this test to enter it's last phase. During phase one the team administers rotational vibrations by hand at frequencies derived through various models. Phase four allows the team to ensure that those administered disturbances are realistic by conducting a comparison with the IMU data taken from the integrated flight test. If the data taken from the integrated flight test is less "severe" than what the camera endured during phase one, then the Object Determination Test is complete and FR1 is validated. If not, phase one through 3 of this test must be redone, capturing the appropriate disturbances.

Given the situation of not being able to complete this test, we can expect relatively positive results that would confirm our craft will be able to take the necessary images of orbiting objects with the specified precision and accuracy. Beginning with the first phase of the test, taking the images with one second exposure times, using varying frequencies, we would expect to see images similar to figures shown in table 8.

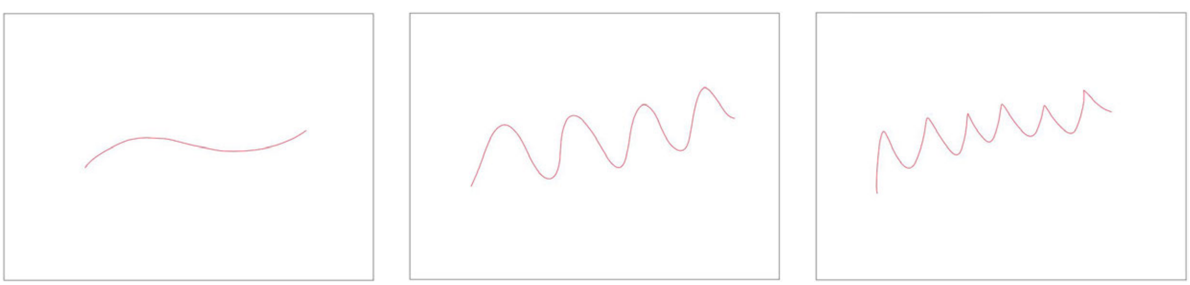

Table 8 One-second exposure LED images in 1 Hz, 4 Hz, and 6 Hz frequencies

Using the IMU sensor data and knowing the distance from the camera to the "space object" LED, we would expect to be able to digitize and plot the motion, which can be seen in table 9.

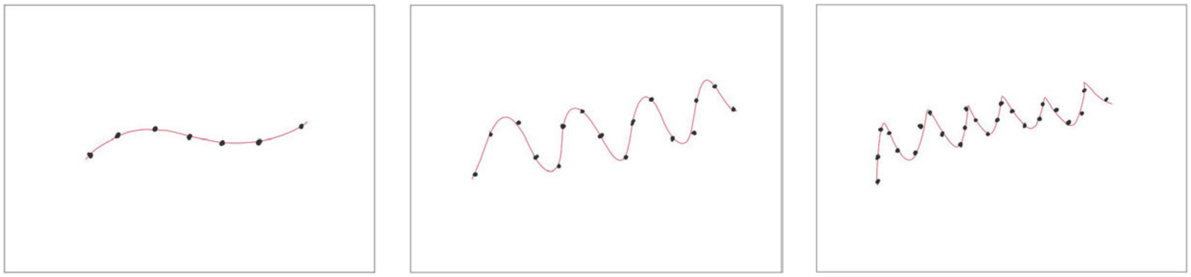

Table 9 LED images with overlaid digitized motion, extracted from on-board IMU sensor

After running the images and data through a deconvolution algorithm, the motion can be extracted and a the final resulting image of the LED "space object" can be determined, resulting in an expected image shown in figure 48.

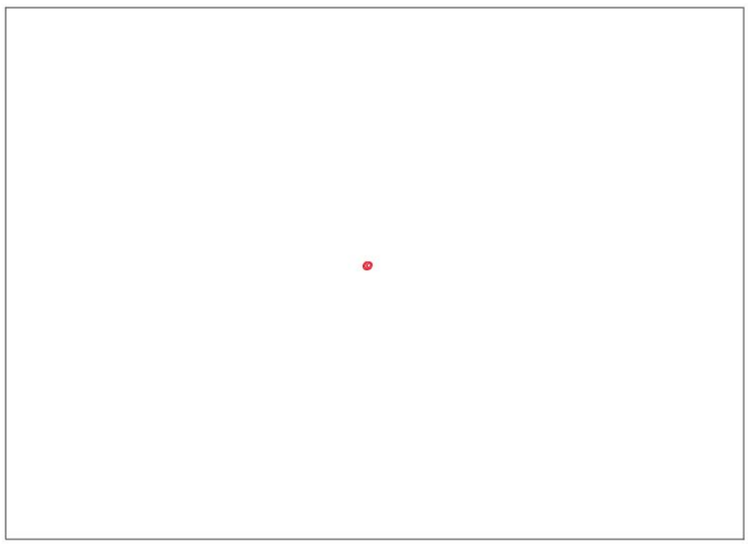

Fig. 48 Image of LED after passing previous images through deconvolution algorithm software, resulting in image with motion backed out

With the resulting image from figure 48, it would then be passed to our customers graduate team for post-processing. It would be expected that the "object's" centroid could be determined within 3-sigma/10 arc-second accuracy/precision.
With the data collected from the IMU and the deconvolution algorithm verified, this information would be used to compare to the fully integrated non-tethered test flight. Provided the aircraft's motion is kept below 6.7 Hz, or whatever frequency the deconvolution algorithm breaks down at, then this test verifies that the aircraft is capable of taking stable enough images of orbital objects and determining their RA and Dec parameters.

D. Integrated Flight Test

In early April we planned on conducting both the indoor and outdoor tests. While we budgeted appropriately for two flights worth of Helium, it would have beeen ideal to conduct both tests in the same day to save money and refilling time. The indoor flight test would take place in the AERO indoor flight test center; NESSIE had three days scheduled - April 6th, 8th, and 13th. These were scheduled with Michael Rhodes who would give us access on those days. We had three days scheduled as we needed to ensure the weather will be ideal for our outdoor flight which will happen in the same day. The outdoor flight ideally will happen in the space behind the AERO building, however, this needed be deemed possible by Dan Hesselius first. In the instance that this location was not possible, there were two other possible locations for our outdoor flight: CU-Boulder South and Table Mountain (pending special permission). For both these locations we would need to use both Helium fills and might not do both tests on the same day. The biggest challenges for the outdoor test would be determining location, creating specific flight patterns, and writing safety plans as the patterns and safety plans will be dependent on the location. Additionally, finding a day that will satisfy our weather requirements might be difficult. However, we were trying to minimize this issue by testing in the morning. Figure 49 shows an example of the setup for the outdoor flight test.

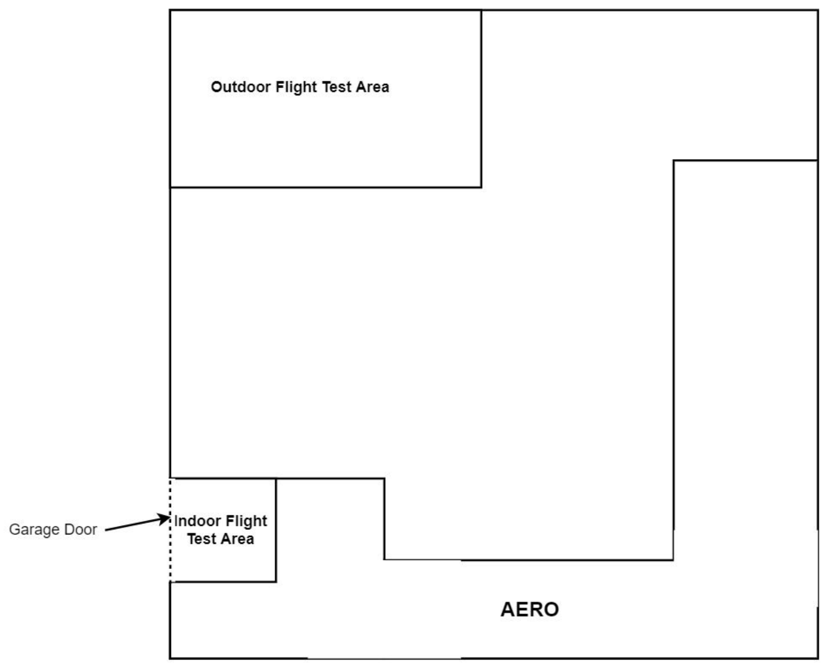

Fig. 49 Outdoor Test Setup

1. Tethered Flight Test

In detail the indoor flight test would be conducted in the indoor flight center as stated previously. The torus would have loose flight lines connected to the envelope arms away from the motors. These lines would be used as a backup safety measure in case the torus does not respond properly to command inputs. The main purpose of this test was to ensure that the aircraft could takeoff and land safely. As the torus does not ever land on the ground this can also be stated as being able to control the aircraft to the altitudes required. The envelope would not be fully filled for this initial test as we wouldn't be flying higher than approximately ten feet above the ground. The test would be conducted the pilot with a few members serving as the ground crew. Initially, the torus will be connected to the flight lines at approximately four feet off the ground. The pilot would then use the handheld controller to arm the motors and input a slight command to increase in altitude using the elevator and throttle. Once the torus was steady at its maximum altitude of about ten feet above the ground, the throttle would be dialed back to approximately 25%. Some simple tests of turning would be performed using differential thrust control. After the pilot feels comfortable with the flight performance, they would input controls to the elevator and motors to command the vehicle back down to approximately four feet above the ground. Once at four feet the motors would be turned off and disarmed before the ground crew would take control of the vehicle again. Figure 50 represents the setup for the indoor area and Figure 51 shows the CONOPS for the indoor test.

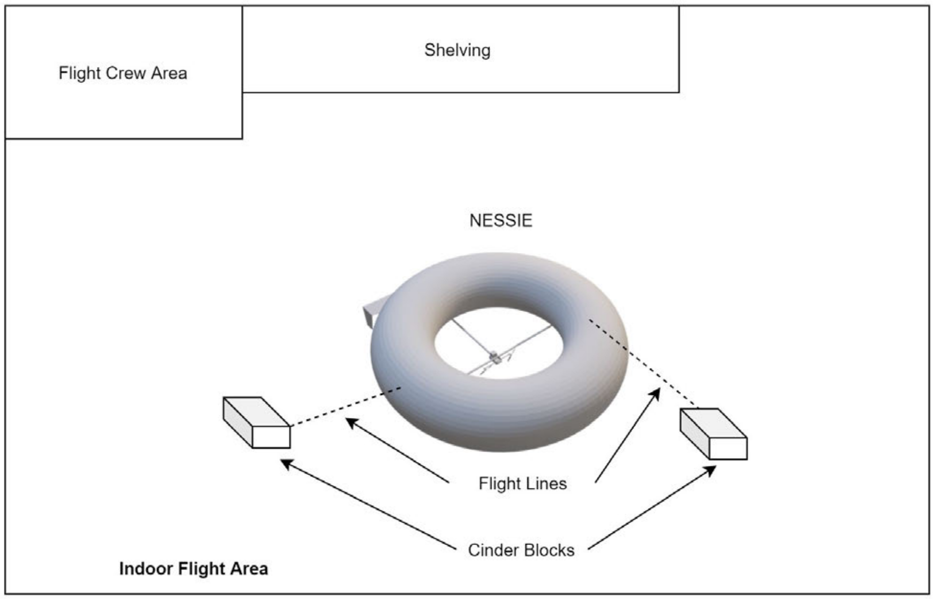

Fig. 50 Indoor Test Area

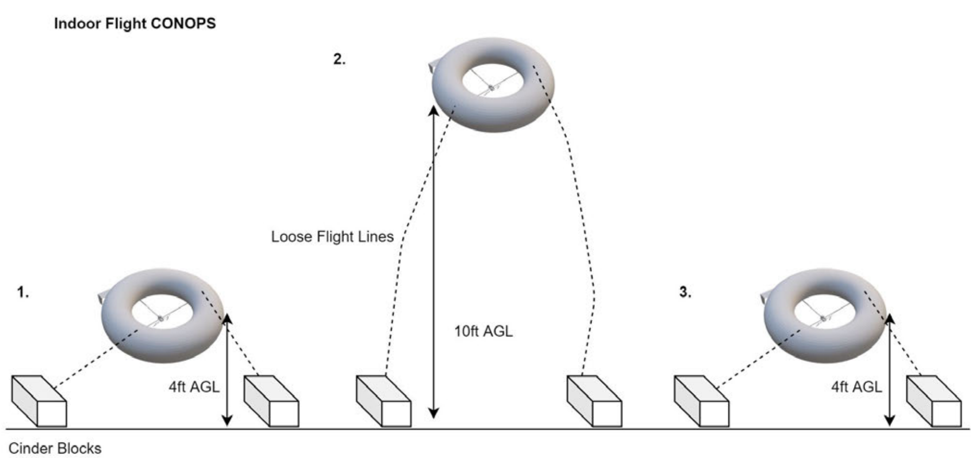

Fig. 51 Indoor Test CONOPS

2. Non-tethered Flight Test

The outdoor flight test would have also included an airworthiness requirement. Dan Hesselius would be on location to assist the pilot in the airworthiness tests as well as serve as the Visual Observer (VO) per the FAA. The flight test would be initiated by filling the envelope to the required amount to reach the maximum altitude. It's important to note that if the flight test were to take place behind the AERO building the maximum altitude would be 80 feet above the ground due to the proximity of the Boulder Municipal Airport. If the test was conducted at CU-Boulder South or the Table Mountain the maximum altitude would be 400 feet above the ground level. In the case of either of these locations, the envelope wpuld need to be deflated after the indoor flight test. Then the Helium tank and equipment as well as the aircraft would be transported to the location before refilling to the necessary volume. Continuing on the test plan, after the envelope is fully filled it will be tethered to the ground at approximately four feet above the ground using provided tethers from the vendor and stakes in the grass. After a short surface check performed by the pilot (satisfying both the pilot and Dan), the tethers will be released while the motors are disarmed. Once the flight area is clear of team members and all personnel the motors will be armed. At this point the torus should already be climbing due to the Helium. The ground station will be tracking the IMU and GPS data calling out the altitude. Once the torus reaches the maximum altitude, Helium will be vented to ensure the vehicle stays at that point. At this point, a second full surface check will be performed to ensure the vehicle is still behaving properly and commands are still being sent/received. To perform the airworthiness test the pilot will provide inputs to the motors using differential thrust so that the vehicle will follow a box pattern in the air. This box pattern will satisfy both the airworthiness conditions as well as the station keeping requirement of NESSIE. All the data from the IMU will be stored on the Pixhawk 4 Mini on an SD card. Additionally, the flight time will last approximately 30 minutes to an hour depending on satisfaction of controllability from Dan and the pilot. The final aspect of the test will be releasing gas from the valve until the torus reaches approximately ten feet above the ground - ensuring that the volume of the balloon does not drop so much that it will fully fall out of the sky or catch on the motors. At the same time, the pilot will input commands to the motors and the elevator to help the torus land. Once the torus is at approximately four feet above the ground, the pilot will disarm the motors and the ground crew will attach the flight lines to the vehicle as done in the beginning. Following a debrief and full surface check, the ground crew will full deflate the balloon and store the vehicle. The GPS and IMU data will then be stored for further analysis. Figure 52 represents the setup for the outdoor area and Figure 53 shows the CONOPS for the outdoor test.

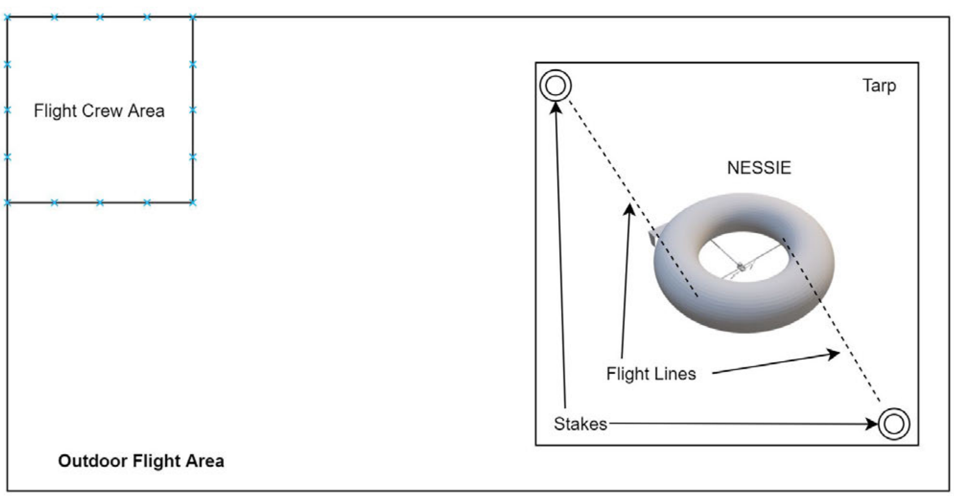

Fig. 52 Outdoor Test Area

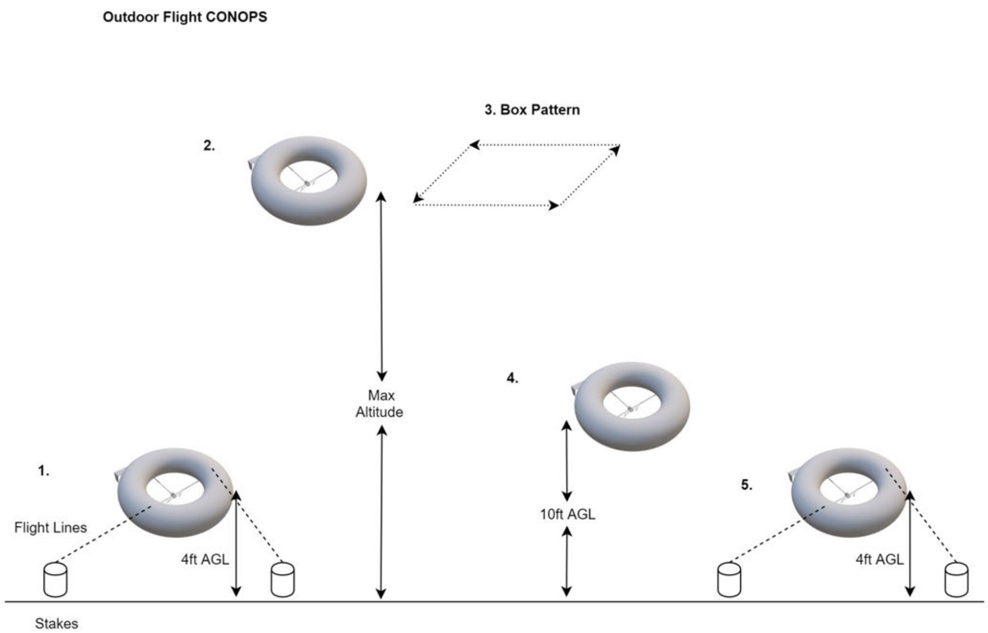

Fig. 53 Outdoor Test CONOPS

6. Risk Assessment and Mitigation

Author 1: Matthew Jonas

A. Risk Identification

In order to better identify possible risks for the project, the set of risks were split into two different categories: logistical risk and component risk. Logistical risks deal primarily with the acquisition of parts and the integration and subsequent testing of these parts. Component risks deal with risks inherent to the various components of the project, focusing on potential structural and electrical issues. The logistical risk components were further split into the following subcategories based on the different expected phases of the project:
1.) Ordering/shipping of parts and components
2.) Receiving/storage of parts and components
3.) Assembly/manufacturing of system/sub-systems
4.) Testing
5.) Modifications
6.) Final Testing

The component risk considerations were split into the following subcategories based on their overarching component type:
1.) Structural
2.) Electrical
3.) Software

1. Logistical

1.) Ordering/shipping of parts and components

During the ordering and shipping phase, project progress is limited by the timeline of the vendors from whom parts and components are being ordered from, along with the method of which they will be shipped. Manufacturing delays, communications issues, and slow deliveries can all impact downstream processes, which then directly impact the timeline and success of the mission.

2.) Receiving/storage of parts and components

When supplies are received in the mail, they can get misplaced, damaged, or simply cannot be stored due to safety or size limitations. If components are lost or not handled properly upon receipt they may need to be re-ordered, resulting in extra time delays and unaccounted for costs. Additionally, if storage space is not sufficient, additional costs could be incurred that push the project over budget.

3.) Assembly/manufacturing of system/sub-systems
While manufacturing or assembling parts and components, the risk for damage goes up, along with the risk of injury, since we will be working with batteries, machinery, cutting tools, et cetera. These risks have greater weight, especially when there is the possibility of personal harm or injury. Any form of injury to the project team or testing staff could jeopardize the entire mission given the large scope and the project and the limited number of people available to work on it.

4.) Testing
The likelihood of catastrophic incidents increasing significantly during the testing phase of the project. Testing will provide the team with an opportunity to see if models built during the design phase accurately predicted the behavior of the applicable sub-systems. Significant inaccuracy in these models could result in complete system failure, loss of entire system, or injury to project or testing team members. These risks generally have the highest importance and will be evaluated with great detail.

5.) Modifications
This phase is generally a repeat of the Assembly/manufacturing phase and will be omitted from the analysis, due to repetition.

6.) Final Testing
This phase is generally a repeat of the Testing phase and will be omitted from the analysis, due to repetition.

2. Component

1.) Structural
This mission involves a large balloon envelope to create a neutral-density aircraft, capable of flying at altitudes of 400 ft AGL. Due to the large size of the envelope, solid structures to both attach the gondola to the envelope and to hold the payload are required. Several failure modes are possible within the structural components of the mission.

2.) Electrical
NESSIE has several components which either produce or consume power. Some electrical components are more prone to failure than others, and current drawn in the system generates heat. Thus, electrical components present the opportunity for several failure modes to occur.

3.) Software
NESSIE relies on flight control software to communicate commands between the aircraft and ground station, and to accurately transform manual control inputs into adjustments of motor speed and control surface deflection. The system also uses software to record data from the IMU and other on-board sensors and then relay this information down to the ground station. These requirements mean there are several possible software related failure modes.

3. Logistical Risk Assessment

Ordering/shipping of parts and components
1.) *Costs exceed project budget* - If the costs of the overall project exceed the budget, then the project cannot be completed and no product will be delivered to the customer.
2.) *Components/parts are on back-order* - If the components are on back-order, then the project will

face delays that could impact the delivery of a completed project.
3.) *Shipping time is excessive for project* - If the shipping time from vendor is too long, then the project will face delays that could impact the delivery of a completed project.
4.) *Materials are damaged/destroyed during shipping* - If ordered parts/components are damaged or destroyed during shipping, then additional parts/components will need to be re-ordered, leading to delays that could impact the delivery of a completed project.

Receiving/storage of parts and components
1.) *Parts/components are misplaced/lost during receiving* - If parts/components are not tracked and are subsequently lost during reception, then they will need to be re-ordered, leading to delays that could impact the delivery of a completed project.
2.) *Parts/components are damaged/destroyed while unpacking/storing* - If parts/components are damaged or destroyed while receiving or placing in storage, then they will need to be re-ordered, leading to delays that could impact the delivery of a completed project.
3.) *Storage space is insufficient/inadequate* - If there is not enough storage space, or no storage space for the components or assembled sub-systems/system, then additional storage space outside of the school would need to be obtained, incurring additional costs that could use up any remaining funds to help complete the project.

Assembly/manufacturing of system/sub-systems
1.) *Materials are broken* - If the parts/components or sub-system is broken or damaged during manufacturing or assembly, then additional parts will need to be ordered, incurring additional costs and time to bring the project back on schedule and deliver a final completed project.
2.) *Parts/components not manufactured to specs* - If the components made by vendors or manufactured by team are not to spec needed for the project, then parts will need to be re-ordered, incurring additional costs and time that could delay the completion of the final project.
3.) *Insufficient spare parts* - If components/parts are lost and there are not enough spares, then additional parts will need to be ordered, which adds additional cost and time to the project that could delay the completion of the final project.
4.) *Physical injury to personnel* - If any physical harm occurs during manufacturing or assembly, then the project could be put on hold by the school, personnel are no longer able to contribute to the completion of the project.

Testing
1.) *Craft is destroyed* - If the fully-assembled craft is destroyed, either leading up to or during testing, then a new craft will need to be constructed, putting major delays on the success of the project.
2.) *Physical injury to personnel or bystanders* - If personnel or bystanders are injured during testing, then the project could be put on hold by the school, personnel are no longer able to contribute to the completion of the project and bystanders could sue the school for lack of safety protocols.
3.) *Pilot is unavailable for testing* - If the team pilot is not available, or their COA is somehow suspended, then testing would be delayed, impacting the timeline of the project.
4.) *No data is collected* - If no data is collected during testing, then the electronic components will need to be analyzed to ensure proper use and testing would need to be rescheduled, adding delays to the project.

4. Component Risk Assessment

Structural

1.) *Propellers break during testing* - If the propellers break off during testing, then they could inadvertently hit a person or cut through the balloon envelope, both of which could drastically delay the project timeline.

2.) *Balloon envelope ruptures/tears* - If the balloon envelope ruptures or tears while filling, transporting, or testing, a new balloon envelope would need to be ordered, adding considerable delay time to the project.

3.) *Linkages break* - If the linkages connecting the gondola to the balloon envelope fail during testing, then the gondola could fall to the ground, likely experiencing catastrophic failure, which would require new parts and assembly time, adding to the delay of the project.

4.) *Tail boom break during landing* - If the tail and tail boom break during landing, then the craft cannot be controlled and a new tail and tail boom would need to be ordered/assembled, adding delays to the project.

5.) *Line to control surface snaps* - If the line to the tail elevator snaps during testing, then the craft could be uncontrollable and the system and all data could be lost, resulting in project failure.

Electrical

1.) *Battery overheats/explodes during testing or while charging* - If the battery is not handled per the instructions of the manufacturer, then the battery could overheat/overcharge either while charging or during flight, leading to injury, catastrophic failure of the craft, or data loss, drastically impacting the success of the project.

2.) *Motors seize/break during testing* - If the motors seize during testing, then control of the craft would be lost leading to system failure and loss of data, impacting the success of the project.

3.) *Servos seize/break during testing* - If the servos seize during testing, then control authority of the craft will be diminished, creating potential to lose the craft and all data, impacting the success of the project.

4.) *IMU is non-responsive or collects no data* - If the IMU is installed incorrectly, or is faulty, then data could be lost, impacting the success of the project.

5.) *PixHawk 4 Mini is non-responsive or does not transmit/receive commands* - If the PixHawk 4 Mini is faulty and does not transmit or receive commands or data, then the craft could be lost, along with the data, impacting the success of the project.

Software

1.) *IMU data isn't stored properly* - If the IMU isn't properly set up to collect data during the flight, there might not be useful data during the test flights, impacting the success of the project.

2.) *Flight software is non-responsive or does not transmit/receive commands* - If the flight software does not transmit or receive commands or data, then the craft could be lost, along with the data, impacting the success of the project.

3.) *Manual commands are transmitted incorrectly* - If the commands by the pilot aren't transmitted correctly the aircraft would be extremely difficult or even impossible to fly, drastically impacting the success of the project.

5. Risk Matrix Determination

These risks were then weighted and placed into a risk matrix to help determine which risks were most important to keep an eye on and which risks needed to be mitigated most. This risk matrix method is

described in the following paragraphs.
In Fig. 54, the main cross-elements to each risk is the likelihood it is to happen and what consequence is a result from it happening. For likelihood, two components are used to evaluate each risk: Probability and Frequency. For Consequence, five components were used to evaluate each risk: People, Data, Facilities, Cost, and Time. For each component, the weighted measures are provided, to help identify the severity of the likelihood and consequence.

					Consequence				
NESSIE: Risk Rating Matrix				People	Single minor injury to single personnel	Multiple minor injuries to a single person	Single moderate injury to single person or multiple minor injuries to multiple people	Multiple severe injuries to one person	Multiple severe injuries to multiple personnel
				Data	Little data loss				No data acquired
				Facilities	Available facilities space		Limited facility space available		No available facilities space
				Cost	< $10 Loss	$10 ~ $100 loss	$100 ~ $500 loss	$500 ~ $1000 loss	Exceeds $1000 loss
				Time	< 1-day delay	1-day ~ 1-week delay	1~2-week delay	2-week ~ 1-month delay	Exceeds 1-month delay
					1	2	3	4	5
	Probability	Frequency			Insignificant	Negligible	Moderate	Extreme	Significant
Likelihood	> 85%	> 5	E	Almost Certain	11	16	20	23	25
	50% ~ 85%	4 ~ 5	D	Likely	7	12	17	21	24
	20% ~ 50%	3 ~ 4	C	Possible	4	8	13	18	22
	5% ~ 20%	2 ~ 3	B	Unlikely	2	5	9	14	19
	< 5%	< 2	A	Rare	1	3	6	10	15

Fig. 54 Risk matrix used to help determine the severity of each risk.

Based on Fig. 54, each risk was evaluated using equation 9, where the total risk weight is determined by the product of the maximum value in the likelihood and maximum value in the consequence.

$$Risk = max(Likelihood) * max(Consequence) \tag{9}$$

The following figures show how the logistical and component risks were weighted:

		Likelihoods		Consequences					Total
		Probability	Frequency	People	Data	Facilities	Cost	Time	
Phase I	Costs exceed budget	1	~	~	~	~	5	~	5
	Items are on backorder	2	~	~	~	~	~	3	6
	Shipping time too long	1	~	~	~	~	~	3	3
	Parts are broken during shipping	1	~	~	~	~	3	3	3
Phase II	Items misplaced	2	~	~	~	~	3	3	6
	Items damaged while unpacking	1	~	~	~	~	3	3	3
	Storage space insufficient	3	~	~	~	5	3	~	15
Phase III	Materials broken	1	1	~	~	~	3	3	3
	Parts not manufactured to spec	1	~	~	~	~	3	3	3
	Insufficient spare parts	1	1	~	~	~	3	3	3
	Physical Injury	1	3	2	~	~	~	4	12
Phase IV	Craft is destroyed	3	3	2	5	~	5	3	15
	Physical injury	1	3	2	~	~	~	4	12
	Pilot unavailable	1	3	~	~	~	2	1	6
	No data collected	1	3	~	5	~	~	1	15

Fig. 55 Logistical risks and their calculated weight totals.

		Likelihoods		Consequences					Total
		Probability	Frequency	People	Data	Facilities	Cost	Time	
Structural	Propellers break during testing	3	2	1	~	~	5	4	15
	Balloon envelope ruptures/breaks	2	1	~	~	~	5	4	10
	Linkages break	1	1	~	~	~	4	3	4
	Tail and boom break during testing	3	1	~	~	~	3	3	9
	Line to control surface snaps	2	1	~	~	~	1	1	2
Electrical	Battery overheats/explodes	4	1	2	1	~	5	3	20
	Motors seize/break during testing	1	1	~	~	~	3	3	3
	Servos seize/break during testing	2	1	~	~	~	2	3	6
	IMU is non-responsive or collects	1	1	~	~	~	1	1	1
	PixHawk Mini is non-responsive	1	1	1	5	~	3	3	5

Fig. 56 Component risks and their calculated weight totals.

6. Hydrogen Risk Identification

Risk identification was also heavily used in generating the safety proposal for hydrogen gas, as this proposal detailed the potential risks involved in using a hydrogen lifting gas over helium. Some of the major identified risks were:

1.) *Hydrogen tank is mishandled* - The hydrogen tank itself was a risk, as mishandling could cause the tank to move violently or explode since the contents were under pressure.

2.) *Hydrogen is exposed to a static electricity ignition source during inflation* - Static shock could cause the hydrogen gas within the envelope to explode, harming people and equipment in close proximity.

3.) *Hydrogen is exposed to a static electricity ignition source during deflation* - Static shock could cause the hydrogen gas within the envelope to explode, harming people and equipment in close proximity.

4.) *Hydrogen is exposed to an ignition source during flight* - If the hydrogen within the balloon were to explode it would cause severe damage to the vehicle and people in close proximity.

7. Global Pandemics

One thing to note is that global pandemics and disasters were not considered on this risk matrix as they are extremely infrequent and almost impossible to predict and mitigate, making any preparations infeasible. However, in light of recent events it should be noted that a global pandemic would fall under the "rare" likelihood category and the "significant" consequence category, giving it an effective risk factor of 15.

B. Risk Tracking

Risk tracking was done through the use of change management documents in addition to monitoring of component arrival, manufacturing, assembly and testing.

1. Logistical Risk Tracking

Ordering/shipping of parts and components

1.) *Costs exceed project budget* - Monitor actual cost of parts relative to expected cost.
2.) *Components/parts are on back-order* - Ensure product availability is taken into consideration when attempting to order parts.
3.) *Shipping time is excessive for project* - Ensure shipping times are accounted for in the project schedule.
4.) *Materials are damaged/destroyed during shipping* - Check product status after receiving the shipment to verify potential damage/destruction.

Receiving/storage of parts and components

1.) *Parts/components are misplaced/lost during receiving* - Ensure item reception checklist is properly maintained.
2.) *Parts/components are damaged/destroyed while unpacking/storing* - Ensure item reception checklist is properly maintained.
3.) *Storage space is insufficient/inadequate* - Ensure tests using storage spaces are on-track for scheduled days.

Assembly/manufacturing of system/sub-systems

1.) *Materials are broken* - Ensure testing procedures and checklists are sufficient to prevent damage to materials and update as necessary.
2.) *Parts/components not manufactured to specs* - Ensure manufacturing procedures are sufficient to produce parts to within specifications and update as necessary.
3.) *Insufficient spare parts* - Track usage of spare parts so that more can be ordered in advance.
4.) *Physical injury to personnel* - Monitor potential hazards to personnel and ensure that they know where to find proper safety procedures.

Testing

1.) *Craft is destroyed* - Discuss operating procedure and test checklists to ensure understanding and identify potential additional safety measures.
2.) *Physical injury to personnel or bystanders* - Discuss safety checklist and operating procedures to ensure understanding and identify potential additional safety measures. Ensure that bystanders know where to get safety information.
3.) *Pilot is unavailable for testing* - Ensure that pilots are still available for testing as the test date approaches.
4.) *No data is collected* - Use subsystem testing checklists and known subsystem issues to inform potential issues on data acquisition.

2. Component Risk Tracking

Structural

1.) *Propellers break during testing* - Testing of propellers will be tracked.
2.) *Balloon envelope ruptures/tears* - Ensure that manufacturer handling instructions are sufficient to prevent damage to balloon envelope.
3.) *Linkages break* - Ensure that manufacturer handling instructions are sufficient to prevent damage to balloon linkages.
4.) *Tail & boom break during landing* - Make sure that capture strap points on balloon envelope are easily accessible and assess effectiveness of the capture mechanism.
5.) *Line to control surface snaps* - Ensure lines to control surfaces are considered during manufacturing and integration.

Electrical

1.) *Battery overheats/explodes during testing or while charging* - Verify heat of battery during charging process.
2.) *Motors seize/break during testing* - Ensure that visual inspections are sufficient to verify integrity of motor components.
3.) *Servos seize/break during testing* - Ensure that visual inspections are sufficient to verify integrity of servo components.
4.) *IMU is non-responsive or collects no data* - Track issues related to IMU data collection.
5.) *PixHawk 4 Mini is non-responsive or does not transmit/receive commands* - Record issues related to Pixhawk 4 Mini to identify any potential problems.

Software

1.) *IMU data isn't stored properly* - Track issues related to IMU data collection.
2.) *Flight software is non-responsive or does not transmit/receive commands* - Record issues related to flight software to identify any potential problems.
3.) *Manual commands are transmitted incorrectly* - Record issues with incorrect transmission and cross-check with other potential software-related issues.

C. Risk Mitigation

Risks were mitigated by examining their risk rating as generated by the matrix and then finding ways to mitigate potential risks, prioritizing risks with higher likelihood first.

1. Logistical Risk Mitigation

Ordering/shipping of parts and components

1.) *Costs exceed project budget* - Additional funds can be requested from EEF to help increase the project margin and ensure all costs incurred are under budget.
2.) *Components/parts are on back-order* - Additional vendors should be sought for, in case parts/components are on back-order.
3.) *Shipping time is excessive for project* - Additional vendors should be sought for, in case parts/components take to long for delivery.
4.) *Materials are damaged/destroyed during shipping* - Unable to mitigate.

Receiving/storage of parts and components

1.) *Parts/components are misplaced/lost during receiving* - Create a checklist for receiving items and

cataloguing where each part is placed.
2.) *Parts/components are damaged/destroyed while unpacking/storing* - Create a checklist for receiving items and proper care.
3.) *Storage space is insufficient/inadequate* - Reduce number of tests and conduct tests on same day, so envelope does not have to be stored inflated.

Assembly/manufacturing of system/sub-systems
1.) *Materials are broken* - Create testing procedures and checklist for conducting tests.
2.) *Parts/components not manufactured to specs* - Follow the "measure twice, cut once" philosophy for manufacturing.
3.) *Insufficient spare parts* - Ensure when ordering enough spare parts are ordered, where necessary, depending on how easily they can be broken.
4.) *Physical injury to personnel* - Use CU safety protocols when working in any shops, as well as ensuring all members using machining tools have completed the appropriate training.

Testing
1.) *Craft is destroyed* - Create operating procedure and test checklist for safe testing of full system.
2.) *Physical injury to personnel or bystanders* - Use CU safety protocols, enlist spotters to cordon off test zone, create safety checklist and standard operating procedures.
3.) *Pilot is unavailable for testing* - Utilize a backup pilot from CU, who has an approved COA.
4.) *No data is collected* - Create testing checklist and monitor data acquisition during flight test.

2. Component Risk Mitigation
Structural
1.) *Propellers break during testing* - Use standard operating procedures from manufacturer to ensure proper use and installation.
2.) *Balloon envelope ruptures/tears* - Follow handling instructions from manufacturer.
3.) *Linkages break* - Follow handling instructions from manufacturer.
4.) *Tail & boom break during landing* - Utilize capture strap points on balloon envelope before craft fully lands
5.) *Line to control surface snaps* - Ensure tube lines for control line are smooth and free of fraying objects.

Electrical
1.) *Battery overheats/explodes during testing or while charging* - Use standard operating procedures from manufacturer to ensure proper charging and use.
2.) *Motors seize/break during testing* - Follow standard operating procedures from manufacturer to ensure proper use and visually inspect before use.
3.) *Servos seize/break during testing* - Follow standard operating procedures from manufacturer to ensure proper use and visually inspect before use.
4.) *IMU is non-responsive or collects no data* - Monitor data acquisition from craft during testing.
5.) *PixHawk 4 Mini is non-responsive or does not transmit/receive commands* - Test connectivity of sub-systems before allowing craft to take off.

Software
1.) *IMU data isn't stored properly* - The IMU data collection process will be verified and tested prior

to flight.

2.) *Flight software is non-responsive or does not transmit/receive commands* - Transmission of commands to motors and control surfaces will be tested and verified before and after integration with the aircraft.

3.) *Manual commands are transmitted incorrectly* - Transmission of commands to components will be tested prior to flight and inputs required during flight will be simulated to ensure the craft is able to be effectively piloted.

3. Hydrogen Risk Mitigation

In addition to the items above, a significant amount of time was spent researching and devising methods for mitigation of hydrogen lifting gas.

1.) *Hydrogen tank is mishandled* - Have trained and trusted individuals from the CU Aerospace Department assist with transportation and handling of the hydrogen tank.

2.) *Hydrogen is exposed to a static electricity ignition source during inflation* - Devise a safe filling procedure with assistance from CU Aerospace Department staff and Air Force guidelines which seeks to eliminate the potential of static shock.

3.) *Hydrogen is exposed to a static electricity ignition source during deflation* - Devise safe deflation procedures with assistance from CU Aerospace Department staff and Air Force guidelines which seeks to eliminate the potential of static shock. Test procedures for viability.

4.) *Hydrogen is exposed to an ignition source during flight* - Design component placement such that potential ignition sources are significantly removed from the shell of the balloon.

D. Impacts on the Project

Many of the risks realized in the project were logistical risks, dealing with the delivery of components on schedule. A significant amount of components were delivered late, which delayed progress on manufacturing and testing. Another risk that presented itself was the change in expected cost of components, especially the carbon fiber, which ate into margins in the budget. Both of these risks were mitigated with extra time and money built into the schedule and budget respectively, as a result of the risk mitigation processes previously discussed.

Another large impact of risk on the project involved the potential use of hydrogen gas, as the risks involved with hydrogen gas shaped a large portion of the development of the project as a whole.

However, the largest impact on the project was the effects of COVID-19 as this permanently stalled progress on the project. Unfortunately, this was a risk that could not be reasonably mitigated, and instead had to be worked around as much as possible. Due to the closure of facilities and social distancing efforts, progress was halted on manufacturing and testing, meaning that instead results had to be drawn from what the group had accomplished thus far.

7. Project Planning

Author 1: Joseph Grengs, Author 2: Cavan Roe

During the formation of the team at the beginning of the fall semester, individuals had to identify this project as the team they were interested in. With all of the people stating their interest, we looked at the project scope and tried to assess what roles/skills would be needed to be on the team. From there, everyone 'interviewed' for specific roles that had multiple people interested in them. Once a person was added to a role, they were then included in the decision-making of who else would join the team. This was done until the team was 12 strong.
With the team formed, a Project Manager was picked immediately, so as to be the main point of contact for the customer, as well as take on the responsibilities of time sheets, meetings, etc... During the scoping of the project, the roles were solidified and the people who vied for each role got their role, with exception for Systems Engineer. Two people were interested in the role, so they were interviewed by the Project Manager, with each pitching their experience and skills. The resulting team organization can be seen in figure 57.

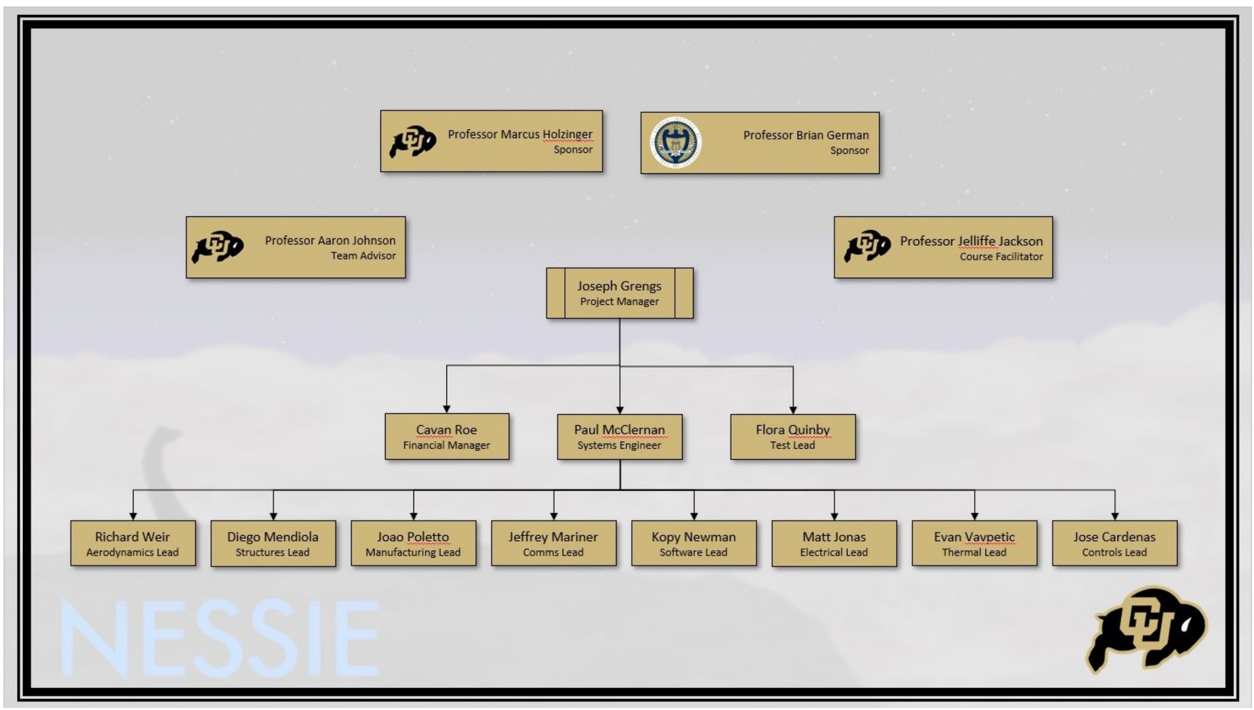

Fig. 57 NESSIE Team Structure/Organizational Chart

One thing to note about the organizational chart is the above is the final hierarchy structure of the team. Originally, there was an Optics Lead position, but due to a rush de-scoping of the project halfway through the semester, the Optics Lead was removed and replaced with an Aerodynamics Lead, since the project reduced to designing an aircraft from scratch.
Once the team was fully defined, each lead role was to review the project scope and determine what work or tasks would be necessary to design, manufacture, and test, to complete the project. Based on the feedback from the team, a Work Breakdown Structure (WBS) was completed, as can be seen in figure 58.

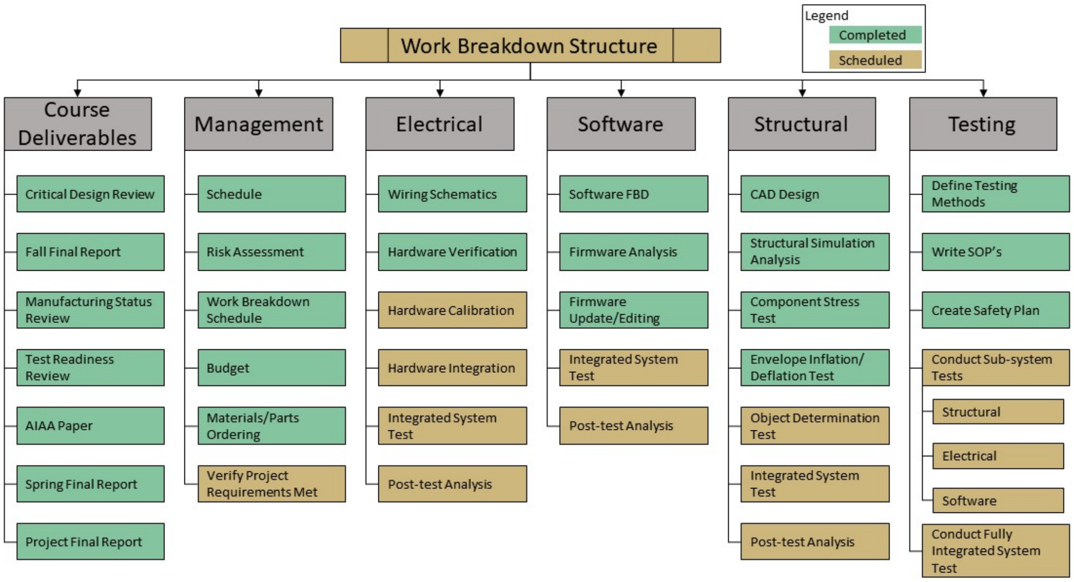

Fig. 58 NESSIE Work Breakdown Structure

Based upon the WBS, the Project Manager and Systems Engineer created an overarching schedule for the project, with due dates for ordering parts/components, to manufacturing assembly, to integration, and finally testing. The schedule for the project, along with the critical path, the items deemed essential to being completed, in order to keeping the project moving along. As can be seen in figures 59 and 60, the critical path ends on testing, but is branched from 3 different sources. The first, is the manufacturing and assembly of the aircraft. The second is the development of the electronics and avionics through testing, the final is the testing of the balloon envelope and control surfaces. These items are crucial to being completed, as if they are not, the final fully integrated system cannot be tested.

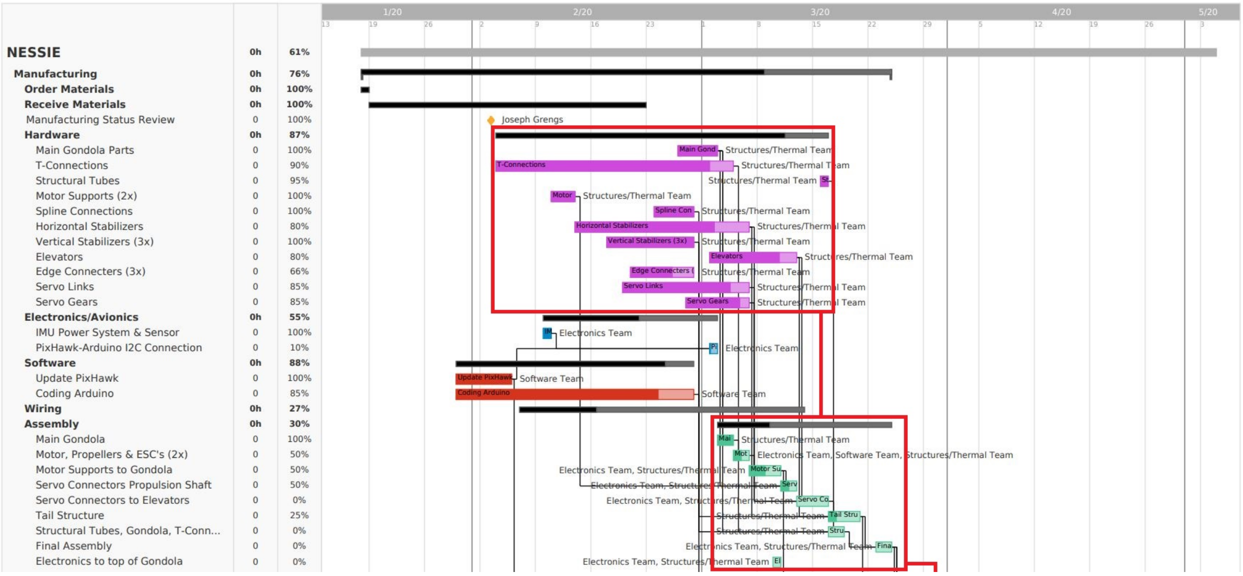

Fig. 59 NESSIE work schedule (manufacturing schedule)

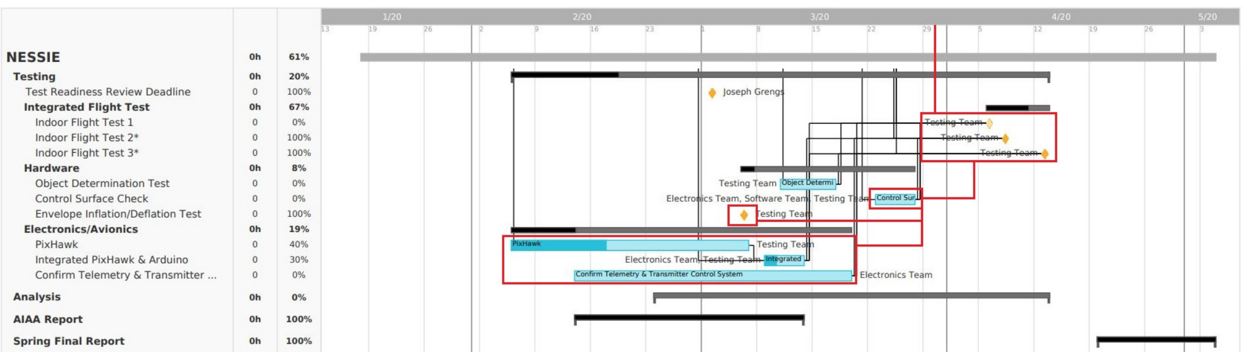

Fig. 60 NESSIE work schedule (testing and final schedule)

Component	Cost	Estimated Shipping	Cost + Shipping	Budget	Margin
Gas Envelope	$1375	$250	$1625	$1804	~10%
Helium (1882 cuft)	$1215	$0	$1215	$1500	~20%
Carbon Fiber	$424	$200	$624	$650	~4.5%
Batteries/Charger	$362.64	$20	$382.64	$400	~4%
Propulsion	$341.8	$0	$341.8	$421	~15%
Flight Controller	$210	$0	$210	$210	0%
Tail and Pins	$110.97	$0	$110.97	$120	~9%
MISC.			$325.99	$395	~17%
Totals			**$4835.24**	**$5500**	**~12%**

Table 10 Project budget as of CDR presentation during fall semester

At CDR, we presented table 10 above. During this time, there were no restrictions on our test plans and we thought we had thoroughly covered almost every aspect of our project. Major items to notice were the Gas envelope, Helium, and Carbon fiber. The helium was estimated off of current market cost that the university could provide. The Gas envelope was determined by a quick quote we received from "Larger than Life Inflatables". and the Carbon fiber was based on a couple sheets that would fully encompass the gondola. There were some assumption here that led to the major changes in the TRR Budget as presented in table 11. For the envelope we assumed that their price would not change since they provided a written invoice. The Lifting gas price was presented by a university staff member and we thought that would be a fixed cost. We also believed we would only needed carbon fiber for the gondola. For all other budgeted sections we thought we had examined every possible unknown or had enough in the misc section to cover it all.

Component	Final Cost	Budget	Margin
Gas Envelope	$1500.00	$1804	~17%
Helium (1882 cu ft)	$1215.00	$1500	~19%
Carbon Fiber	$1396.21	$650	**~-115%**
Batteries/Charger	$393.08	$400	~2%
Propulsion	$566.18	$421	**~-34%**
Flight Controller	$207.95	$210	1%
Tail and Pins	$159.30	$120	**~-33%**
MISC.	$342.49	$395	~13%
Remaining Budget:	**-$72.26**		**~-1%**
Totals	**$5572.26**	**$5500**	**~12%**

Table 11 Project budget as of the TRR presentation during the spring semester

However as can be seen in table 11 We went over the budget by $72.26. This was heavily influenced by weight restrictions. This forced the team to design the mounting tubes out of carbon fiber instead of cheap plastic tubes. In fact this cost went over budget by almost 2X the amount allotted. That increase in weight also meant we needed to increase propulsion. This added additional cost over the allotted propulsion budget. The Tail also had to be designed larger to maintain control ability. This change also slight went over budget. In all other sections we held or improved our margin. Below in Figure 65 one can see the direct comparisons.

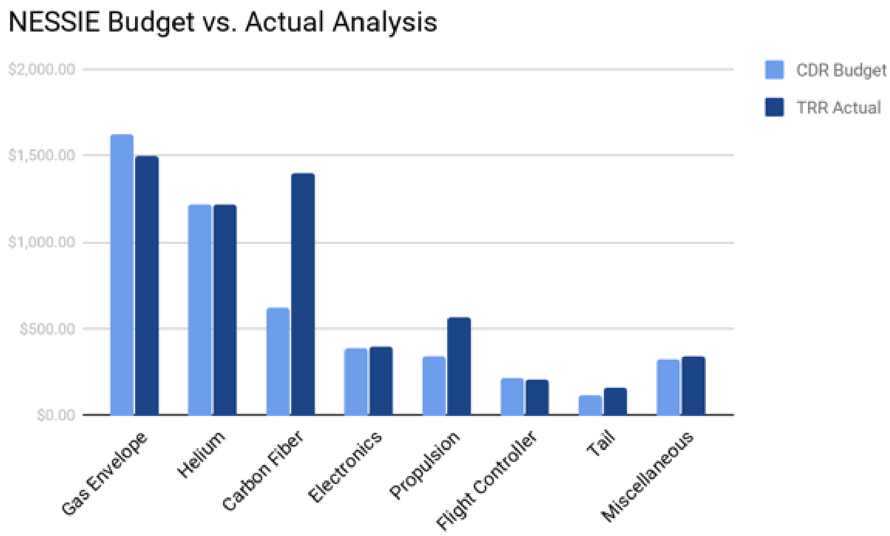

Fig. 61   NESSIE budget comparison between CDR and TRR

In figure 64 one can see the budget comparison breakdown by margins.

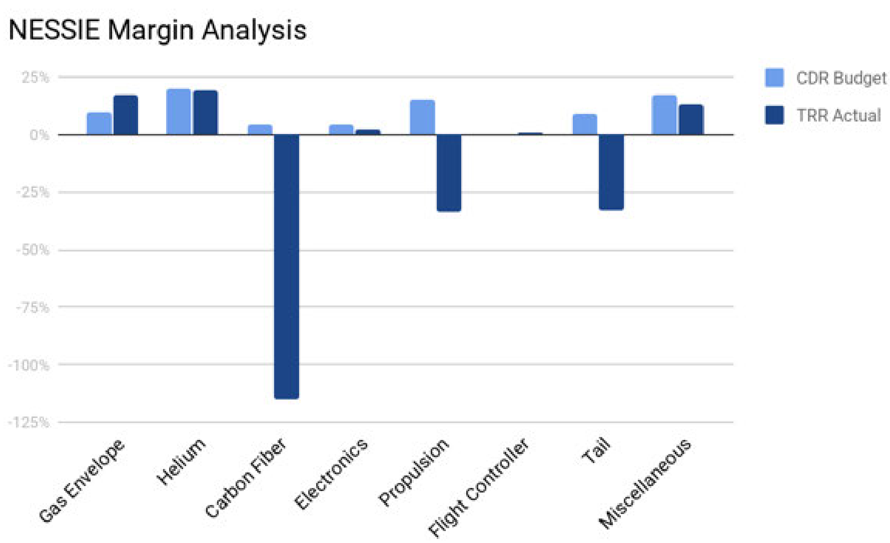

Fig. 62   NESSIE margin comparison between CDR and TRR

This project may have been slightly over budget, but there were already plans in action to have a "sponsor" place a LOGO on the Envelope for promotional purposes during the project exposition. One Bid already received from "The Hunt X,Inc" at $500 would have put us safely in positive margin. Additional talks between several aerospace and other engineering companies were about to begin as well.

	Fall 2019 Semester	Spring 2020 Semester
Hours Worked	3051	1981*
Hourly Cost	$95,353.75	$61,906.25*
Materials Cost	$ 5,772.26	
Overhead Rate (200%)	$190,707.50	$123,812.50
Total Industry Cost	**$477,552.26**	

Fig. 63 NESSIE estimated industry project cost

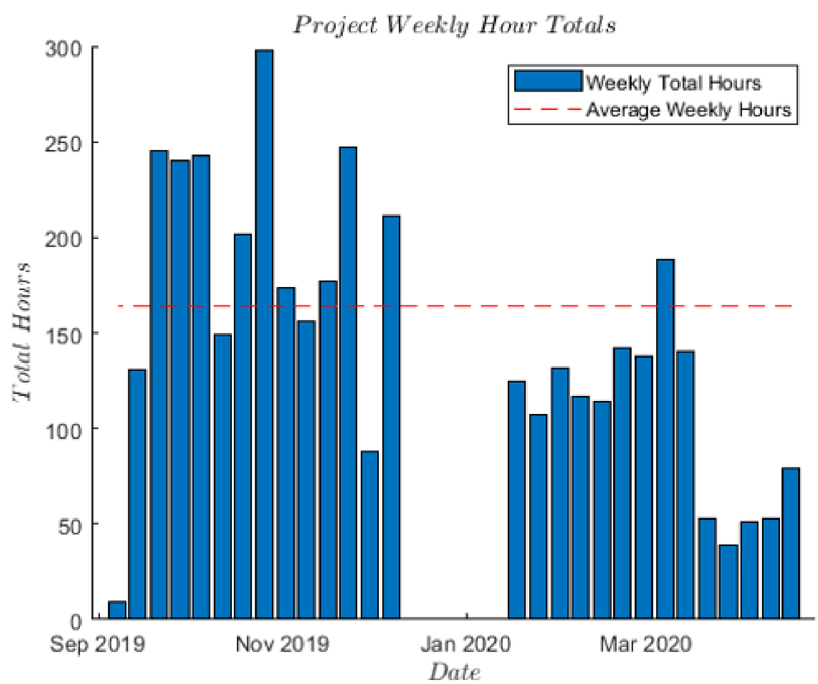

Fig. 64 NESSIE weekly accounted hours, full project

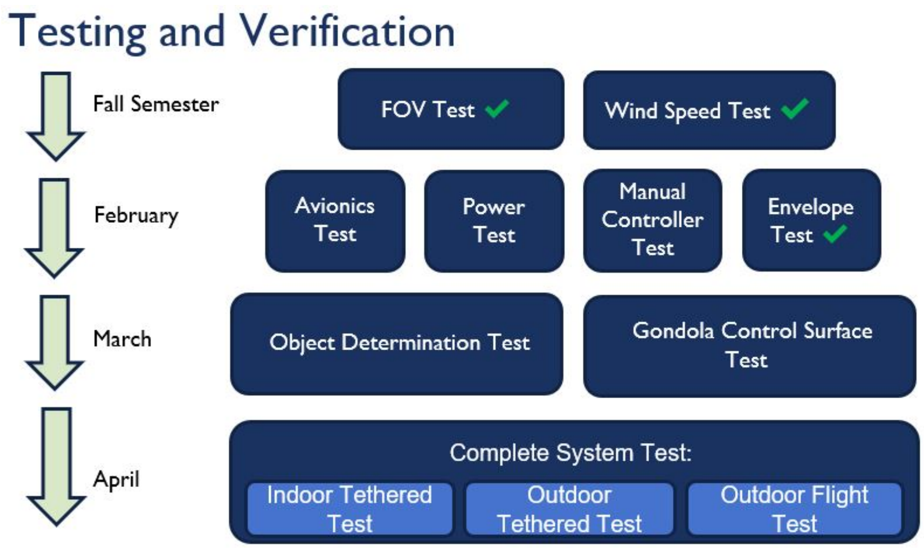

Fig. 65 NESSIE Test Plan

This project was very time sensitive, because final complete system tests needed to be planed months in advance. There would be very little time to reschedule. Due to this constrain testing began in Fall semester. Testing resumed early February right as parts were received. The manufacturing team then had a little less than a month to had the gondola fully build for the next set of tests in March. Testing for individual components would be complete by the end of March. The Manufacturing and Systems teams then had to have the full aircraft completed by early April for the scheduled fully integrated tests.

8. Lessons Learned

Author 1: Joseph Grengs, Author 2: Jeffrey Mariner Gonzalez

Senior projects is a great opportunity for students to show what they know and how they can apply that knowledge to real-world, industry projects. However, it still is a great learning opportunity to flush out some of the things we might not have had experience with yet, as students. Several key takeaways are outlined here that illustrate the struggles and what we did to overcome the challenges to make a successful senior project.

A. Scoping Project

The biggest lesson learned in this project is how to properly scope a project. When this project began, the original scope was to design and build an aircraft with an attached optical system and fly it at 20,000 ft. In our opinion, seniors have a bit of a 'gung-ho' attitude and want to tackle whatever problem is thrown at them. Additionally, this is the first time any of us were exposed to thinking about an entire project and determining whether or not we would have the resources necessary to complete the entire project.

During the initial formation of the team and meeting with the customer, we had a single meeting to get all of the requirements for the project. Never once did we stop and think this was too large of a project to take on for a senior project. What would have been a better method of scoping the project would have been to meet with the customer to get the initial requirements, then step away from the customer and meet to discuss what we can and can't do and give it good thought. Then schedule a second meeting with the customer to lay out what we are capable of doing, to adequately scope/de-scope the project, given the constraints of time and money. Looking back, had we followed this process, we would have not been bogged down with a much larger project than we could handle and would not have been delayed overall due to having to de-scope the project half-way through the fall semester.

B. Change Management

Another big issue that came up during the process of the project was communication within the team, more specifically, when a design changes. Towards the end of the fall semester, it was determined that a small modification to the tail was needed. Unfortunately, this finding happened over the Thanksgiving break, when several of the team members were out of town. As a result, the modification was made, just prior to submitting a report and presentation, without the review of the rest of the team, to make sure the change did not impact other sub-systems, or the system as a whole. While in the end, the modification made did not create any detrimental issues, the people whose sub-system was slightly impacted were felt left out from not being consulted.

To mitigate this lack of communication within the team, a Change Management tool was created to keep track of any changes from the initial design and ensure that all leads of sub-systems are informed of the change proposal. This helps to ensure that a everyone is aware of the change and gives leads an opportunity to voice concerns or state how the change will impact their respective sub-system.

C. Scheduling

During the course of the project, it is crucial to know who is working on what and when. This helps the Project Manager know what resources (team members) are available at any given time. Unfortunately, the discussion around GANTT charts was not brought up in class until close to the end of the fall semester. Had we started using available GANTT chart software (e.g. Microsoft Project Management, www.TeamGantt.com, www.Ganttner.com) towards the beginning of the semester, it would have been easier to schedule people equal amounts of work, as well as ensure work is being done in a timely fashion. In many instances, crucial reports or presentations were not completed until just before they were due, with most of the work completed just prior to the due date & time.

It is recommended that future senior project teams should begin working in some software to create a project schedule using a GANTT chart immediately after forming teams and the Project Manager is assigned. This gives the PM much more time to get used to and comfortable with scheduling work assignments and due dates for completion, and better hold the team more accountable with meeting deadlines.

D. Late Design Changes

Unfortunately, during the winter break, a deadline for an additional source of funding was missed, which was included in the budget for making NESSIE a success. As a result, we had to evaluate the lifting gas we used for the project and began work towards evaluating the possible use of Hydrogen versus Helium, primarily due to the cost. Making this change created a persistent issue that occurred during the manufacturing phase. Both gases where effectively the only option, not just from a cost perspective, but also from a safety one, as well. This led to a debate with upper management for which specific gas to use. As a result, for much of the spring semester there was a certain level on uncertainty in which gas would be used, with the team proposing Hydrogen, but the PAB denying and settling back on Helium.

This proved to be a valuable lesson in preparing for multiple paths forward. As both new considerations for additional funding and additional safety systems had to be put in place, for helium and hydrogen respectively. Moving forward this could prove to be a useful skill as the future is often unpredictable and the ability to plan for multiple outcomes or paths forward could prevent the derailing or failure of projects.

9. Individual Contributions

A. Paul McClernan

PFR: Wrote project purpose, project Objectives/Functional requirements, and helped with Design process and Outcome sections. Various edits throughout. Also I took all of the component pictures that we didn't already have. Content-wise: those sections content were pretty collaborative, but I created the FBDs myself. I was pretty heavily involved in developing FR1 and its DR's. I was the main contact with the balloon vendor (and subsequently had to make the final decision on the balloon size). I designed the jig needed for cutting the tail from foam stock. I wrote the procedure for the inflation/deflation test. Also system's engineering tasks, which didn't really appear as content in this paper.

B. Joseph Grengs

Wrote the Object Determination Test subsection of the Verification Validation section and added Integrated Flight Test subsections from the FFR (due to not having very many changes from that report). Wrote the Project Planning section from beginning to the Work Plan subsection, while amending some of the schedules and WBS images contained in that subsection. Added descriptions of both MANTA and NESSIE CONOPS figures. Wrote the Lessons Learned section from intro to sub-section C. Proofread document, based upon previous feedback from Professor Johnson on past reports/presentations, as well as notes from the PAB.

C. Richard Weir

Contributed to section 3, Design Process and Outcome. Specifically detailed how NESSIE derived it's requirements (both functional and design) from an optical system point of view after the project went through de-scoping. Contributed to the verification and validation section by elaborating further on the object determination test. Proof reading, formatting, grammar, etc.

D. Flora Quinby

Contributed to the Verification and Validation section. Proofread the document and made edits where necessary.

E. Cavan Roe

Edited and added to Section 3: Design Process and Outcome. Wrote The cost plan and test planning sections of Project planning.

F. Matthew Jonas

Wrote the Risk Assessment and Mitigation section, and adapted the Risk section from the FFR report.

G. Jeffrey Martinez Gonzalez

Contributed to Lessons Learned, and validation and verification sections. As well as the vehicle and avionic related section of the FFR's section trade studies.

H. Evan Vavpetic

Design Process and Outcome: Conceptual Design Alternatives and Final Design

I. Jose P. Cardenas Abedrop
Assisted in writing section 1 and section 2. Corrected levels of success based on feedback from Prof. Johnson. Assisted in formatting requirements flowdown.

J. Diego Mendiola Campillo
Worked on Manufacturing Section in all three parts tasks, outcomes and integration.

K. William (Kody) Newman
Assisted in organizing and detailing section 2. Wrote parts A and B in the testing and verification section. Added the software+avionics information to the manufacturing section. Edited the report.

L. Joao Guilherme Poletto Widerkehr
Worked on the manufacturing section. Produced all the pictures in the manufacturing section, Worked on manufacturing tasks, outcomes and integration.

Appendix

Design Process and Outcome

Vehicle Type Trade Study

Table 12 Vehicle type metrics, weightings, and justifications

Metric	Weight	Driving Requirements	Description & Rationale
Cost	0.1	Budget	The cost of the hardware/software should be minimized without taking away from functionality.
Availability	0.2	Project Timeline	Whether the product is custom built or COTS.
Integration complexity	0.1	Project Timeline	Whether the product can integrate with other parts of the system easily.
Weight	0.2	FAA restrictions, DR 2.4	Payload weight vs vehicle weight.
Power draw	0.15	DR 2.4	The amount of power required for sustained flight.
Flight time	0.15	DR 2.2	The duration of the flight.
Command-ability	0.1	DR 3.3, DR 3.3.1, DR 3.3.2, DR 3.3.3, DR 3.4.2	The ability to input commands.

Table 13 Optical Sensor metric values

Metric	1	2	3	4	5
Cost	>$4000	$3000-$4000	$2000-$3000	$1000-$2000	<$1000
Weight	>15lb	10-15lb	5-10lb	1-5lb	<1 lb
Performance	Apparent Magnitude <7, small pixels, small FOV, small area	Apparent magnitude 7-10, small pixels, small FOV, medium size area	Apparent magnitude 10-13, medium size pixels, medium size FOV, medium size area	apparent magnitude 13-15, medium to large pixel size, medium to large FOV, medium to large area	Apparent magnitude >15, large pixel size, large FOV, large area
Integration Complexity	Not possible	Part needed are hard to find and integration is complex	Extra parts necessary with some complexity	Easily assembled with minimum extra parts needed	Easily attached without extra parts
Power Consumption	>5W	1W-5W	10mW-1W	2mW-10mW	<2mW

Multi-rotor:
Cost, 5: Multi-rotors have a large range in prices. The cheap options range from $120-$200 while the more expensive are around $1,000.
Availability, 4: Given the project requirements, the most likely option will include COTS but only some parts meaning purchasing only some of the parts needed.

Integration complexity, 4: It is simple to integrate all the parts since multi-rotors generally have platforms already for gimbals.
Weight, 3: Most multi-rotors can only carry around 5lb or less as a payload.
Power Draw, 1: The multi-rotor will need constant power for sustained flight.
Flight Time, 2: The maximum flight time for a multi-rotor, in ideal conditions, is around 30 minutes, meaning most flights have a shorter duration.
Command-ability, 5: All multi-rotors can have input commands for all surfaces allowing for command-ability in all directions.

Fixed wing:
Cost, 5: The upper range for most fixed wing vehicles is around $650-$750 for COTS.
Availability, 3: The vehicle choice will most likely need to be customized as most fixed wing aircraft are modified for certain specifications.
Integration complexity, 4: The system is simple to integrate, since fixed wing aircraft have a lot of surface area where other parts of the system can be integrated.
Weight, 3: The fixed wing aircraft can only carry around 5lb or less as a payload.
Power Draw, 4: This vehicle will not need constant power draw as most fixed wing are designed to glide or have a low power mode.
Flight Time, 3: While most fixed wing vehicles have low endurance, however, with customized parts it's possible for fixed wing to fly up to 3 hours.
Command-ability, 5: Most fixed wing can have input commands for all surfaces allowing for command-ability in all directions.

Blimp:
Cost, 4: The blimp will be more costly as they are not very common on the market. For example only one company sells fully built blimps for a higher cost as they are each custom built for the customer.
Availability, 1: As there are very few blimps on the market, the vehicle will most likely need to be completely customized from a vendor or built in house.
Integration complexity, 3: The vehicle may be difficult to integrate with other parts since most blimps don't have very good platforms for integration.
Weight, 4: The blimp has a slightly larger payload capacity than multi-rotor or fixed wing but still has a very small payload/aircraft weight ratio.
Power Draw, 4: Blimps have almost no power draw since they only use power for maneuvering.
Flight Time, 4: Most blimps have a decently long flight time as they have a large range and don't need much power.
Command-ability, 3: This vehicle can only take lateral commands and moves very slowly when reacting to input controls.

Balloon:
Cost, 5: A balloon is quite cheap meaning the main cost would be helium. However, some kits are sold for $200-$400 depending on balloon size.
Availability, 5: This vehicle is easy to purchase as COTS material in kits.
Integration complexity, 2: With a balloon it is more difficult to get the parts together since there is no formal platform or payload carrying system attached to the balloon.
Weight, 4: A balloon can carry significantly more payload depending on balloon size.
Power Draw, 5: The balloon has no power draw needed for flight, which is a big positive for this vehicle type.
Flight Time, 4: A balloon has a very long flight time and could be increased with modifications to

the balloon, however, there is much less time sustained at one altitude unless the vehicle is modified to deal with the pressure balances.
Command-ability, 1: The biggest downside to the balloon is that it's not commandable in any regard. It floats up to a set altitude and pops to come down.

Commercial UAS:
Cost, 1: All commercially built and fully integrated systems are very expensive costing upwards of $1 million.
Availability, 1: The majority of the commercially built UAS are privately owned and cannot be bought.
Integration Complexity, 3: Given the ability to purchase a commercially built vehicle, the integration would not be very difficult as the platforms could be modified for individual specifications.
Weight, 2: The payload weight ratio of many commercially built aircraft is low in comparison to the gross takeoff weight. This is due to long endurance goals of the vehicle without landing, adding to specific weight requirements for the propulsion method. Additionally, the aircraft has the ability to glide meaning the overall weight carried needs to be minimized.
Power Draw, 2: Many of the commercially built vehicles have long range endurance goals meaning they have a large propulsive need. This means that the vehicle will be drawing large amounts of power when commanding inputs.
Flight Time, 5: The commercial vehicles have a much longer flight time as endurance for prolonged missions is the general mission goal. In many cases the vehicles can fly for upwards of 10 hours.
Command-ability, 4: Commercial UAS have the ability to input commands for both lateral and vertical controls. Majority of the vehicles are also programmed for specific autonomous controls for the extended flight time.

Propulsion Type Trade Study

Note that the propulsion system is highly coupled with the vehicle type that is chosen as a result of section 4.1. That trade study is given precedence and therefore any results found in the following trade study are subject to incompatibilities with the selected vehicle type.

Table 14 Propulsion system metrics, weights, and justifications

Metric	Weight	Driving Requirements	Description & Rationale
Cost	0.1	Budget	Project has to satisfy Budget. Propulsion will take a large part of the budget to maintain long flight time during the night.
Power/fuel Consumption	0.2	FR 4	The weight restriction on the vehicle also limits the available power, therefore the efficiency of the propulsion system is essential for long flight times.
Control-ability	0.2	DR 3.3.1, DR 3.3.2, DR 3.4.2, FR 4, DR 4.1, DR 4.2	The propulsion system has to control altitude and attitude and also respond to altitude and attitude wind perturbations. The ability of the propulsion system to control position and attitude is a key factor to be considered.
Design Complexity	0.1	Project Timeline	The design of a complex propulsion system can significantly increase the number of hours required to finish project.
Weight	0.15	DR 2.3	FAA regulations limit the mass of the vehicle to a maximum of 55 lbs. The propulsion system has a great impact in the total mass of the vehicle. Therefore the mass of the propulsion system compared to the payload capacity is an important factor.
Ease of Integration	0.1	Project Timeline	The propulsion system has to combine smoothly to the structure of the vehicle and be easily integrated to the other subsystems.
Risk	0.15	DR 2.2, DR 3.3.1, DR 3.5, DR 3.5.2	System must be reliable to carry expensive payload and complete mission. The system requires enough propulsion power so it can stay in required radius from ground station and also come back and land safely near the takeoff location.

Table 15 Propulsion system metric values

Metric	1	2	3	4	5
Cost	>2500	$1500-$2500	$1000-$1500	$600-$1000	<$600
Power	Least efficient	Less efficient	Moderately efficient	More efficient	Most efficient
Control-ability	Least control-ability		Moderate control-ability		Most control-ability
Design Complex-ity	Challenging	Hard	Moderate	Easy	Trivial
Weight	Heavyweigh		Moderate weight		Lightweight
Ease of integration	Very difficult	Difficult	Moderate	Easy	Trivial
Risk	Risky to launch		Safe to launch		Most safe to launch

Regulated Balloon:
Cost, 5: The average price of balloon is less than $600, the most part of the cost is the helium gas used for lift.
Power, 5: A balloon system produces lift with no power draw, which is a efficient option.
Control-ability, 1: The only control authority of the system is in altitude using the pressure regulator.
Design Complexity, 5: The design of the balloon system is simple and is widely available COTS.
Weight, 5: The balloon system has low weight and has good payload capacity.
Ease of Integration, 3: The integration ease of the balloon with other subsystems is moderate, specially structural integration.
Risk, 1: The system has no ability to fight the wind so it can be carried away and lost.

Vertical Rotors:
Cost, 5: Vertical rotors average price is <$600 for a good payload capability .
Power, 1: System requires active power draw for constant lift production.
Control-ability, 5: Vertical rotors can provide really good attitude and altitude control.
Design Complexity, 4: The design of the system can be complex, but there are several options COTS.
Weight, 1: The vertical rotors system has high weight compared to the payload capacity.
Ease of Integration, 4: The integration with the other subsystems is easy since several COTS options are available .
Risk, 3: Vertical rotors provide good longitudinal control, so the vehicle safe from being carried by the wind. On the other hand it is not reliable, if one of the rotors fails the vehicle crashes into the ground.

Combo, consists of a Neutral-Density system with vertical rotors:
Cost, 4: The average price for the two systems is in the $600 to $1000 range.
Power, 4: The combination of a Neutral-Density with vertical rotors is efficient since it uses buoyancy for lift and the rotors for attitude and altitude control.

Control-ability, 5: The vertical rotors provide good attitude and altitude control.
Design Complexity, 3: The Design complexity is moderate since 2 systems have to be designed.
Weight, 4: The combination of the systems has low weight compared to the payload capacity, but it does not perform better than the balloon due to the addition of the vertical rotors.
Ease of Integration, 2: Integrating the two systems is difficult, specially smoothly integrating the structure.
Risk, 5: Due to the addition of the rotors the system has ability to fight wind. Also if one of the vertical rotors fails the buoyant force still provides lift, making the system reliable and safe.

Fixed-Wing:
Cost, 4: The price of fixed wing systems with good payload capacity ranges from $600 to $1000.
Power, 3: The power efficiency of the propulsion system is moderate compared to the high efficiency Neutral-buoyant and the low efficiency vertical rotors.
Control-ability, 3: The fixed-wing option has good control-ability, but can not stay in steady hover.
Design Complexity, 5: The fixed-wing design is less complex since most of the parts used are COTS.
Weight, 4: The fixed-wing system has a good propulsion system weight compared to payload capacity.
Ease of Integration, 4: The integration of the other subsystems is easy specially due to the structural configuration.
Risk, 4: The fixed wing has a really good ability to fight wind. Also in the case of an engine failure the vehicle can glide and land safely. In the other hand in the case of a structural damage the vehicle crashes.

Control Input Type Trade Study

Table 16 Methodology of communications metrics, weights, and justifications

Metric	Weight	Driving Requirements	Description & Rationale
Cost	0.15	Budget	The cost of the hardware/software should be minimized without taking away from functionality.
Assembly Complexity	0.3	Project timeline	The assembly must be completed within given time restraints. Additionally all components must interface with each other and avionics.
Control-ability	0.2	DR 3.3.1, DR 3.3.2, DR 3.4.2, FR 4, DR 4.1, DR 4.2	Should implement instantaneous changes (~10ms latency) to aircraft movement based on control inputs both manually and autonomously.
Availability	0.25	Project timeline	The system must be completed and be thoroughly tested within the given time restraints.
Heritage/ Risk	0.1	Project timeline, DR 4.1, DR 4.2	The extent to which the system is used and trusted within industry. Additionally the amount of risk associated with the components.

Table 17 Methodology of communications metric values

Metric	1	2	3	4	5
Cost	>$1000	$700-$1000	$600-$700	$200-$600	<$200
Assembly Complexity	Impossible	Difficult	Moderate	Simple	Comes built
Control-ability	Does not transmit	>500ms transmission time	~500ms transmission time; Purely manual controls	~100ms transmission time	~10ms transmission time; Both manual and autonomous controls
Availibility	Will not be completed within time requirement	>1 month timeline for production	1 month timeline for production	2 week timeline for production	~3-5 business days timeline for production
Heratige/ Risk	Experimental	Rarely used in industry	Moderately used in industry	Common knowlege in industry	Industry standard (most commonly used)

Manual:
Cost, 3: There are some hand held controllers that are relatively expensive but there is a wide range of costs based on performance. Given the specifications of this project we will probably want a mid-range controller.
Assembly Complexity, 4: Given COTS specifications it's incredibly simple to integrate both the aircraft and controller. Additionally both will work with any Mavlink flight controller (avionics).
Control-ability, 3: The manual controller has the ability to give direct commands via controls but

does not have an autonomous feature.
Availability, 5: A manual controller is easy to order as a COTS product that is not customized.
Heritage, 5: Controllers are commonly used in industry and are very reliable, however, they are rarely used without some sort of ground station control.

Autonomous:
Cost, 4: The software for a completely autonomous system will need to be developed in house which shouldn't cost as much as COTS.
Assembly Complexity, 3: The autonomous software could be difficult to integrate with all the aspects within the given time frame. Full testing of the system would only be possible once given it's fully autonomous control system.
Control-ability, 4: It is easy to put in commands to the autonomous system as well as plan the flight path and readjust for any disturbances during flight.
Availability, 2: The autonomous control would be custom made which could take a very long time.
Heritage, 2: There is only one known company that has fully functional completely autonomous products on the market, meaning the completely autonomous approach is a relatively new concept.

Hybrid:
Cost, 4: The hybrid system could be costly given both manual and autonomous controls meaning more parts to purchase separately.
Assembly Complexity, 4: For the hybrid controller, all parts are commonly integrated and interface well with Mavlink systems (avionics).
Control-ability, 5: The hybrid system can input commands both manually and autonomously quickly and efficiently.
Availability, 4: While all parts for the hybrid system are common in industry it could be timely to receive them as there are most COTS parts for the combined system.
Heritage, 5: The hybrid system is commonly used in industry and is a standard for hobbyists and professionals alike.

Flight Controller Trade Study

Table 18 Flight controller metrics, weights, and justifications

Metric	Weight	Driving Requirements	Description & Rationale
Cost	0.05	Budget	This is not the most expensive hardware, but it is one of the most fundamental ones, hence the low Weight.
Reliability	0.1	FR3.5	Reliability of the controller is important to ensure the safety and recovery of the aircraft and its payload.
MCU Processing Speed	0.3	FR3.4-3-2 FR2.2	The MCU processing speed will ultimately limit the vehicle's stabilization capabilities, higher PS will allow for a more complex and faster control algorithm.
Software Availability	0.2	Project Timeline	Software heritage will allow the team to use/modify software for the mission needs.
Input Voltage	0.3	FR4	The input voltage for the controller is proportional to the power drawn. For this purpose, it is crucial to have an energy-efficient controller.
Weight	0.05	FR2.3	This is a small component and hence the weight for this factor.

Table 19 Flight controller metric values

Metric	1	2	3	4	5
Cost	>$300	$250-$300	$200-$250	$150-$200	<$150
Weight	>0.5 lb (227g)	0.25lb-0.5lb (114g-227g)	0.125lb-0.25lb (67g-114g)	0.07lb-0.125lb (33g-67g)	<0.07lb (33g)
MCU[***]	<200 DMIPS[†††]	200-250 DMIPS	250-300 DMIPS	300-350 DMIPS	>300 DMIPS
Software Availability	Experimental software	New software with few open resources	Good amount of open resources for a small range of applications	Vast open source software implementation for various applications	Vast amount of different applications software as well as hybrid applications
Reliability	No backup MCU nor fault detection functions	IO MCU available but no fault detection functions	IO MCU available and geofence and automatic landing when C2 missing available	Previous plus automatic parachute release, and pre-arm safety check	Previous plus return to launch if battery low
Input Voltage	>25V	17V-25V	11V-16V	6V-10V	<6V

Pixhawk 2 Cube

Cost, 3: Considering the prices of other common flight controllers, this is among the expensive options in the market.
Weight, 4: Comparing to the weight of the chimera of 12grams, this is almost twice the weight of the chimera, nonetheless this weight addition is almost negligible.
MCU Processing, 2: Compared to the chimera's and PixHawk 4, that use a STM32F7xx series, this processor falls short.
Reliability, 4: PX4, the Pixhawks' software, counts with many fundamental fault detection functions but chimera does have more.
Software Availability, 4: PX4 is a widely used platform, however paparazzi is more commonly used for hybrid applications which is more likely to be our case.
Input Voltage, 5: This board requires less voltage than the other two to function.

Ppz Chimera

Cost, 2: Considering the prices of other common flight controllers, this is a very expensive board to build from scratch.
Weight, 5: Since it is the board with the components alone, it is lighter than the other two.
MCU Processing, 5: This board uses a STM32F7xx series, this is among the fastest MCUs in flight controllers available.
Reliability, 5: Paparazzi is the open source software used in chimera and comes with an extensive available fault detection functions.
Software Availability, 5: Paparazzi is commonly used for hybrid applications which provides a broader range of configurations of aircraft controls.
Input Voltage, 2: This board consumes from 6V-26V.

Pixhawk 4

Cost, 3: Considering the prices of other common flight controllers, this is among the expensive options in the market.
Weight, 5: At 15 grams, it is a very light board.
MCU Processing, 5: This board uses a STM32F7xx series, this is among the fastest MCUs in flight controllers available.
Reliability, 4: PX4, the Pixhawks' software, counts with many fundamental fault detection functions but chimera does have more.
Software Availability, 4: PX4 is a widely used platform, however paparazzi is more commonly used for hybrid applications which is more likely to be our case.
Input Voltage, 4: This board slightly more voltage than its predecessor but significantly less than chimera.

Power Supply Trade Study

Note that these comparisons were done for batteries in the 12V 40AH range so that reasonable comparisons could be drawn between the different battery types.

Table 20 Power metrics, weights, and justifications

Metric	Weight	Driving Requirements	Description & Rationale
Cost	0.2	Budget	The cost of the hardware should be minimized without taking away from functionality.
Weight	0.3	DR 2.3	Power density is the most important aspect in choosing a battery as weight is a severe limiter on design and batteries are a significant portion of the vehicle's overall mass.
Capacity available at low temperatures	0.15	FR 2, FR 4	The battery should be able to function at low temperatures representative of those found at night at 20,000ft. This is mitigated by a thermal system.
Maintenance	0.2	Safety	Batteries should require minimal maintenance to store/transport/charge and minimal monitoring during charge and discharge.
Volume	0.15	DR 2.4	The size of the system, which should be minimized to provide space for other components.

Table 21 Power metric values

Metric	1	2	3	4	5
Cost	>$1000	$800-$900	$600-$700	$300-$500	<$200
Weight	45 lb (10.67 Wh/lb)	35 lb (13.71 Wh/lb)	25 lb (19.20 Wh/lb)	15 lb (32 Wh/lb)	5 lb (96 Wh/lb)
Capacity available at low temperatures	20%	40%	60%	80%	100 %
Maintenance	Battery must be constantly monitored.		Battery must be monitored often.		Battery can be left alone.
Volume	500 cu in	400 cu in	300 cu in	200 cu in	100 cu in

<u>Lead Acid:</u>

Cost, 5: Lead acid batteries are the cheapest, costing approximately $80.
Weight, 2: Lead acid batteries are very heavy, weighing about 35 lbs.
Capacity available at low temperatures, 3: Lead acid batteries have 65% of capacity at 5 F.
Maintenance, 4: Lead acid batteries require low maintenance outside of charging and occasional monitoring.
Volume, 3: Lead acid batteries are typically around 330 cubic inches.

Lithium Ion:
Cost, 4: Lithium batteries cost approximately $500.
Weight, 4: Lithium batteries are relatively light, weighing about 15 lbs.
Capacity available at low temperatures, 4: Lead acid batteries have 70% of capacity at -4 F.
Maintenance, 4: Lithium batteries require low maintenance outside of charging and occasional monitoring.
Volume, 3: Lithium batteries are typically around 330 cubic inches.

Nickel:
Cost, 4: Nickel batteries cost approximately $425.
Weight, 4: Nickel batteries are relatively light, weighing about 15 lbs.
Capacity available at low temperatures, 3: Nickel batteries have 60% of capacity at 0 F.
Maintenance, 2: Nickel batteries require multiple charging components for the same AH capacity, increasing either price or charging time. They also must be more closely monitored since they are susceptible to extreme capacity loss after discharging below a capacity threshold.
Volume, 4: Nickel batteries are around 170 cubic inches.

Manufacturing pictures

Fig. 66 Picture of the Edge connector when manufacturing ended

Fig. 67 Picture of the gondola when manufacturing ended

Fig. 68 Picture of the T-connection when manufacturing ended

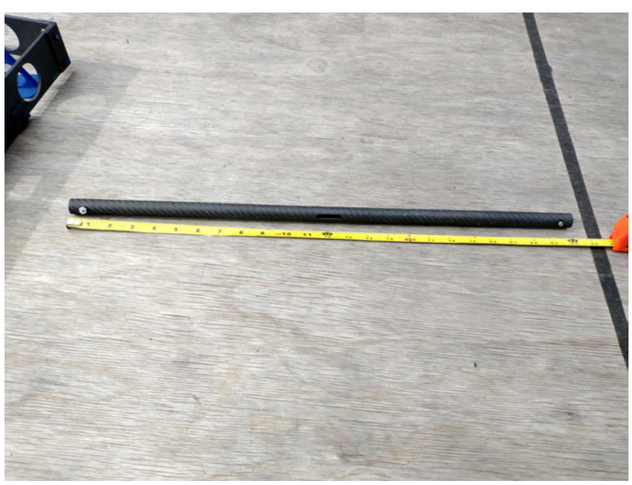

Fig. 69 Picture of the Tilt Shaft when manufacturing ended

Fig. 70 Picture of the motor mount when manufacturing ended

Fig. 71 Picture of one motor

Fig. 72 Picture of propellers

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