University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project Final Report

EMU
(Endurance Multi-rotor UAS)

Monday 4th May, 2020

1. Information

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Nomenclature

AGL	Above Ground Level
CONOPs	Concept of Operations
COTS	Commercial Off-the-Shelf
EKF	Extended Kalman Filter
EMU	Endurance Multi-rotor UAS
FBD	Functional Block Diagram
GCS	Ground Control System
GUI	Graphical User Interface
HD	High Definition
HITL	Hardware In The Loop
IDE	Integrated Development Environment
IRISS	Integrated Remote and In-Situ Sensing
LOI	Location of Interest
MSR	Manufacturing Status Review
NIST	National Institute of Standards and Technology
POI	Point of Interest
PSCR	Public Safety and Communication Research Division
PWM	Pulse-Width Modulation
RPM	Revolutions per Minute
RTL	Return to Launch
SDS	Senior Design Symposium
SFC	Specific Fuel Consumption
SITL	Software In The Loop
TOW	Take Off Weight
TRR	Test Readiness Review
UAS	Unmanned Aerial System
V & V	Verification and Validation

2. Project Purpose

Dakota Labine, Michael Flores

The Integrated Remote and In-Situ Sensing (IRISS) group at the University of Colorado, Boulder has expressed the need for an unmanned aircraft to carry a heavy payload for a long duration. This aircraft would allow IRISS to provide scientists with a vehicle capable of hosting elevated scientific experiments. The project originated from a National Institute of Standards and Technology (NIST) competition that required teams to create a multi-rotor aerial system capable of holding communications equipment for firefighters during mountainous rescues. Due to timing and logistical issues, IRISS was not able to complete the project, so they passed it on to the EMU team. The EMU team was tasked to create a scalable proof of concept system to fulfill the need for a heavy lift, long duration unmanned aerial system (UAS) for future customers.

The EMU team will take this project concept from IRISS and create a multi-rotor UAS with the capability of holding a steady hover at specific Points of Interest (POI) for up to two hours while supporting a five pound payload. This payload will include a camera that is able to focus on a specific Location of Interest (LOI) on the ground and provide live stream video back to the ground station. The successful completion of this project, with appropriate scalability documentation, will allow IRISS to provide a UAS system to a wide-range of customers looking to complete scientific and potentially life-saving missions.

3. Project Objectives and Functional Requirements

Michael Flores, Dakota Labine

3.1. Levels of Success

Table 1 shows how success will be defined for the project. In each of these success areas, each level shows how the UAS (referred to as system) and other components must perform. Each added level of success adds more complexity but also improves the performance of the system and makes it more capable. Not all success areas were laid out to have four levels but the highest level in each area represents the highest agreed upon capability and a fully integrated and functioning system.

Table 1: Success Definitions

Objective	Level 1	Level 2	Level 3	Level 4
Controls	Successful virtual simulation of control response with input the system attitude and altitude changes	Mechanical controls appropriately vary in response to changes in attitude and altitude	System can maintain trimmed, steady, level flight (constant attitude and altitude)	System can translate to any position in 3D space (up to a 500 meter lateral radius and altitude of 400 ft) and maintain steady, level flight (constant altitude)
Flight Endurance	System engine can provide power necessary for steady hovering and climb up to 400 feet altitude	System is able to hover in place with payload at a low altitude for 15 minutes	System is able to fly up to an altitude of 400 feet, fly for 2 hours with payload, and fly down	—
Power Plant	All power plant components functioning and integrated on a control board	Power plant components are integrated on the system and functioning	The system is capable of flight without a payload for less than two hours	System capable of flight for two hours with a payload
Chassis	Chassis is able to support all the system components without plastic deformation during flight and landing	Chassis supports quick release of payload and removable landing gear	—	—
Autonomy	System is able to receive commands and transmit telemetry necessary to be manually flown up to commanded height (up to 400 ft maximum altitude) and landed	System able to autonomously maintain position within flight cube	System able to take off, ascend to desired position, maintain position within flight cube until desired time or 2 hours, then land	System able to take off, then fly to a commanded location within 500 meters of user and ascend to desired position. While hovering, the system will accept new desired locations from ground station
Safety	System has a kill function that immediately ends system operations and functions	System has emergency landing feature that returns to ground in addition to lost link controls and return-to-launch functionality	—	—
Ground Station	Ground station software is able to transmit kill commands and control avionics	Ground station software accepts goal location commands from user in addition to emergency commands and transmits these to the system, and receives video stream	Ground station software accepts goal location, desired landing time, and emergency commands from user and transmits these to the system at a distance of up to 500 meters away	Ground station software accepts mid-flight changes to goal location and desired landing time and transmits these updates to the system
Payload	5 lb distributed payload with video recording capability	5 lb distributed payload with HD video streaming capability	Level 2 and camera has gimbal stabilization	Level 3 and camera has pointing capabilities

3.2. Concept of Operations

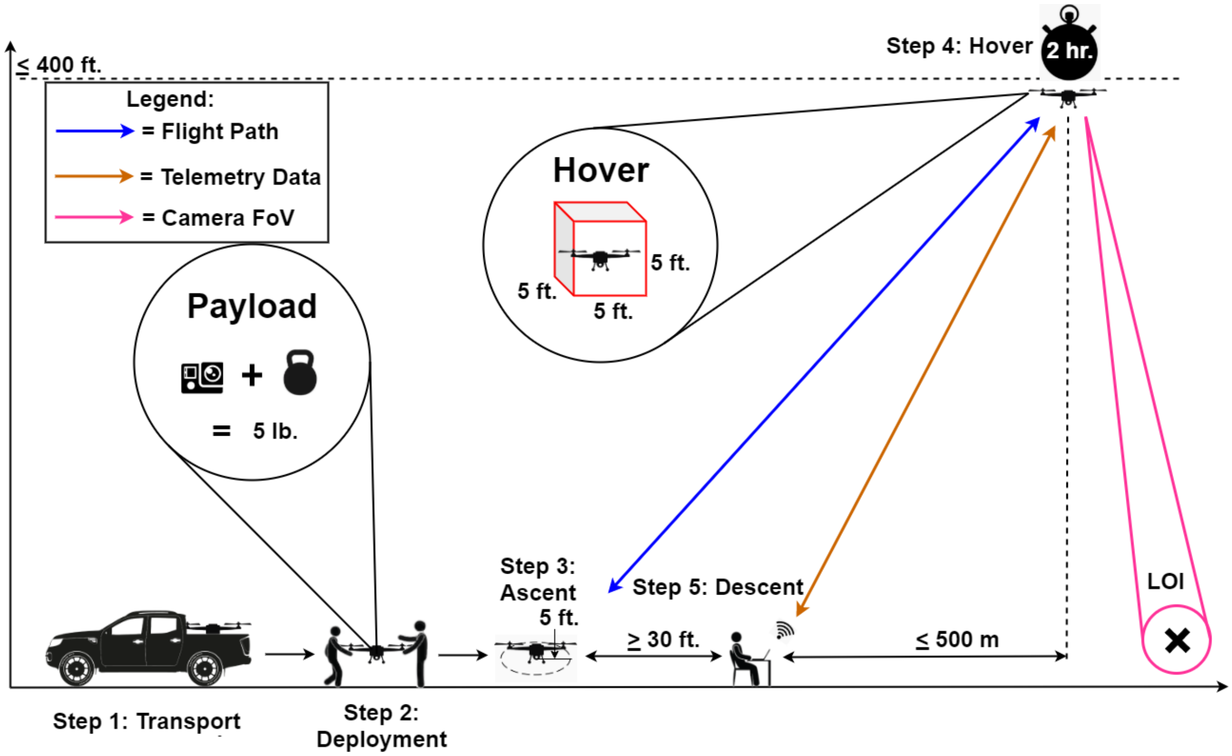

Figure 1: Concept of Operations Diagram

Figure 1 is a diagram representing the ideal operation of the UAS when delivered to the customer. This concept of operation begins with the transportation of the UAS to the mission site. The diagram does show the UAS in the back of a pickup truck despite their not being a specific size requirement for the system. Rather, this is to demonstrate that the UAS will be relatively easy to transport using conventional means, such as an automobile. The second step is the deployment of the UAS. During this step the UAS will be fueled, batteries will be inserted, and the camera payload will be attached to the system. The important note for this step is that the camera payload will have supplementary mass to ensure it will weigh five pounds at take off. The other step in deployment is the set up of the ground station. Illustrated by the person at the desk, this ground station will establish wireless connection to the UAS flight electronics, allowing it to send updated flight and kill commands, and will also determine the center of the operational area. For safety, there must remain at least 30 feet between the ground station and the UAS.

Step three begins the flight in which the ground control station will start the UAS launching it. From here the system will fly autonomously by first ascending to its Point of Interest (POI). This location will be presented as GPS coordinates provided by the ground station and can be updated at any point during the flight through wireless commands. The POI must also not exceed 400 feet above ground level (AGL) and be no more than 500 meters laterally from the ground station. Step four begins once the UAS reaches the POI. Once there, the system will hover autonomously for two hours and keep the center point of the system within a five foot cube around the defined POI. The camera at this time will be required to direct itself to a Location of Interest (LOI) where it will transmit live video back to the ground station of that point. This LOI will once again be provided by the ground station as GPS coordinates and can be updated throughout the flight as well. Once this hover period ends, step five begins in which the UAS will autonomously descend back to the ground to land. The location that the UAS touches down at must be within five feet of the takeoff location. From This point the mission has ended and the UAS will shut down to be retrieved.

3.3. Functional Block Diagram

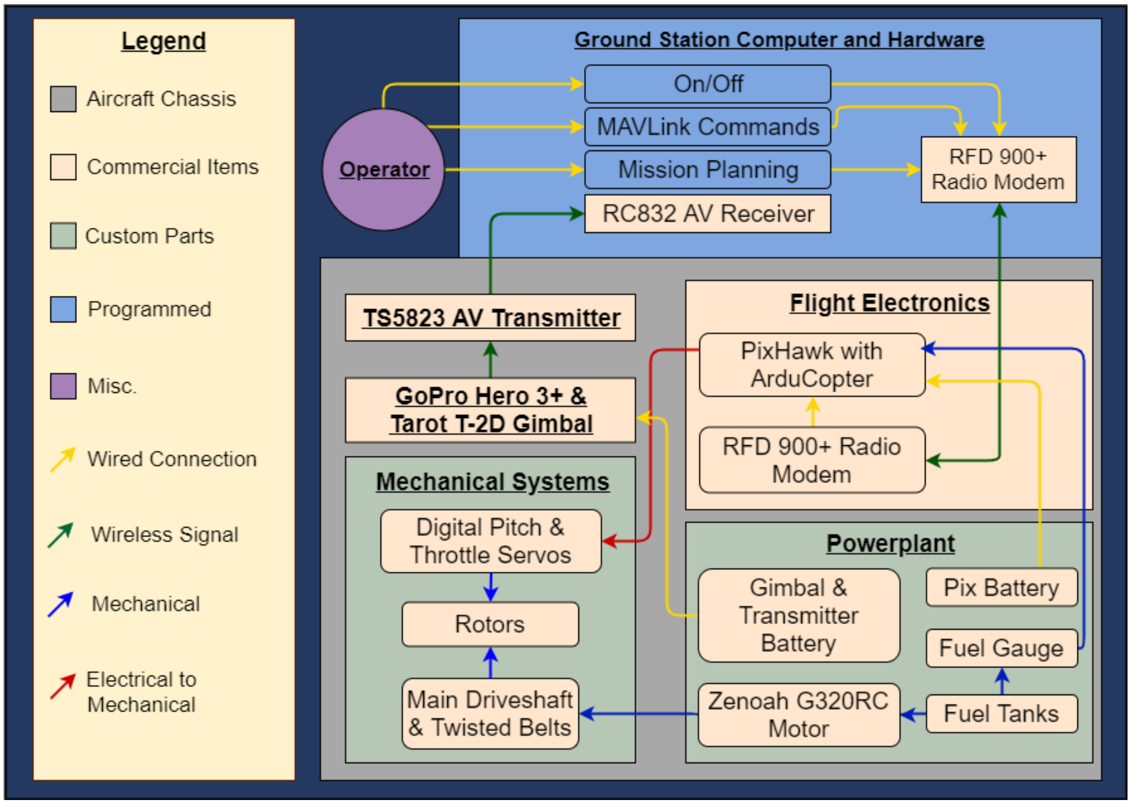

Figure 2: Functional Block Diagram

The Functional Block Diagram (FBD) represented in Fig. 2 shows the main systems that will be required for a successful project and how they will interface with each other. Starting with the ground station, the operator can power the UAS on and off, input the desired altitude and flight time, and access the emergency control options through the Graphical User Interface (GUI). The ground computer has a transmitter that sends data to the receiver in the on board flight controller. This information is then sent to the feedback control software to provide instructions to the avionics and in turn control the servos attached to the rotor pitch control mechanism. The control software also takes input from the on-board flight sensors in order to maintain stable flight. Power is supplied by a gas powered engine and data from a fuel gauge is sent back to the flight controller. There is an attached RPM governor attached to the engine as well that reads the output rpm and commands a servo to maintain the desired output RPM. The power from the engine is transmitted through the drive train to the rotors to provide power and spin the blades. The HD camera communicates to a receiver on the ground station to stream the live video feed. This camera and gimbal will each be given dedicated power supplies.

This design is dominated by commercial off-the-shelf (COTS) items but does include a few custom parts that will be manufactured/assembled by the team. This means that all data transmission will be handled by COTS items and manufacturing/assembly will be limited to drivetrain, chassis, and power plant mounting solutions. The control software and GUI will be programmed by the team. At time of delivery to the customer, the EMU team will be delivering a chassis with all the components needed for flight including an engine and flight electronics, a fully tuned and ready flight software, and a fully functioning ground station software. The team will not be providing the ground station hardware necessary to run the ground station software despite it being necessary for the UAS to function properly and fly.

3.4. Functional Requirements

Each functional requirement given within Table 2 has an associate requirement number to assist with tracking derived design requirements. These requirements represent key aspects of the projects function and were developed from analyzing the functional objectives of the system as they were given from the customer. Each of these high order requirement is a necessary section of how the system needs to function overall in order to have a successful operation.

Table 2: Functional Requirements

Requirement ID	Requirement	Rationale
1	UAS shall operate within a defined flight envelope.	The UAS needs to be operable within a specific flight envelope. This flight envelope is customer defined and ensures the UAS has a large enough operation area to complete missions.
2	UAS shall operate autonomously.	This is a customer requirement. The UAS needs to be capable of hands free operation due to its long flight time and the type of missions it will perform.
3	The ground station shall communicate with the UAS.	This is a customer requirement. The UAS needs a ground station in order to communicate commands and receive data.
4	UAS shall be gasoline powered.	This is a customer requirement. Using a gasoline engine allows for quick turn around in between flights.
5	UAS shall carry a camera payload.	This is a customer requirement and will allow the UAS to perform as an observation point.
6	UAS shall operate safely.	This requirement is customer driven and is needed to ensure that the UAS can be operated in close proximity to people.
7	Chassis shall support all UAS components.	This requirement is necessary in order to have a system that can be reliably operated.

4. Design Process and Outcome

4.1. Rotor Blades

Henry Moore

4.1.1. Conceptual Design

The propeller choice for the EMU project is extremely important, as the wrong propeller type can lead to reduced efficiency and thus less endurance. Additionally, different propeller types will be more or less difficult to design control laws for, connect to the power plant, and may require additional mass for components such as motors or alternators.

The propeller type choice will be influenced by, and influence, both the powerplant trade study and the drivetrain trade study. Another consideration that was ultimately excluded was the control system type trade study. The decision of what type of control system will be used will be influenced greatly by the different type of propellers, and thus is left as later work.

Further design choices that will flow down from the propeller type will be additional design possibilities such as fan ducting or vane control for thrust vectoring. Again, these choices do not make sense to trade study yet, as they are influenced by multiple higher-level design choices.

Variable Speed Propeller

Variable speed propellers are the classic propeller of choice for small multirotors. They allow relatively simple control systems and are powered by electric motors controlled by Electronic Speed Controllers (ESCs). Variable speed is a clear winner for small, battery-powered multirotors due to the lack of power conversion required. However, for EMU, the solution is less obvious. Because EMU will utilize gas power, variable speed would require a hybrid-electric generation system to convert the mechanical energy generated to electric power to in turn power the motors. Despite the conversion losses, variable speed propellers can still achieve extremely high efficiency during hover. This is because the aerodynamic twist can be optimized for the varying speed that each section of the blade will see. Because our project will spend a large majority of its total flight time at hover, this efficiency is extremely desirable. Additionally, higher efficiency can be achieved with a larger rotor blade at a slower angular speed. A major downfall of the variable speed option is the high cost associated with the electric motors and ESC's required to drive the propellers. Online research at a popular multirotor parts retailer 'tmotor.com' revealed that the cost of four electric motors, ESC's and propellers that meet our estimated thrust requirements would be in excess of $1600. The pros and cons of variable speed propellers can be seen in Table 46.

Variable Pitch Propeller

The variable pitch propeller type is not commonly used for multirotors but offer some significant advantages over the traditional variable speed propellers. One positive for this propeller choice is the higher rate of change of thrust compared to variable speed propellers, which take longer to alter their thrust due to rotor and motor inertia. Variable pitch also offers improved power transmission efficiency over variable speed due to a mechanical drivetrain that directly connects the rotors to the engine, reducing losses due to power conversion. The pros and cons of variable pitch propellers can be seen in Table 48.

Variable Speed and Variable Pitch Propeller

The variable speed and pitch propeller is a quite novel concept, not seeing much use outside of technical research papers. For this reason, it was excluded despite several extremely desirable qualities. It can achieve the best performance and efficiency of the three rotor types due to combining the best of both variable pitch and speed. However, its lack of commercial availability, necessarily complex drive train and powerplant, and largescale lack of adoption make it a poor choice for the EMU project. The pros and cons of variable speed, variable pitch propellers can be seen in Table 48.

The propeller blade selection weighting can be seen in Table 54.

Scale Assignment

The scale assignment can be found in Table 50.

Trade Matrix

The scores for each option are shown in Table 51. In-depth reasoning for each assignment is provided below. Due to the complexity and novel design, a variable-speed variable-pitch combination is excluded from the in-depth explanation.

Variable Speed

- **Hover Efficiency**: 5 - Variable speed propellers can be very carefully optimized for the exact hover conditions they will operate at. This, however, also requires specifically-sized rotors that would also be commercially unavailable.
- **Cost**: 2 - Variable speed propellers are extremely common and their price reflects this.
- **Drivetrain Simplicity**: 3 - Variable speed propellers require an alternator to convert the engine's output power to electrical energy and ESCs to control and supply power to the propellers themselves. This would require significant electronics expertise as well as result in a higher risk of failure.
- **Mass**: 3 - Variable speed propellers come with a significant mass cost, due to them requiring power conversion from mechanical to electrical and back again as well as Electronic Speed Controllers (ESCs).
- **Maneuver Efficiency**: 4 - Variable speed propellers are quite efficient in maneuvers.
- **Control Capability**: 3 - Variable speed propellers have some delay in control inputs due to the rotational inertia of each rotor system.

Variable Pitch

- **Hover Efficiency**: 3 - Variable pitch propellers lose some efficiency as compared to variable speed. This is because they must have extra thrust available and thus cannot operate at their most efficient conditions.
- **Cost**: 4 - Variable pitch propellers are usually relatively costly, since they are commonly used as main helicopter rotors.
- **Drivetrain Simplicity**: 4 - Variable pitch propellers require a complex drivetrain to operate, but do not require any power conversion and are thus simpler than variable speed propellers.

- **Mass**: 4 - Variable pitch propellers are relatively light-weight, requiring only a drivetrain and not needing power conversion or ESCs.
- **Maneuver Efficiency**: 4 - Variable pitch propellers have a high efficiency for maneuvering.
- **Control Capability**: 4 - Research shows that variable pitch propellers actually have more control authority than variable speed propellers in most cases.

4.1.2. Detailed Design

As laid out previously, variable pitch propellers was decided as the thrust method of the UAS. For the purpose of quickly iterating through designs and ensuring validity of chosen rotor sizes, a program was created to take in design variables of the rotor and output the thrust produced, power required, and torque required.

This program was then implemented in a GUI for easier use. Additionally, another program was created to sweep different geometric angles of attack and save the resultant thrust, torque, and power required as functions of the angle of attack. This data was plotted, as shown in Figs. (71)–(73), to ensure the thrust was relatively linear as a function of angle of attack at steady hover conditions. Additionally, this data was used in the EMU dynamics simulation.

The propeller simulation is discussed below.

The propeller simulation was also used to find the optimal rotation rate and geometric angle of attack of the rotors, also described below.

Propeller Simulation

Many of the equations used in this section come from *Principles of Helicopter Dynamics*[24]. *XFOIL*[25] was used to acquire the sectional lift and drag coefficients used in the process.

To begin, the downwash distribution, λ, was calculated along the blade. The equation for this is

$$\lambda = \sigma \frac{2\pi}{16F}\left(\sqrt{1 + \frac{32F \times \theta(r) r}{\sigma 2\pi}} - 1\right) \tag{1}$$

where r is the non-dimensional distance from the blade axis of rotation given by $r = \frac{y}{R_o}$. In this equation, y is the dimensional distance from the axis of rotation and R_o is the outer radius of the blade. σ is the blade solidity and is given by $\sigma = \frac{A_{blade}}{A_{disk}}$.

The F term in Eq. (1) is known as Prandtl's tip loss function, and is given by

$$F = \frac{2}{\pi}\cos^{-1}\left(e^{-f}\right) \tag{2}$$

$$f = \frac{N_{blades}}{2}\left(\frac{1-r}{r\phi}\right) \tag{3}$$

This complicates things, as $\phi = \frac{\lambda(r)}{r}$, and λ is also a function of F (as shown in Eq. (1)). Thus, an initial guess of $F = 1$ is used. Then, the system iteratively calculates F, and plugs the final value into Eq. (1). The F values calculated in this way agree with those in *Principles of Helicopter Dynamics*[24].

After the downwash is calculated as a function of the non-dimensional span-wise location, r, we know the physical angle of attack at each of these points is $\theta(r) - \phi(r)$. Thus, we can calculate the necessary values of C_l and C_d. Because these variables do not have analytical functions, XFOIL[25] is used to gather C_l and C_d values at 10 different span-wise locations and the physical angle of attack at each respective point.

These values are then interpolated into functions so that the sectional lift and drag coefficients can be accessed at any point along the blade. Next, we create the integrands of the thrust and torque coefficients as a function of non-dimensional span-wise location. These take the form

$$dC_T = 0.5\sigma C_l(r) r^2 \tag{4}$$

$$dC_Q = \lambda(r) C_l(r) r^2 + C_d(r) r^3 \tag{5}$$

We then integrate both of these (($C_T = \int_0^1 dC_T dr$ and $C_Q = \int_0^1 dC_Q dr$) to find the coefficients of thrust and torque, and multiply those coefficients by environment variables. This gives us

$$T = C_T \rho A_{disk} \omega^2 R_o^2 \tag{6}$$

$$Q = C_Q \rho A_{disk} \omega^2 R_o^3 \tag{7}$$

where ρ is the atmospheric density and ω is the rotation rate of the propeller blades. Finally, we can multiply the torque by the blade rotation rate to find the power as follows:

$$P = \omega Q \tag{8}$$

This method utilizes XFOIL, which accounts for viscous flow, and the tip loss function in an attempt to emulate real-world losses. Additionally, in calculating the required power at nominal hover conditions, a figure of merit taken from real-world data (*Static Thrust Analysis of the Lifting Airscrew*[26]) was used instead of the data as generated by the program. However, it is worth noting that the figure of merit values generated for EMU agreed well with theoretical data from *Principles of Helicopter Dynamics*[24], which demonstrates the validity of the program. The power, thrust, and torque of the vehicle are shown in Figs. (71)–(73), as is the program GUI initialized at steady hover conditions. The GUI of the propeller simulation is shown in Fig. 74

Rotor Optimization

The rotor optimization function utilizes the propeller simulation outlined above. It uses MATLAB's built in fminsearch function, a derivative-free function minimization function. This function takes a cost function and finds a set of inputs that minimize the cost. For EMU, the cost function is simply the power required. It also includes large penalties for thrust lower than the weight of the vehicle to prevent the function simply going to the minimum thrust and hover.

In this way, the function was initially used to find the optimal size rotor and the optimal rotation rate and geometric angle of attack of this rotor. Once this size was found, a rotor head assembly was chosen. From here, the most closely sized rotor compatible with this chosen rotor head assembly was chosen. The dimensions of this final rotor were then given to the cost function, and it was made to vary the rotation rate and geometric angle of attack of the blade while leaving the rotor dimensions constant. Thus, the Align 380 mm blades spinning at 2350 RPM and at 11.05° are the best blades and nominal hover conditions in terms of power consumption. This equates to a longer endurance for the vehicle, and thus provides the best chance of success for the system as a whole.

4.2. Rotorhead Assembly

Libby Hasse

4.2.1. Conceptual Design

The design process for the rotorheads started with the functional requirements found in Table 3 as well as several design requirements from our customer. Given that each of the four rotorheads has many small moving parts it was at the forefront of the design process to minimize the number of moving parts needed and overall complexity of the manufacturing process. Safety for this mechanism was the primary driver for reducing the manufacturing complexity of the system. In addition to manufacturing complexity the requirement for autonomous flight was also a driver for a reduction in the control law complexity which simply correlated to a reduction in the number of servos needed per rotorhead. Reducing the number of servos also ties into some of the design requirements such as the weight limit and budget provided by the customer.

Table 3: Major Requirements for Rotorheads

Requirement Type	Requirement Number	Rationale
FR	2	UAS shall operate autonomously
FR	6	UAS shall operate safely
FR	7	Chassis shall support all UAS components

The rotorhead design started with a stock swashplate from an RC Helicopter. With no manufacturing done to the swashplate or any of the rotorhead components, the design would require 3 servos, which was the first design option. Although this design would eliminate the need for manufacturing and satisfy the safety aspect of our functional requirements the fullest degree, the negative impacts on the cost, weight and control law complexity combined outweigh the benefit of the design. The second design aimed to fix the error in the first design by adding a plate beneath the swashplate that would connect the three servo connection rods, shown in Fig. 3, and have only one contact point closest to the main shaft for one servo to push the swashplate up and down. This design increased the level on manufacturing needed, but reduced the control law complexity by reducing the number of servos. The last design required the removal of the uniball currently in the swashplate followed by the addition of a recirculating linear bearing. Overall this last design required the most manufacturing. However, opposite to the situation with the first design the cons are outweighed by the positive aspects. Not only does the cost and weight of the entire mechanism decrease, but the overall complexity of the system decreases. The results of the trade study on these three designs can be seen in Table 4.

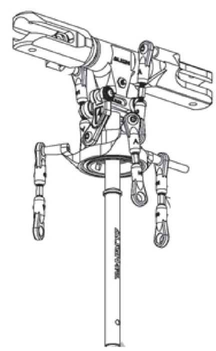

Figure 3: Stock Rotorhead Design

Table 4: Trade Matrix for Rotorhead Design

Criteria	Weight	Options		
		3-Servo	1-Servo with Adaption Plate	1-Servo Linear Bearing
Manufacturing Complexity	40	5	3	4
Control Law Complexity	30	1	5	5
Weight	25	1	3	5
Cost	15	1	2	2
Total	**100**	**2.70**	**3.75**	**4.65**

3-Servo Design

- **Manufacturing Complexity**: 5 - This design exactly fit the criteria 5 description. No manufacturing would be necessary.
- **Control Law Complexity**: 1 - In this design cyclic control would need to be taken into account which adds a lot of complexity in order to produce the proper outputs for the servos.
- **Weight**: 1 - Out of the three designs this configuration increases the weight by 3x
- **Cost**: 1 - Out of the three designs this configuration increases the cost by 3x. The needed number of spare parts affects this cost greatly.

Single Servo Design with Adaption Plate

- **Manufacturing Complexity**: 3 - The first part of this manufacturing process is the same as the last design but requires the additional manufacturing of the plate which increases the manufacturing level slightly.
- **Control Law Complexity**: 5 - Similar to design 3 a single servo requires the simplest control law.

- **Weight**: 3 - The addition of the adaption plate puts this design slightly higher in weight compared to design 3
- **Cost**: 2 - A large cost of the rotorhead mechanism lies in the servo. A single servo decreases this cost greatly from design 3.

Single Servo Design with Recirculating Linear Bearing

- **Manufacturing Complexity**: 4 - Replacing the uniball with the linear bearing will be a lot of work but that is the extent of the manufacturing unlike design 2.
- **Control Law Complexity**: 5 - A single servo requires the simplest control law.
- **Weight**: 5 - This design will have the minimum amount of necessary parts thus making it the lightest design.
- **Cost**: 2 - Although the cost of a linear bearing is greater than a plain sleeve bearing, it evens out in criteria to design 2 since this design does not include the cost of the adaption plate.

4.2.2. Detailed Design

The chosen design from the trade study results in Table 4, describes a rotorhead mechanism with a modified swashplate and the use of a single servo per rotorhead. The most important aspect of the rotorhead mechanism was the modification of the swashplate. An important factor that was eliminated when choosing this design was the even distribution of force applied to the swashplate with the use of three servos. Early on it was imperative to determine if the use of a single servo would cause binding between the shaft and the linear recirculating bearing. By using force balance equations and the coefficients of friction of the materials in question the binding ratio or the maximum lever arm to bearing length ratio was determined and found to be in a region that allow for free motion of the mechanism. In order for the recirculating linear bearing to sit in the right position inside the swashplate Fig. 4 shows a shim and two retaining clips that were added to seat the bearing.

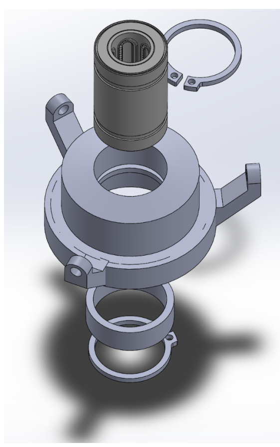

Figure 4: Exploded Swashplate

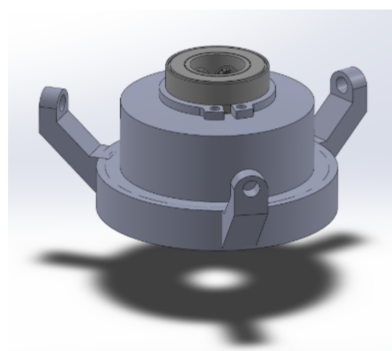

Figure 5: Assembled Swashplate

The remaining parts required for this design were all bought and assembled as is with no modifications. The upper section of the rotorhead was assembled first followed by the insertion of the main shaft. The modified swashplate was then added and connected via linkage rods. At this point the rotorhead assembly was then inserted into the bearing blocks and the servo was attached last. Fig. 6 and Fig. 7 show the entire assembly with the connecting pulley which will be discussed the drive train section to follow.

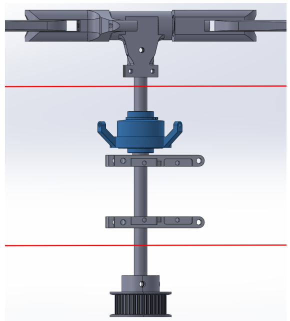

Figure 6: Partitioned Rotorhead

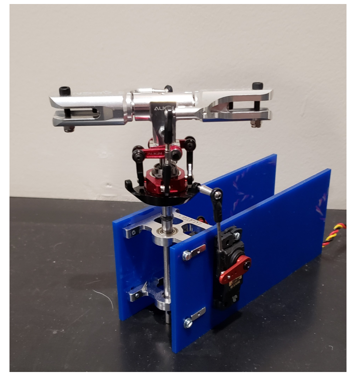

Figure 7: Full Rotorhead Mechanism

4.3. Chassis

Rebecca Rivera

4.3.1. Conceptual Design

The driving functional requirements that went into the chassis conceptual design are represented in Table 5. These functional requirements flow down to specific design requirements that were considered when making conceptual design choices. The major design requirements flowed from FR 1 are DR 1.2.2 and DR 1.4 which respectively state that the UAS shall produce necessary thrust to maintain steady hover and the UAS shall weigh a maximum of 25 lbs without the payload. In order to satisfy these requirements, the chassis must be light weight and allow for sufficient propeller surface area to generate the required thrust. All of the requirements that flow from FR 4 are relevant to the chassis design because it was essential to develop a design with enough space to hold a gas powered engine and a fuel tank large enough to support two hours of hover. Regarding the camera payload mentioned in FR 5, the most relevant design requirement is DR 5.2 which states that the payload shall be rigidly attached to the UAS. This is another requirement regarding the amount of space available to mount components on the UAS. Finally, all the design requirements flowed from FR 7 were taken into account. These design requirements go into further detail about how the chassis is expected to support all components, include landing gear, and support a drivetrain to deliver power to the rotors.

Table 5: Major Requirements for Chassis

Requirement Type	Requirement Number	Rationale
FR	1	UAS shall operate within the defined flight boundary
FR	4	UAS shall be gas powered
FR	5	UAS shall carry a camera payload
FR	7	Chassis shall support all components on the UAS

For the chassis conceptual design, the team considered how to best support the UAS and payload. Stability, efficiency, safety, complexity, and payload interference were all taken into consideration while choosing the rotor position, rotor configuration, and chassis shape.

The choices analyzed for rotor position were the pusher, as seen in Fig. 8 versus the puller, as seen in Fig. 9. The pusher configuration uses the lift produced by the propellers to push the UAS structure up from below whereas the puller configuration pulls from above.

Figure 8: Pusher Configuration

Figure 9: Puller Configuration

This trade study resulted in a puller configuration where Table 6 shows the final evaluation of each option. The criteria used in the evaluation were the propeller surface area, manufacturing complexity, payload interference, and efficiency. Based on the system requirements these were determined to be the most important criteria used to make the design decision.

Table 6: Trade Matrix of Pusher vs. Puller Configuration

Criteria	**Weight**	**Options**	
		Pusher	**Puller**
Propeller Surface Area	35	3	5
Manufacturing Complexity	25	3	5
Payload Interference	25	2	4
Efficiency	15	5	3
Total	**100**	**3.05**	**4.45**

The three rotor configurations considered were the quadcopter design as seen in the pusher versus puller options, the hexagonal six rotor configuration in Fig. 10, and the coaxial, triangular, six rotor configuration in Fig. 11. These options were chosen to evaluate the influence of the number of rotors and their configuration on UAS performance.

Figure 10: Hexagonal Configuration

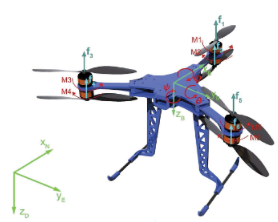

Figure 11: Coaxial, triangular, six rotor configuration

A quadcopter configuration was chosen based on weight, efficiency, manufacturing complexity, maneuverability, cost, and safety. Table 7 shows the scoring and results.

Table 7: Trade Matrix for Number of Rotors

Criteria	Weight	Options		
		Quadcopter	**Coaxial, Triangular, Six Rotor Configuration**	**Hexagonal Six Rotor**
Weight	25	5	4	3
Efficiency	25	5	4	3
Manufacturing Complexity	15	5	3	1
Maneuverability	15	5	3	2
Cost	10	5	3	2
Safety	10	3	4	5
Total	**100**	**4.8**	**3.6**	**2.65**

With a quadcopter configuration, three main shapes were considered; the X-frame, H-frame, and XH-frame in Figs 12, 13, and 14 respectively. These are the most common quadcopter frame shapes and the most suitable based on our previous selections. Each frame is relatively stable and will allow for symmetry along two axes.

Figure 12: X-Shaped Quadcopter Frame

Figure 13: H-Shaped Quadcopter Frame

Figure 14: XH-Shaped Quadcopter Frame

This trade study resulted in an H-frame quadcopter because the H-frame is the only option with enough space to mount the power plant and power delivery systems required for the UAS to meet its weight and flight time requirements. This trade study was based on the available mounting space, weight, mechanisms complexity (for power delivery), manufacturing complexity, and stability and control as seen in Table 8.

Table 8: Trade Matrix for Chassis Shape

Criteria	**Weight**	**Options**		
		X-Frame	**H-Frame**	**XH-Frame**
Mounting Space	30	1	5	3
Weight	20	2	4	3
Mechanisms Complexity	20	2	3	2
Manufacturing Complexity	15	2	4	3
Stability & Control	15	3	4	4
Total	**100**	**1.85**	**4.1**	**2.95**

The three trade studies were conducted with respect to the system functional requirements in Table 5 and their respective design requirements. To make an engineering decision and satisfy the requirements, the pros and cons of each design choice were tabulated, next, criteria were determined and weighted in such a way that the design choice indicated by the trade study would be the best option. Standards for scoring each option were determined and then each choice was evaluated with weighted scoring. The pro/con tables, weighting assignment table, and scoring criteria table can all be found in Appendix B, Tables 52 - 65. This process resulted in a puller, H-frame quadcopter baseline design.

4.3.2. Detailed Design

The chassis detailed design is driven by the requirement that it must support all components on the UAS in flight and on the ground. The final chassis design is shown in Fig. 15. The major elements of the chassis are the main beams, propeller arms, mounting plates, and landing gear (not shown in Fig. 15). The main beams refer to the tubes that run the length of the middle part of the ”H” supporting the component mounting plates, the propeller arms are the long parallel plates that make up the sides of the ”H” and hold the rotorheads, the engine mounting plate is the widest plate in the middle, and the avionics pate is the second widest plate mounted on top of the main beams. Figure 16 shows the chassis, including the landing gear, integrated with the power plant, drivetrain, and rotorhead subsystems.

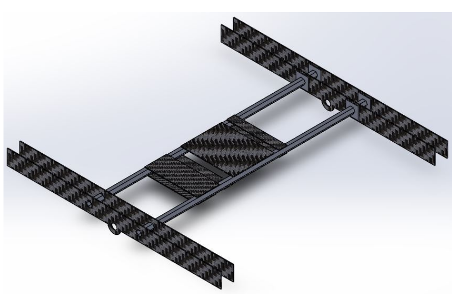

Figure 15: Chassis Design

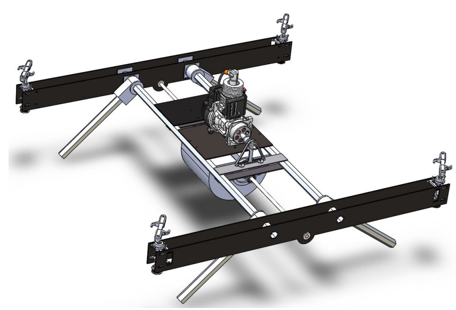

Figure 16: Chassis Integrated

The quadcopter dimensions were determined based on the propeller length and engine size. The goal was to design the smallest chassis possible with no propeller tip overlap. It would have been possible to make a slightly smaller frame with some propeller overlap because the propellers will spin out of phase but it was decided that to mitigate risks, there should be no overlap in case of misalignment in the assembly or belt slip. A MATLAB program was written to calculate the chassis dimensions based on the diagram in Fig. 17. Inputs to this program are the propeller length, the necessary gap between propeller tips, the length between propeller axis of rotation and where the propeller mounts on to the rotorhead, the dimensions of the engine mount plate, the necessary gap between engine mount and propeller tips, and the width of the bearing blocks that hold the rotor turning shafts. The program outputs the length of the main section, the length of the propeller arms, the width between the propeller arms, and the width between the main beams. The measured weight of the chassis is 5.3 lbs which translates to about 21% of the overall weight of the EMU not including the payload and the final design has the following dimensions listed in Table 9.

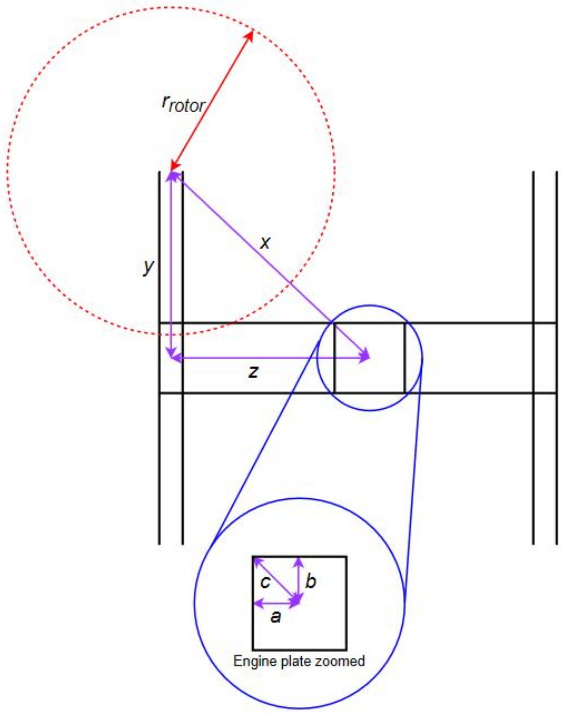

Figure 17: Diagram for Calculation of Chassis Dimensions

Table 9: Dimensions of Chassis Main Components

Component	Dimensions [in]
Main beam length	35.6
Main beam diameter	0.86
Propeller arms	35.3 x 2.50
Engine mount plate	6.6 x 8.50
Avionics plate	4.92 x 8.50

The chassis is almost completely constructed from carbon fiber. The main beams are hexagonal carbon fiber tubes that were purchased from Rock West composites and cut to length. The remaining tubing was used as the legs in the landing assembly. The rest of the components were cut from a quasi-isotropic carbon fiber plate purchased from Dragon Plate. The carbon fiber components are held together using the 3M Scotch Weld DP6990NS urethane adhesive. The landing assembly includes 3D printed PLA parts that allow the landing legs to rotate freely around the main beams and provide mounts for the landing shocks. The shocks are off the shelf RC car shocks from Redcat racing (part number 07103). Images of the landing gear components can be found in Appendix C where Figs 75 - 77 show the 3D printed parts that allow the carbon fiber tube legs to freely rotate around the main beams. Figures 78 and 79 show the 3D printed parts designed to mount the landing gear shocks and Fig. 80 shows the shocks that were chosen.

4.4. Power Plant

Max Alger-Meyer, Michael Flores

The power plant subsystem is the system responsible for producing the power necessary to turn the propellers and create lift. It is comprised of comprised of the engine, the fuel system, and the clutch for safe drivetrain integration.

4.4.1. Conceptual Design

The design for the power plant began by assessing the functional requirements in Table 10. The first requirement for the power plant is given in functional requirement 4 which states that the UAS must be powered by liquid fuel. This presents the first challenge for the power plant because these types of aircraft typically use four individual electric motors to control the speed of each rotor individually and maneuver the aircraft in doing so. Since gas powered motors are significantly heavier than electric motors, this requirement limits the power plant to a single motor that would have to deliver power to every motor through a drive train rather than individual motors. The second functional requirement pertaining to the power plant is functional requirement 6 which states that the UAS must operate safely. In speaking with the project's client, it was specified that the vehicle would need to be able to be turned out without the propellers spinning. Since gas motors must always spin at a minimum of their idle RPM, this requirement meant that a clutch would need to interface between the power plant and the drive train so that when the motor is at idle, the propellers do not move.

Table 10: Major Requirements for the Power Plant

Requirement Type	Requirement Number	Rationale
FR	4	UAS shall be gas powered
FR	6	UAS shall operate safely

With the functional requirements in mind, the next step in the conceptual design of the power plant system was to conduct trade studies to decide which type of motor would best suit the needs of the project. Five different, viable engine configurations were considered to determine which option is the optimal choice to give the best chance of success. All of the motor types considered are designed to integrate with remote control vehicles.

In addition to studying different types of motors, a trade study was performed to determine the feasibility of retrofitting aftermarket clutches on engines not initially designed to integrate with clutches. This was deemed a necessary endeavor because many of the engines considered were designed for use with remotely controlled hobbyist aircraft, which do not generally require the use of clutches. As briefly touched on in Section 2, IRISS attempted to build a similar vehicle that failed to ever take to the skies. The primary failure point of the aircraft was that it used a twin piston engine retrofitted to work with an aftermarket clutch that failed upon engagement. With this in mind, the advantages and disadvantages of engines with and without built in clutches were compared and analyzed.

Figure 18: Single Piston Engine

The first engine type considered was a single piston engine. The single piston engine provides a simple, reliable engine design with the least amount of moving parts. Due to the simple and conventional design, it is one of the most inexpensive options available on the market. Since it only contains a single piston, it creates vibrations that can compromise the integrity of its mount and cause perturbations that effect the stability of the UAS which could prove difficult to correct with controls. Furthermore, this is the most abundant option available, as there are hundreds of different single piston engines available to RC hobbyists. This would prove to be advantageous as it would allow for a more specialized selection for this application.

Figure 19: Twin Piston Engine

Twin piston engines are similar to single piston engines, but with two horizontally opposed pistons instead of a single piston. Because of their configuration, twin piston engines cut down from the vibrations created by their single piston counter parts. Twin piston engines also create better torque than single piston engines due to the nature of having two different power strokes offset from each other. On the other hand, twin pistons usually have a worse power to weight ratio than their single piston counterparts and run at lower RPMS. Furthermore, they are more complicated, and are generally more expensive. Similar to the single piston engine, twin piston engines are widely available and relatively affordable.

Figure 20: Radial Engine

The radial engine design is extremely common in aviation due to its high cooling efficiency through its large surface area. The reliable characteristics of the radial engine lead its large use in aircraft until higher speeds required new engine types, and its circular fire pattern disperses and moderately dampens the vibrations caused during operation. Due to the nature of their configuration, radial engines have a much smaller compression ratio than other reciprocating pistons, and because of this have a worse power to weight ratio. Furthermore, their large surface area and cooling benefits might not be as advantageous in this application as they would for a fixed wing aircraft as airflow will be very limited due to the nature of the mission profile, and therefore their inherent passive air cooling may still not be enough.

Figure 21: Turbine Engine

The turbine engine is the lightest option and creates the greatest balance among the different engine types considered. Although balanced and light, it is also the most expensive option as well as the least maintainable as its lifespan is only a fraction in terms of flight time before it must be repaired when compared to the other engine types mentioned. Furthermore, despite some turbine engines being highly efficient considering their power output, all of the turbine engines available at this scale would suffer in efficiency compared to their reciprocating piston engine counterparts.

Figure 22: Electric Motor

Most of the engines available for use on this vehicle are not designed to interface with clutches. Because of this, using a retrofitted clutch would have allow for the use of a larger motor, and therefore a larger power to weight ratio for the aircraft. Furthermore, this would have allowed for the use of any of the four gas powered motors discussed previously (an electric drive would not require the use of a clutch for safe operation). Conversely, selecting a motor not designed to interface with a clutch would have required additional analysis and would be a potential failure source that we otherwise wouldn't have.

After comparing all of the aforementioned options it was decided that the vehicle will employ a single piston engine with a built-in clutch. Although using a twin piston motor would dampen vibrations caused by the reciprocating piston, concerns regarding engine-clutch misalignment on a retrofitted system proved too great to ignore.

Table 11: Trade Matrix for Power Plant

Criteria	**Weight (%)**	**Engine Type**			
		Single Piston	**Dual Piston**	**Radial**	**Turbine**
Efficiency	25	5	4	3	2
Weight	20	4	3	2	5
Cooling	15	3	4	5	2
Reliability & Maintainability	10	5	4	4	2
Vibrations & Balance	10	1	4	3	5
Cost	10	5	5	3	1
Drivetrain Integration	10	5	1	1	1
Total	**100**	**4.1**	**3.6**	**3.0**	**2.7**

4.4.2. Detailed Design

Figure 23: Electric Motor

The engine ultimately selected for the vehicle was the Zenoah G320-RC as show in Fig. 23. Early analysis showed that the engine selected would need to produce an excess of 6 horsepower but with more precise and refined modeling, that figure ultimately dropped to just 2.65 horsepower. With this reduced power requirement, a smaller motor with a built-in clutch could be selected. This solution alleviated any concerns over possible misalignment between the engine's output shaft and the clutch. Another advantage of the selected engine is that it uses a recoil starter that interfaces with the engine's cooling flywheel when pulled. The addition of this starter means the purchase of a separate starter would not be necessary. As mentioned, this engine also has a flywheel attached to the crankshaft opposite the clutch which pulls air through vents around the engine and over the cylinder. This flywheel means that the engine is self-cooling and would not require any additional after-market cooling system. Furthermore, this engine was also advantageous because unlike most of the other motors considered, the manufacturer provided specific fuel consumption data that could be used to more precisely model the fuel consumption of the motor during flight. This figure and the other key engine parameters are given in Table 12

Table 12: Zenoah G320RC Engine Parameters

Engine Parameters	
Displacement (cc)	31.8
Max Power (HP)	3.22
Max Torque (ft-lbs)	1.60
Specific Fuel Consumption (lb/hour/hp)	0.85
Weight (lbs)	5.07
Speed Range (RPM)	4000-20000
Clutch Engagement Speed (RPM)	6000
Speed of Max Power (RPM)	13,000

The specific fuel consumption (SFC) listed in Table 12 was used to determine the amount of fuel that the engine would require during the duration of the flight. In order to do so, thrust and power outputs with respect to geometric angle of attack, defined by the rotor blade model, were used to equate engine power to thrust produced.

This model began by first taking the weight of the UAS and determining the angle of attack at which the thrust created by the propellers was equal to the weight of the vehicle. Next, the model would take that specific angle of attack and find the required power value from the blades to produce that thrust. This value was then increased to account for 30% drivetrain losses. The *SFC* value was then multiplied by the this final power value and the time step to determine how many pounds of fuel were burned in that time step. For the ascent and descent conditions, the parameters were changed slightly. Each maneuver period was allotted five minutes, which represented a maximum UAS speed of four miles per hour in the worst case scenario. This speed is easily achievable and therefore bounds the maneuver periods. During ascent, the thrust value was assumed to be 120% of that at hover and for descent the thrust value was assumed to be only 90% of hover thrust. Finally, once this mission profile was integrated over, the team applied a 15% fuel reserve to compensate any extra power and maneuvers not tracked in this model. This fuel reserve is common in similar applications. The results of this integration with the applied reserve factor yields a total fuel weight of 4.67 lbf of fuel. Using the volumetric density of gasoline, this amount of fuel equates to 95 fl-oz of fuel.

To hold this fuel, the team needed to design a tank. Driving this design was the unique shape of the UAS, the limited mounting space due to the driveshaft, and the aim to not have a changing center of gravity throughout the flight. The outcome of these driving factors was a half cylinder shape with a cutout in the center to allow for driveshaft clearance. Such a design allows for clearance of the driveshaft through the center and mounting points to a plate attached to the two hexagonal tubes running along the UAS. The ideal length for the fuel tank was calculated to be 0.18 meters which would allow the vehicle to carry 100 fluid ounces of fuel.

With the fuel tank designed, the next step in the power plant design was to determine the best way for the engine to integrate with the drive train. As mentioned, this engine has a built-in clutch. For the purposes of this vehicle however, the gears that the clutch is designed to integrate with will be replaced with pulleys to save weight, and to allow freedom in the distance between the output shaft of the clutch and the driveshaft. Since the pulleys needed to be under high levels, a bracket was designed to support that engine's output shaft. This bracket was necessary because otherwise the clutch bell would be cantilevered which could lead to the binding of bearings supporting the clutch bell, possible misalignment of the shaft, and undesirable forces on the bearings supporting the clutch bell. Figure 24 shows the design of this component and Fig. 25 shows how it integrated with the chassis and engine.

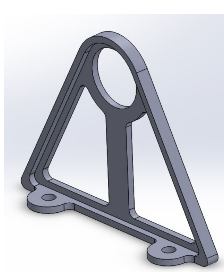

Figure 24: Output Shaft Bracket Design

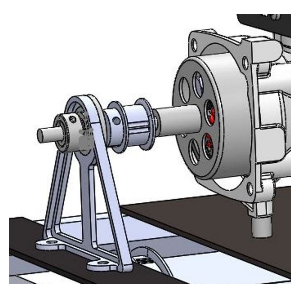

Figure 25: Integrated Bracket

4.5. Drivetrain

Nathan Hetzel

During the design process, the drivetrain was split into two subsystems: engine engagement and power delivery. Both of these subsystems provide an essential role for EMU to obtain flight, so several design options for both systems were compared using simple pros & cons tables. Along with the pros & cons, the requirements for the system were also used to determine which option would be the best for the system. A quick description of the options provided in the *Conceptual Design* subsection, along with a discussion of the process used to selected the final options. The pros & cons tables used for the drivetrain determination process are presented in *Appendix B: Trade Studies* section under the *Drivetrain* subsection as Tables 66 - 73. After each option is selected to satisfy the project requirements, the details of the design including analyses and final component selection are provided in the *Detailed Design* subsection.

4.5.1. Conceptual Design

For the engine engagement system, four options were compared: clutches, direct drive, torque converters, and alternators. The first three are options for a system that uses a mechanical source of power such as an engine. An alternator would only be used if the UAS is either fully electric or a hybrid system.

A clutch system allows the engine to be disconnected from the main drivetrain by creating a break between two parts of the output shaft. Clutches commonly come in one of two forms: centrifugal and plate. Clutches are generally lightweight systems and as mentioned, provides different options as well. A direct drive system would not break the output shaft into separate parts, and directly power the propeller blades when the UAS power is turned on. Due to safety constraints and customer requirements, this would prevent the engine to run without spinning the propellers, and most likely be eliminated as an option unless it provides major benefits. Direct drive systems are simple systems, but do not allow the engine to run without rotating propellers. A torque converter is a system that uses fluid coupling to transfer rotational energy, and are commonly used on automatic vehicles. Generally, they are complex and heavy systems, so much like the direct drive option, torque converters are most likely to be eliminated. The last option is the use of an alternator and brushless motor system if a hybrid option is selected. This would convert the mechanical energy from an engine into electrical power, where different electronic systems can be used to remotely power each rotor when desired, allowing for the engine to run and the propellers remaining stationary.

Much like the engine engagement system, four options were compared for the power delivery system: drive shafts, belts, chains, and electric connections. In a similar fashion, the first three are all options that would be used for a mechanical system while the last is only for an electric or hybrid system.

A drive shaft system would use joints such as gears boxes to change the direction of the shaft rotation and orientation to transfer the rotational energy from the engine to each of the propellers. A drive shaft would be able to spin at a constant rate and allow all propellers to spin the same rate as one another. Belts would be coupled with pulleys in order to change the plane of rotation to deliver the power to each propeller. Belts would be combined with another system, and provide a lightweight option to spin the propellers at the same rates as one another. Chains work the same ways was belts, but have different properties since they are metal links as opposed to being rubber. Chains are generally heavier than belts and size options do not allow for intermittent sizes since links are a set size. Electronic wires would transfer the energy from the engine to the rotor motors through electric currents. Each wire would connect to brushless motors that are attached to each propeller and send signals to spin each propeller independently if needed.

Throughout the design process, the system requirements a played a huge role in eliminated options for the drivetrain. Table 13 below shows the main requirements the drivetrain either directly affected or was directly affected by.

Table 13: Major Requirements for Drivetrain

Requirement Type	**Requirement Number**	**Rationale**
FR	4	UAS shall be gas powered
DR	6.2	All UAS functions shall be shut down at any time
DR	7.4.1	Drivetrain shall deliver power from engine to all rotors
DR	7.4.2	Drivetrain shall stably spin the rotors

During the final stages of selection for the drivetrain components, it is necessary to know if the power plant of the UAS would be a mechanical system, an electrical system, or a hybrid system. As the power plant conducted their trade studies, the UAS was leaning towards a mechanical system, which would result in the options considering a hybrid or electrical system to be eliminated as options.

For the engine engagement system, a clutch option is chosen as it provides a combination of being lightweight, relatively inexpensive, satisfying safety and customer requirements, as well as being a system that is easier to understand and integrate compared to some of the other options. For the power delivery system, a combination of a central drive shaft accompanied by belts to connect the output shaft to the main shaft and the main shaft to the propellers were chosen as they are the most lightweight option as additional gears and shafts would exceed the weight available for the system and the chassis design would not be able to easily accommodate a strictly belt driven system.

Since the team was able to easily eliminate choices that would not fit within the constraints provided by the customer, a need for a trade matrix was not necessary for this specific subsystem. Since a clutch system was selected further research is required and will be discussed in the next section, along with detailed analysis of rotating shafts and belts.

4.5.2. Detailed Design

When conducting a more refined design of the drivetrain, several different analyses were conducted on the main drive shaft including a torsional analysis of different shaft sizes and materials, a critical speed assessment, and an endurance model for a rotating shaft using modified Goodman's equations. Custom clutch designs and materials were also analyzed such as the required clamping force required for different clutch lining materials for a variety of different clutch sizes, as well as a sizing model that includes different actuator options and material failure speeds. When the engine for the UAS was selected, a customized clutch was not needed as the engine had a centrifugal clutch that is pre-integrated into the system.

For the ability to remain concise, an overview of the system as a whole will be provided and will include diagrams of the final design and a table of the key parameters, as well as mention which components are the most important and how they were addressed during the analysis process. Below is a list of the main components of the drivetrain system and include some general details about each component. It should be noted that the main drive belt and the four rotor belts are not included in the table as they were to be purchased later on to ensure the correct belt size is selected. Fig. 26 shows a CAD diagram of the drivetrain, as well as the clutch bell housing and output shaft support. The second portion of the output shaft would rotate once the clutch engages with the outer housing, rotating the output shaft pulley. This pulley is connected to the main drive pulley that has a radius four times greater, providing a gearing ratio of 4:1, decreasing the shaft spin rate when compared to the engine spin rate. This main shaft then turns the four pulleys on the ends which are connected to the rotor shaft pulleys through a belt connection which is not shown here for visual reason.

Main Components

- **Main Drive Shaft:** 36 inch long AISI 4340 alloy steel rod, 3/8" in diameter
- **Output Shaft Pulley:** 1/4" bore, 3mm GT2 belt type polycarbonate pulley with a 0.752" pitch diameter
- **Main Shaft Drive Pulley:** 3/8" bore, 3mm GT2 belt type polycarbonate pulley with a 3.008" pitch diameter
- **Main Shaft Rotor Pulleys:** 3/16" pre-manufactured bore, 40D.P. belt type aluminum pulley with 0.936" pitch diameter, manufacturing to 3/8" bore
- **Rotor Shaft Pulleys:** 3/16" pre-manufactured bore, 40D.P. belt type aluminum pulley with 0.936" pitch diameter, manufacturing to 6mm bore
- **Propeller Arm Support Bearings:** 3/8" bore flanged bearing
- **Motor Plate Support Bearings:** 3/8" bore mounted open needle-roller bearing

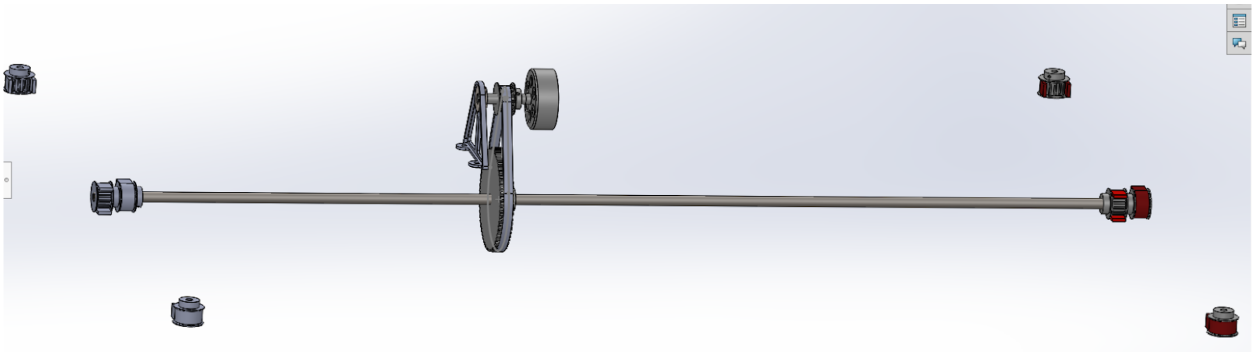

Figure 26: Drivetrain Layout

One of the most important components of the drivetrain that required analysis is the main drive shaft. This part was the center around three different analyses: torsional analysis, critical speed modal analysis, and fatigue & endurance analysis. The torsional analysis was conducted with the torsion created by the main shaft pulley while full power engaged suddenly, and was used to determine the drive shaft diameter and material. The critical speed analysis is a form of analysis that is effected by the material properties of the shaft, second moment of inertial, as well as the length of the shaft. In order to increase the critical speed of the shaft - the speed at which it will undergo a critical mode and fail - a smaller distance is required. To decrease the distance, support bearings are added along the length of the drive shaft, and their locations can be seen in Fig. 27 below, where the two center bearings are the needle-roller bearings and the outer four are the flanged bearings attached to the inner part of the propeller arms.

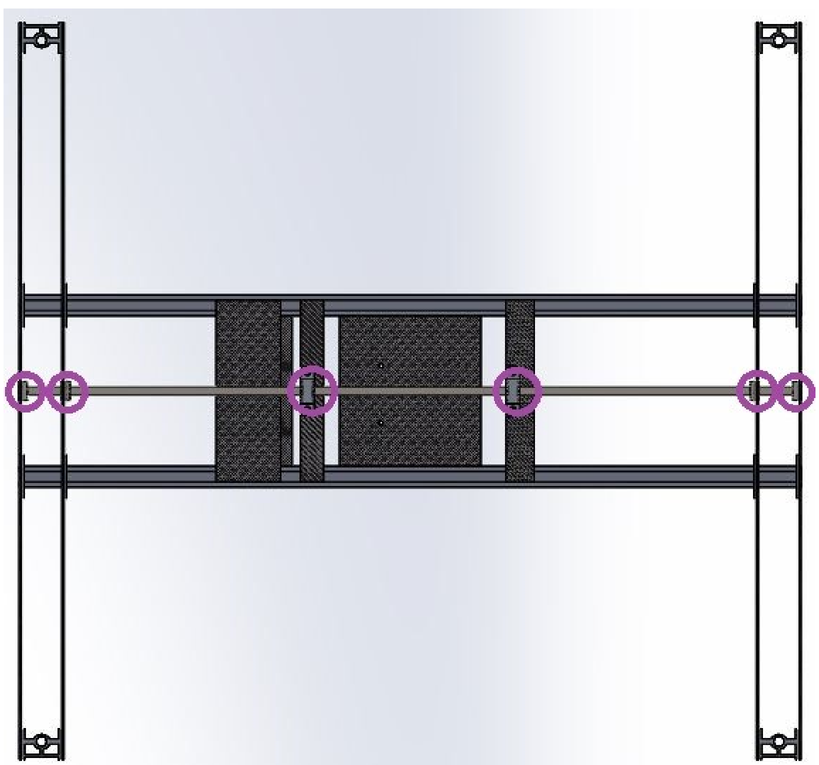

Figure 27: Locations of Bearing Supports

Another large analysis of the drive shaft is an endurance model using modified Goodman's equations, which show the endurance limit of a material over a number of cycles. For this analysis in particular, since the drive shaft is composed of steel, the endurance limit flattens after a number of cycles that varies on the order of $10^6 - 10^8$, which is around the range to of cycles to fulfill 1000 hours of flight for the UAS. This process accounts for a variety of factors of the shaft, including how it was processed, temperature, size, load type, and more. Goodman's equations use the endurance limit derived through these parameters, along with the alternating and midrange stress, to determine a safety factor for the drive shaft after, for the case of steel, N-cycles. Several locations for forces and variances of supports where used and for all cases the safety factor for the drive shaft was above a satisfactory level.

The last important aspect considered during the design process is the use of a quarter turn drive system, which can be seen in Fig. 28 below. This design allows for belts to be twisted 90° in order to transfer power between the main drive shaft and the rotor shaft as they are in different planes from one another. This design was not only chosen because of its use in other systems similar to EMU, but was also chosen because of the documentation on how to design quarter turn drive system available allowed for easy implementation, instructions for the belt choices for lengths, and instructions for the installation process.

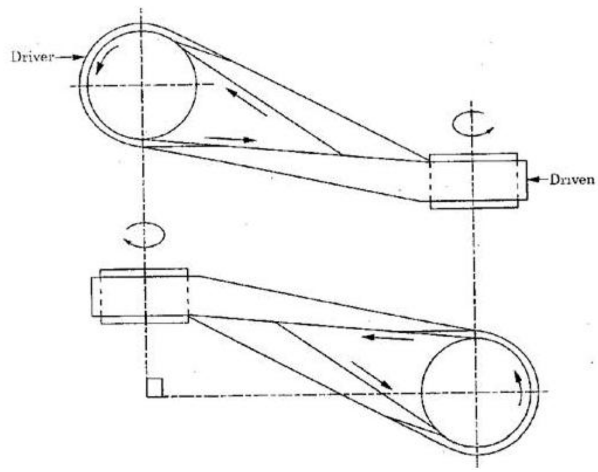

Figure 28: Quarter Turn Drive System

4.6. Electronics

Alejandro Castillo

The electronics subsystem of the EMU encompasses all the electronic components, peripherals, sensors and harnessing on the quad-copter chassis. It's primary purpose is to provide consistent and sufficient power to all subsystems and ensure proper connections between components. It is essential in the proper operation of the EMU.

4.6.1. Conceptual Design

The conceptual design of the electronics subsystem began after an appropriate flight controller board and a gimbal/camera payload were selected. Flight controller board selection is discussed in the next section. Gimbal selection was determined through a thorough trade study of different custom made gimbal configurations and commercial off the shelf options. The driving requirement behind the camera selection was its ability to point at a specific locations and live stream clear video back to the ground station. The driving requirements drove the trade study to be based around four different factor. These factors are: pointing control, video stability, system complexity, and weight of the system.

The gimbal and cameras pointing control was considered in the trade study due to the need to accurately point the camera at the user defined location. On the low end of point control, the gimbal would be non-existent and only allow pointing by changing the attitude of the UAS, while on the high end the gimbal would allow for pointing control in all three axis. The ability to stabilize the video is essential in ensuring that clear video is streamed back to the ground station. The video stability was ranged from having no system stability, which would depend on the UAS to be completely stable, to having stability about all three principles axis as well as vibration stability. The systems complexity was weighted because it directly effects the systems control and integration to the UAS. Using a system that can not be integrated serves no purpose to the project, while using a completely off the shelf solution allows the team to easily integrate and control. Due to weight constrictions on the entire UAS and more specifically the payload, the weight of the system was consider, ranging from being under three pounds to under one pound.

With the trade study confirming a commercial off the shelf gimbal and camera selection, the GoPro Hero3+ Black and the Tarot T3D gimbal were selected.

Criteria	Weight (%)	Options				
		Rigid Mount	1-Axis	2-Axis	3-Axis	Off-The-Shelf
Pointing Control	40	2	3	4	5	5
Video Stability	35	1	2	3	4	5
System Complexity	15	5	4	3	3	4
Weight	10	5	5	4	3	4
Total	**100**	**2.4**	**3**	**3.5**	**4.5**	**4.75**

Table 14: Trade Matrix for Gimbal and Camera Configuration

Further, the appropriate peripheral components for the flight controller had to be selected. Among these, the most important included an extremely accurate GPS module for navigation, transmitters and receivers with sufficient range to meet flight distance requirements, servos with appropriate torque rating for changing the rotating blades' pitch, and others. A power budget, Figure 29, was developed in order to keep track of the power usage of all of these components. It also served as a baseline for selecting an appropriate battery for the aircraft. Power consumption values in the power budget were retrieved from component data sheets for ”wort case” scenarios. This meant that it was assumed that each component was operating at max load. The purpose behind this was to create a safety net in terms of power capacity. Reserve capacity of 20% of the planned two hour flight time was also added into the power budget. This allowed the aircraft to fly for a total of 144 minutes.

Part Name	Quantity	Max Supply Current (mA)	Supply Voltage (V)	Power	Max Power Subtotal (W)	Max Total Current Draw (A)	Min. miliAmp Hour Rating Required
PixHawk 2.1	1	300	5	1.5	9.75	1.95	**4680**
Servos (Rotors)	4	1400	5	7			
Throttle Control Servo	1	250	5	1.25			

Ignition Power Bus

Part Name	Quantity	Max Supply Current (mA)	Supply Voltage (V)	Power	Max Power Subtotal (W)	Max Total Current Draw (A)	Min. miliAmp Hour Rating Required
-	-	-	-	-	-	-	-

Payload Power Bus

Part Name	Quantity	Max Supply Current (mA)	Supply Voltage (V)	Power	Max Power Subtotal (W)	Max Total Current Draw (A)	Min. miliAmp Hour Rating Required
Tarot T-2D Gimbal	1	500	12	6	9	0.75	**1800**
Gimbal Transmitter	1	250	12	3			

Flight Time (Including Reserve)
144 Min

Figure 29: Power Budget

4.6.2. Detailed Design

A detailed overview of the final design of the electronics subsystem is shown in the diagram below, Figure 30. This diagram shows all of the main components of the subsystem as well as all of the relevant connections. The main battery powers both the flight controller and all the servos but not directly from the same connection. There is an intermediary power module the splits this connection to each. There are five total servos in the subsystem. Four servos are dedicated to controlling the pitch of the propellers and the fifth serves as the throttle of the motor. The peripheral connections to the flight controller include a transmitter/receiver, a buzzer and GPS module. The diagram also includes a view of the power redundancy circuit on the middle-bottom. This simple circuit is composed of a 1000μF capacitor and a 5.8V zener diode connected in parallel. It ensures that in the event of a failure of the main power port the flight controller will be able to power itself from the servo rail without experiencing disruption. This is important because if this buffer was not installed and there was a quick power disruption to the Pixhawk, the board could reset itself mid-flight and subsequently cause a crash.

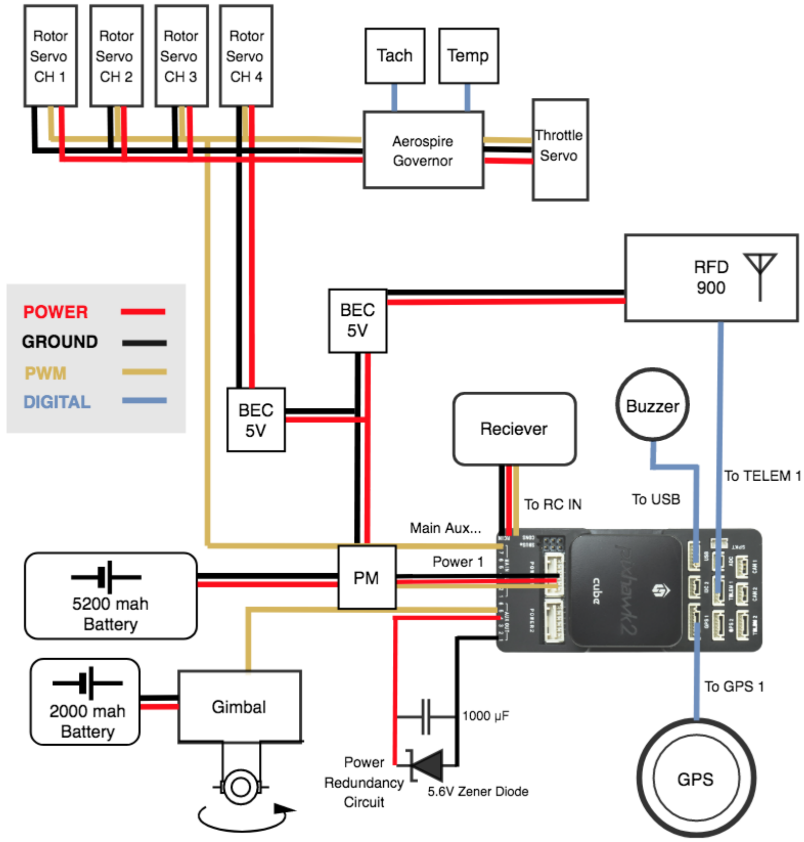

Figure 30: Electronics Diagram

Main Components

- **GoPro Hero 3+ Black**: The GoPro Hero 3+ Black is a versatile action sports camera that can shoot 1080p video at 60 frames per second. This far surpassed the camera requirements for the project. It is also widely used which meant there was tons of technical support available online. GoPros are also well known for their reliability and user friendliness. For these reasons the GoPro Hero 3+ Black, Figure 31, was chosen for the project.

Figure 31: GoPro Hero 3+ Black

- **Tarot T-2D Gimbal**: This off the shelf 2-axis gimbal, Figure 32, was the best option for the project as it had proven functionality with the Pixhawk and had a dedicated transmitter for live video. It was also came with a built in GoPro Hero 3 carrier, which fit the Hero 3+ perfectly as they are the same dimensions. The only issue with the gimbal was that it required the use of a separate battery and therefore added some more weight to the quad-copter.

Figure 32: Tarot T-2D Gimbal

- **Main Battery**: After finalizing the power budget, the best option for a battery was the Zeee 5200 mAh, 7.4V, 50C LiPo battery, Figure 33. This battery had more than enough capacity and discharge rate to meet the needs of the quad-copter. In fact, it even surpassed the required capacity and added another 18 minutes to the reserve battery.

Capacity	5200mAh	Voltage	7.4V
Continuous Rate	50C	Configuration	2S1P

Figure 33: Main Battery

- **Here 2 GPS Module**: The Here 2 GNSS GPS module, Figure 34, was the perfect choice for the project. This GPS module was designed primarily for use with the Pixhawk 2.1 and therefore was very straight forward when integrating. It had a built in barometer, 3 axis gyro, 3 axis accelerometer and 3 axis compass. It also had a position accuracy of 2 meters.

Figure 34: Here 2 GPS Module

4.7. Flight Controller

Mitchell Spencer

4.7.1. Conceptual Design

During the design phase, an in depth trade study was conducted to identify the best option for the flight controller firmware. Four options were considered: ArduPilot, PX4, BetaFlight and a custom controller designed by the team. These firmwares are used to load control laws onto various flight controllers and can often be applied to a multitude of UASs including quadcopters. One important metric used to evaluate each firmware is the availability of existing resources and online forums for various types of projects. The chosen firmware needed to be able to account for the EMU aircraft's unique design and specifications.

Table 15: Trade Matrix for Flight Control Firmware

Criteria	**Weight (%)**	**Options**			
		ArduPilot	**PX-4**	**Betaflight**	**Custom**
Integration Complexity	30	2	1	1	1
Customizability	25	5	5	4	5
Resource Availability	20	5	4	5	2
Intended Function	15	4	5	1	5
Hardware Support	10	5	2	5	5
Total	**100**	**3.95**	**3.3**	**2.95**	**3.2**

From the results of the trade study on flight control firmware, it was objectively asserted that the ArduPilot firmware was the most appropriate for the project, scoring a 3.95/5. While all of the selected options proved to be reasonably complex in terms of modifying the control law to fit the needs of this project, it was ArduPilot that offered the most resources/documentation to aid with the level customization that is needed. Due to its GPL (General Public License) open source license, ArduPilot has amassed a large community of developers who have detailed very thorough approaches to a wide range of design problems, which has proven to be incredibly useful when constructing a control regime for the UAS. With a relatively straightforward operation scheme for general autonomous flight and with support for just about any flight controller with any extraneous peripherals, ArduPilot was the best option for the purposes of this project.

4.7.2. Detailed Design

Figure 35 is a high-level block diagram which indicates what is happening in the main loop of the code, which is running at a rate of about 400 Hz. The PixHawk takes in information from internal sensors like the IMUs and the barometer as well as peripheral sensors like the GPS, and uses all of this within an extended Kalman filter (referred to as the EKF) to determine the current state. With an accepted desired state received from the ground, the code then determines the appropriate control response by implementing the proportional, integral, and derivative (PID) gains on the error between the desired and current states. Finally, the motor requests defining the actual state are converted into individual servo PWM outputs given additional calibration info provided before flight. This is passed from the PixHawk to the servos via one of its fourteen pins. The Hardware Abstraction Layer (HAL) is the interface between the code and the physical PixHawk board. Whenever any PWM values are defined within the code, the HAL converts those values into actual signals to be sent out of the pins.

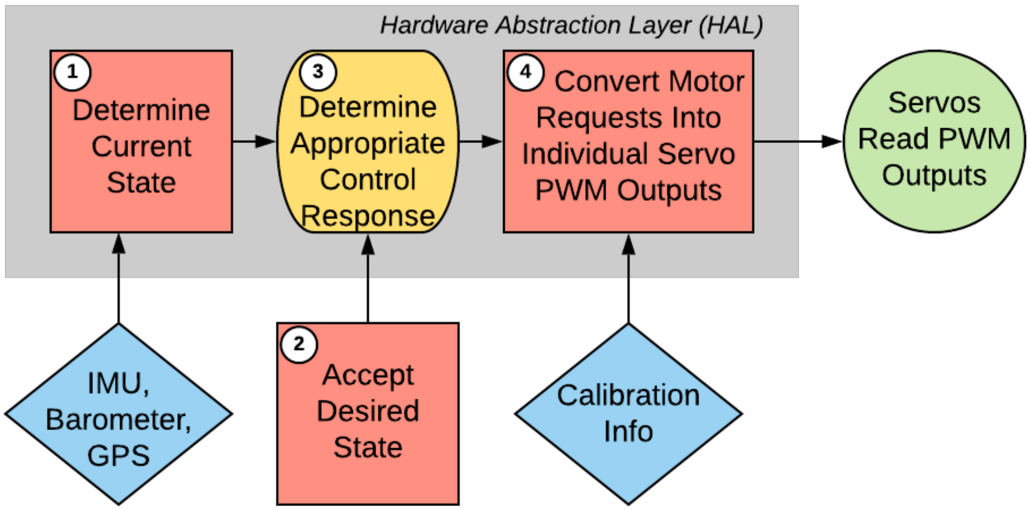

Figure 35: High Level Control Code Diagram

All four of the stages shown in Fig. 35 can be broken into individual systems with corresponding block diagrams.

- **Stage One - Determine Current State:** In stage one, the state is determined with an extended Kalman filter (EKF), which is represented in the block diagram in Fig. 36 and found inside the files `AP_NavEKF3.cpp` and `AP_AHRS.cpp`. Within the body frame of the copter, the code creates an initial state prediction and compares that with measurements in the earth frame, accounting for error in measuring devices and state calculations. For instance, the on-board barometer might have a better prediction of the copter's altitude at a given time than the IMU's have over time (different sensor functions exist for different types of hardware, including `AP_InertialSensor.cpp`, `AP_Baro.cpp`, and `AP_GPS`). This difference between body frame measurements and earth frame measurements is known as the "innovation", and is summed with the physical state measurement error and the state covariance matrix which each ultimately account for the inaccuracies of state determination over time. The result in all of this is the state correction which is then used to curb the initial state prediction, thus yielding the determined state.

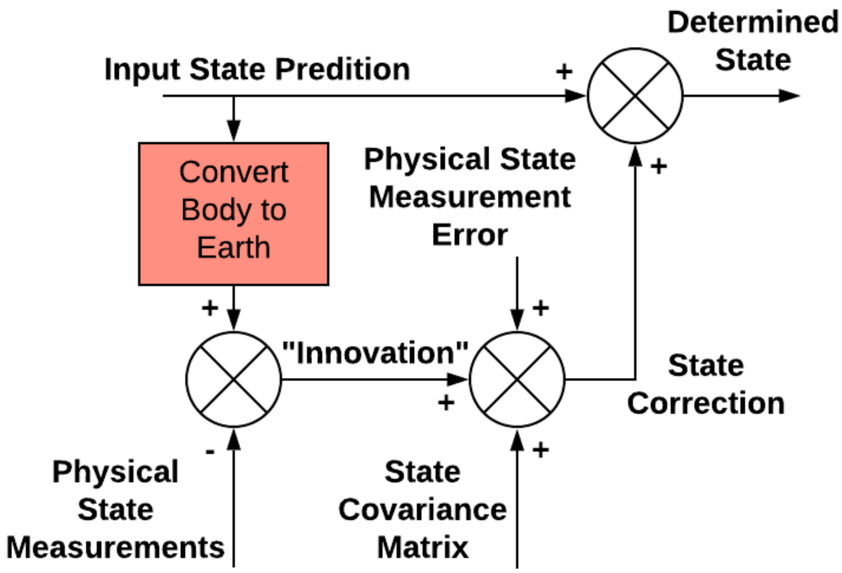

Figure 36: Extended Kalman Filter Diagram

Conveniently, due to the PixHawk's triple-redundant IMU system, there are three EKFs which can run in parallel with each other to provide the most optimal and accurate determination of state.

- **Stage Two - Accept Desired State from GCS:** In stage two of Fig. 35, where the PixHawk accepts the desired state from the ground station, it is important to consider how the ground station sends autonomous commands in the first place regarding different flight modes.

  There are lots of different flight modes which can be activated for a vehicle running on ArduPilot, though if an operator wishes to run an autonomous mission, the procedure displayed in Fig. 37 is to be followed. Once the copter is armed, flight mode AUTO must be (manually) engaged to begin the autonomous mission, which is represented as a waypoint file. This waypoint file can specify all of the different locations the copter is to travel to and which changes of modes should occur at which relative times. Figure 37 displays a mission in which the copter takes off (flight mode TAKEOFF), navigates to a single waypoint, waits for a prescribed amount of time (flight mode LOITER), and then returns to the launch location (flight mode RTL). As these are the most frequently used flight modes, examinations were made for LOITER, RTL, and AUTO.

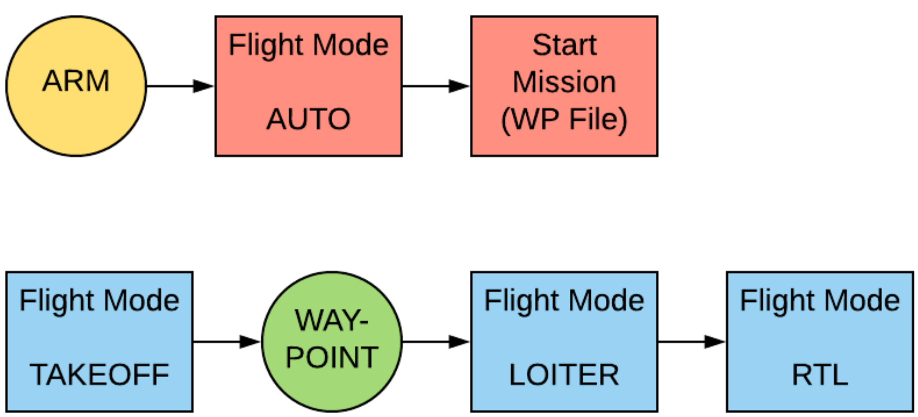

Figure 37: Flight Mode Progression for an Autonomous Mission

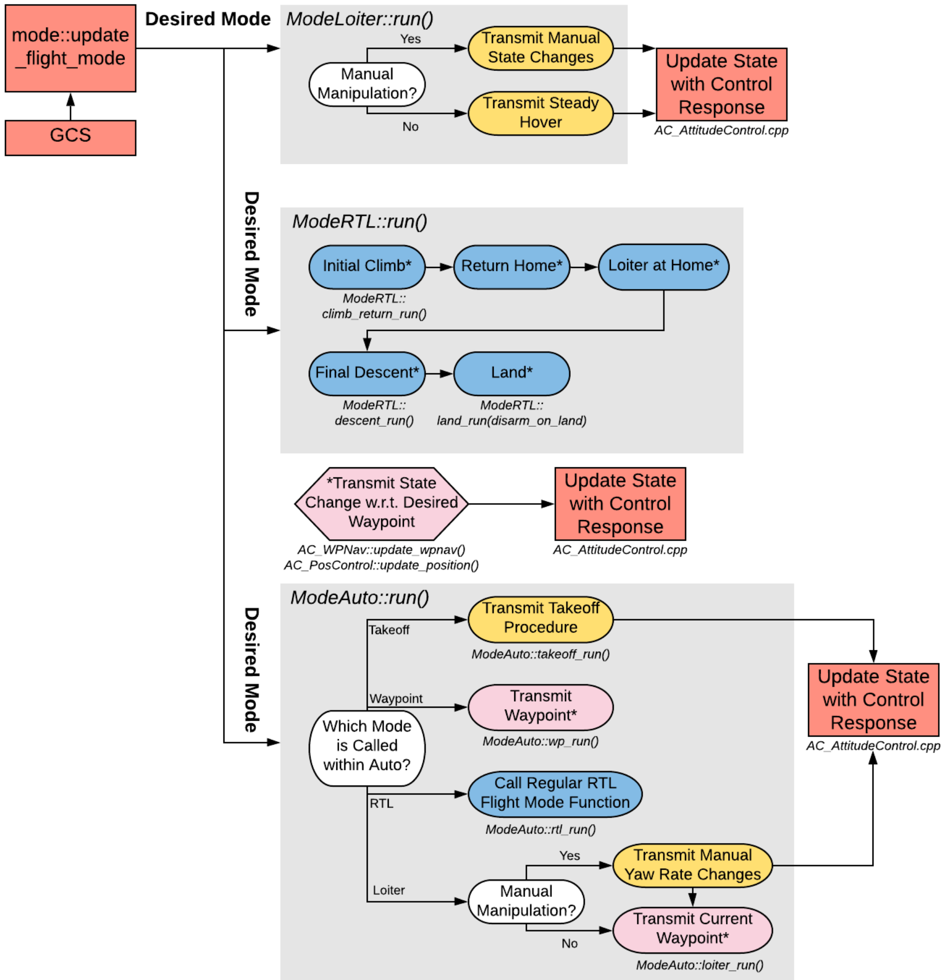

Figure 38: Flight Mode Functionality Diagram

The block diagram in Fig. 38 above considers flight modes LOITER, RTL, and AUTO (where the function `mode::update_flight_mode` calls the corresponding functions `ModeLoiter::run()`, `ModeRTL::run()`, and `ModeAuto::run()`, respectively). LOITER mode is used to keep the copter in the same position over time. If it is manually manipulated by a pilot on the ground, the mode will update the state with the control response following the pilot's commands. Otherwise, the copter will slow down to a steady hover and maintain that state until otherwise commanded or the mode is changed.

RTL, or Return To Launch mode, is used to command the copter back to its launch location, which is defined as the location where the copter was initially armed. In the Return To Launch process, there are five integral steps. First, the copter climbs (or descents) to a specified altitude manually given in the GCS. This is so that the copter is able to fly over any trees or other obstacles which might otherwise be in the way of a direct path back to the launch location. Next, the copter maintains this altitude as it returns to the location right above the launch location. In the third step, the copter loiters for a specified amount of time. In step four, the copter descents (defined in `ModeRTL::descent_run()`). Lastly, once the copter is close enough to the ground, it lands and disarms itself so a new mission cannot be immediately started (according to `ModeRTL::land_run(disarm_on_land)`). As the governing main loop of the code continues to cycle, ArduPilot will determine which of these five steps the copter currently exists in and whether or not to progress to the next step.

The third flight mode examined is AUTO which is a comprehensive flight mode which is used to run defined missions in waypoint files. If the waypoint file specifies a mode change, the copter will still technically exist in AUTO mode but change modes within that flight mode. The bottom section of Fig. 38 shows how different flight modes called within AUTO allows for the copter to autonomously perform tasks, like takeoff, navigating to waypoints, running Return To Launch, or loitering.

- **Stage Three - Determine Appropriate Control Response:** In stage three of Fig. 35, the ArduPilot firmware determines the appropriate control responses given the EKF determined state (from stage one) and the desired state transmitted as a flight mode from the GCS (from stage two). With this information, and the gain values which were uploaded to the PixHawk before flight (which were manually entered into the GCS), the code can appropriately output appropriate state changes (via `AC_AttitudeControl.cpp` and `AC_PosControl.cpp`).

  Figure 39 outlines how this process works. In a larger view, the acceleration limiter and the input mitigation stage are used to curb any extraneous desired state inputs that the copter cannot appropriately react to, and instead allows for a gradual ramping of desired state inputs. The acceleration limiter sets bounds for the desired state accelerations which is then further fed into the feed forward function. The error between the desired state and the position and angle of the measured state are then fed into a square root controller which, along with the output of the feed forward process is used to define a more appropriate set of desired rates to be executed by the copter. By taking the error between these desired rates and the measured state rates of the copter, PID control can be performed given the gains initially given to the copter as stated earlier. The output is then sent to stage four where the motor requests are to be converted into individual servo PWM outputs.

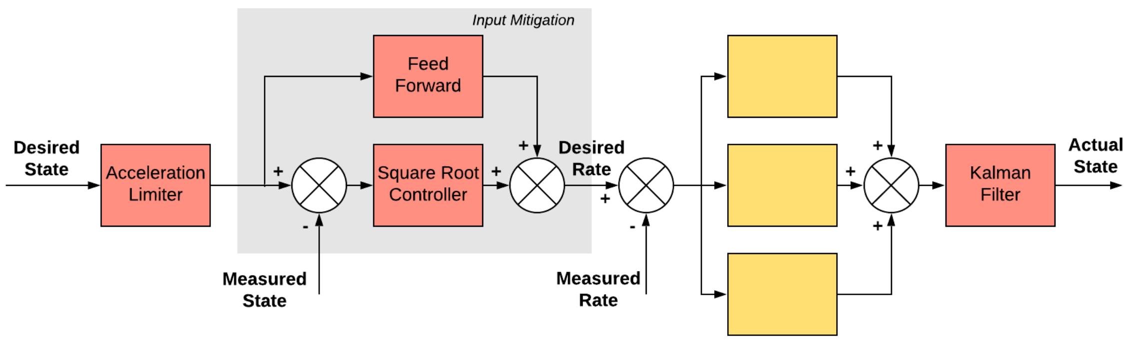

Figure 39: Control Response Block Diagram

- **Stage Four - Convert Motor Requests into Individual Servo PWM Outputs:** This fourth stage of Fig. 35 requires a description of the physical characteristics of the quadcopter to convert the motor requests into individual servo PWM outputs. If the quadcopter is to perform a combination of simultaneous roll, pitch, yaw, and thrust requests, then each rotor will be acting differently. Individually, each rotor has a key role in all of these maneuvers. For instance, if the copter is commanded to roll to the right, the two rotors on the left half of the copter will be required to increase their thrust output. All complex maneuvers sent to the copter can likewise be reduced to roll, pitch, yaw, and thrust requests for each rotor. Therefore, the total thrust output for each individual rotor can be represented by Eq. (9), where all of the thrust values are scaled by appropriate factors listed in Eqs. (10), (11), (12), and (13), listed below. These factors are individual to each rotor according to the geometry of the chassis—specifically, the angle of which each rotor sits relative to the body frame y-axis ("East" axis) (see Fig. 40 for a definition of this angle).

$$T_{rpyt} = (T_r \cdot f_r) + (T_p \cdot f_p) + (T_y \cdot f_y) + (T_t \cdot f_t) \tag{9}$$

$$f_r = -0.5\frac{\sin(\theta)}{\cos(45^\circ)} \tag{10}$$

$$f_p = 0.5\frac{\cos(\theta)}{\cos(45^\circ)} \tag{11}$$

$$f_y = \begin{cases} -0.5 & \text{clockwise} \\ 0.5 & \text{counter-clockwise} \end{cases} \tag{12}$$

$$f_t = 1 \tag{13}$$

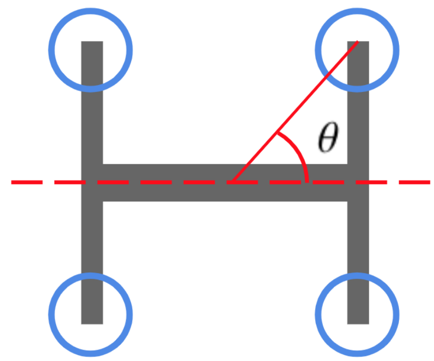

Figure 40: Definition of θ For Rotor Thrust Scaling Factors

With the thrust values defined for each rotor at every step in time, the ArduPilot firmware then converts these thrust values to appropriate PWM outputs to be sent to the individual servos of each rotor to pitch the rotor blades. This relies on previous information manually provided to the copter upon pre-flight calibration. This means that the maximum and minimum desired blade pitch angles must be calibrated to a corresponding PWM value which will take some trial and error on the part of the EMU team. Upon determining which PWM output values yield the desired maximum and minimum blade pitch angles, a PWM value corresponding to a hover-state blade pitch angle must also be determined (this is the angle at which the copter could theoretically fly in a hover state). These maximum, minimum, and zero-climb PWM values are assigned to the parameters 'H_COL_MAX', 'H_COL_MIN', and 'H_COL_MID' (respectively) in the GCS before flight.

Figure 41 shows exactly what is happening in stage four at each step. Programs `AP_MotorsMatrix.cpp` and `AP_MotorsHeli_Quad.cpp` scale the commanded maneuvers to individual rotor thrust commands. Next, these individual thrust values are converted to PWM values through the means of the provided calibration parameter settings. Lastly, this information is sent through the Hardware Abstraction Layer (defined in `SRV_Channels.cpp` and `AP_HAL:RCOutput.cpp`) to the individual output pins of the PixHawk board.

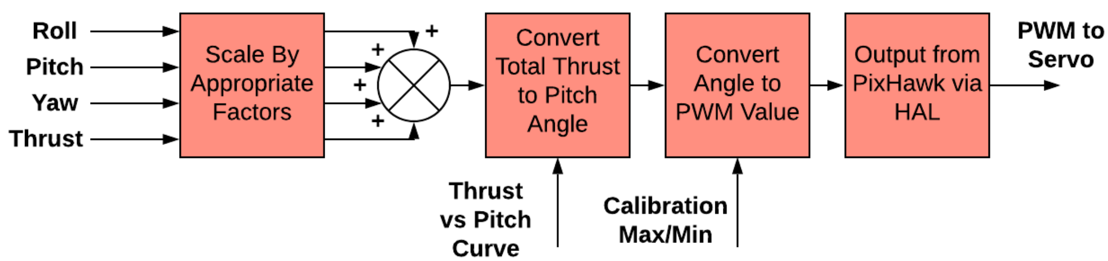

Figure 41: Motor Requests Conversion Block Diagram

4.8. Ground Station

Matthew Lehmann

4.8.1. Conceptual Design

The EMU team considered three different options for developing the ground station software that would manually and autonomously control the UAS in flight. The main functional requirements the ground control station needs to meet are addressed and considered for the chosen options. A trade-study between a custom-built ground station program (developed by the EMU team), APM planner 2.0, and the commercially available Universal Ground Control Station (UgCS) platform is presented below.

Each of the 3 options being considered in this trade study were given a score for each of the 6 categories illustrated in the trade matrix below. It should be noted that the term **autopilot** in this case refers to the mission planning aspect

Table 16: Major Requirements for Ground Station

Requirement Type	Requirement Number	Rationale
FR	2	The UAS shall operate autonomously
FR	3	The GS handle all communications with UAS
DR	3.2.4	GS shall send commands to UAS
DR	3.5	GS Shall have manual control capability

of controlling the UAS. That is to say, sending the UAS on a full flight path from launch, to its destination, and telling it to return home and land. The on-board flight controller handles the stabilization of the aircraft within its flight envelope. An assessment on how well the chosen option meets requirements is included.

Table 17: Trade Matrix for Ground Station Software

Criteria	Weight (%)	Options		
		Custom Software	APM Planner 2.0	UgCS
Manual Control Delivery	25	3	5	5
Autopilot	25	2	4	4
Cross-Platform Capability	15	5	5	5
GUI Development Resources	15	3	5	5
Development Time	10	3	4	4
Cost	10	5	5	2
Total	**100**	**3.25**	**4.65**	**4.35**

The completed score assignment for each of the options considered for the ground station software is shown in the table above. The best choice for the EMU team according to the weighting of each score in each category of the table is APM Planner 2.0. The in-depth reasoning for the each of the given scores is presented below.

Custom Software

- **Manual Control Delivery**: 3 - Handling commands and telemetry downlink is a nontrivial task when it comes to custom designing communications software. Error handling would consume a large portion of time and while possible, it is not the most practical option.
- **Autopilot**: 2 - Developing an autopilot from scratch to handle full mission planning for multiple way-points is a very difficult task to achieve. Especially when the considering the fact that the on-board flight controller is meant to work with available, open source ground station software to begin with.
- **Cross-Platform Capability** 5: - Developing software from scratch does make it simple to transfer from one machine to another so long as an open source language like python or C++ is used.
- **GUI Development Resources**: 3 - The amount of resources available depends on the chosen programming language. Choosing the appropriate language will also depend on the programming skill set of EMU team members.
- **Development Time**: 3 - The development time is immediately dependent on the skill set of the team, and based on everyone's experiences in programming, the language chosen may not be optimal for actually developing a ground control station that can actually meet all of the project requirements.
- **Cost**: 5 - Using an open source language will result in no cost financially to the team.

Universal Ground Control Station (UgCS)

- **Manual Control Delivery**: 5 - UgCS actually runs some of APM and Mission planner's software under the hood to handle command transmissions to a UAS. This does mean that manually controlling the aircraft will be similar to using APM planner 2.0.

- **Autopilot**: 4 - Once again the user inputs a list of way-points for the UAS to move to in order to complete a full mission. The user therefore still has to develop an appropriate flight path, however, delivering the coordinates of each way-point at the appropriate time is handled in the background.
- **Cross-Platform Capability**: 5 - UgCS is available on Mac, Windows, and Linux operating systems making it completely cross-platform compatible. Moreover, since there is no required programming, the ground station software will be identical on different machines.
- **GUI Development Resources**: 5 - The GUI is completely defined, no GUI development is required when using this commercially available software.
- **Development Time**: 4 - There is still some development time when using UgCS since the physical design of the quadcopter must be defined in the autopilot firmware to handle the controls and mission planning.
- **Cost**: 2 - UgCS is not a free ground station software and introduces significant cost to a subsystem that cannot afford it.

APM Planner 2.0

- **Manual Control Delivery**: 5 - APM Planner 2.0 utilizes MAVLink commands that are immediately recognized by the on-board flight controller once they are received. Installing the appropriate ArduPilot firmware to the flight controller ensures that the process of sending these signals is handled by ground station software itself.
- **Autopilot**: 4 - Sending new GPS destinations to the UAS is handled by the ground station once the user inputs each of the desired locations into the GUI pre-flight. Therefore, the signals for when to change course are delivered at the appropriate times by the ground station, but the user must still define these way-points.
- **Cross-Platform Capability**: 5 - APM Planner 2.0 is open source and available on Mac, Windows, and Linux operating systems making it completely cross-platform compatible. Moreover, since there is no required programming, the ground station software will be identical on different machines.
- **GUI Development Resources**: 5 - No GUI development is required when using this commercial software.
- **Development Time**: 4 - There is still some development time when using APM Planner since the physical design of the quadcopter must be defined in the autopilot firmware to handle the controls and mission planning.
- **Cost**: 5 - APM Planner 2.0 is free on each operating system.
- **Requirements**: - APM Planner 2.0 meets each of the requirements in table 16. It supports autonomous mission planning (sending a script of commands to the UAS for the UAS to handle autonomously) and for manual control input from a pilot at the ground base from an RC controller.

4.8.2. Detailed Design

As discussed in the conceptual design section of this report, APM Planner 2.0 will be the ground station software of choice for the EMU project. Some of its capabilities were outlined earlier but it certainly did not cover some of the lower level advantages APM Planner offers. These will be presented below:

- **SITL Capabilities**: One of the most attractive aspects of APM Planner 2.0 is its software-in-the-loop simulation packages. APM Planner can run a full 2-D and 3-D simulation of an aircraft with the appropriate controller firmware and make the GCS behave as if it was actually communicating with a physical UAS in flight. This will provide an excellent means of testing the behavior of the quadcopter before assembling any of the hardware to ensure that the UAS can remain within the provided flight envelope at all times and meet the overall requirements of the project. Below is an image of a Chinook helicopter being simulated in a version of APM Planner in 2-D and 3-D with a plot of its state-space variables and how they are behaving during its mission.

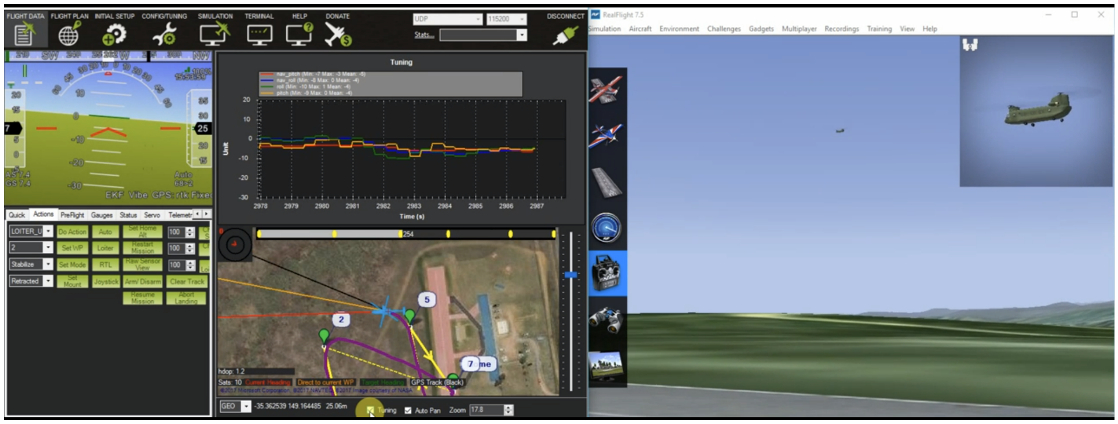

Figure 42: SITL simulation in APM Planner with Chinook Helicopter

This will provide the team with an excellent basis for monitoring the performance of the control gains that are input into the controller software pre-flight. Moreover, there is already documentation for modeling a collective pitch, H-frame quadcopter in APM Planner and FlightGear (the 3-D simulation software) which we can use to further validate our own SITL testing.

- **ArduPilot Compatibility**: Another benefit of using APM Planner is the fact that it is one of ArduPilot's recommended ground control stations for interacting with an on-board UAS controller that has ArduPilot firmware installed. This is ultimately the functionality that makes sending commands between the ground station and flight controller on the UAS a much easier task than it would have been programming a custom ground station software platform. The necessary drivers for working with ArduPilot in flight and in simulation are included when installing the APM Planner software.
- **Gain Adjustment Page**: APM Planner actually has a specific tab that allows the ground station operator to adjust the control law gains that the on-board autopilot uses to keep the UAS stable. Everything from yaw, pitch, and roll PID gains (including yaw rate, pitch rate, and roll rate) to handling the stabilization of an on-board camera if there is one.
- **GPS Location and Telemetry Display**: Throughout the mission and SITL simulation, APM Planner provides a 2-D view of the UAS's GPS location on a map at all times, and displays the live state-space values for the UAS as it moves throughout its mission. All of the information presented in these two windows will be crucial to monitoring the performance and behavior of the aircraft in flight and in the 2-D and 3-D SITL simulations to ensure that the project requirements are being met.
- **Way-point and Mission Planning**: APM Planner allows the user to define multiple GPS locations for the UAS to travel to during the course of a single mission. The sending of these commands is then timed appropriately to limit the required amount of user input.
- **MAVProxy Terminal**: MAVProxy is essentially a programming language within the massive ArduPilot base that is used for commanding the flight controller on-board a UAS to take the aircraft to a specific location, to take off, to land, etc. Therefore sending the UAS manual and individual commands can be done through the use of this MAVProxy language that APM Planner has built-in packages for (including for use within the SITL simulation).

There is not a massive amount of hardware required for the ground station. The main necessities will include radio modems to transmit telemetry and commands back and forth between the ground station and the UAS flight controller, as well as AV transmitters and receivers for handling the live video feed coming from the UAS. Each of these components is discussed below.

- **RFD 900+ Ultra Long Range Transmitter**: These radio modems have a transmission range of 40 km and are specifically made to work well with the pixhawk flight controller the team intends to use on-board the UAS.

Figure 43: RFD900+ Radio Modem and Omni-directional Antenna Package

- **TS5823 AV Transmitter and RC832 AV Receiver**: These two devices work together to transmit and receive video up to a range of 1.5 km which will be well beyond the required maximum 515 m distance the team needs the quadcopter to be able to fly to. They each come with an omnidirectional antenna as well.

Figure 44: Audio/Video Transmission and Receiver Kit

The RFDesign 900+ ultra long range transmitters will handle the uplink and downlink of telemetry data and mission commands while the TS5823 and RC832 transmitter and receiver respectively, will handle the AV video feed that will be live streamed from the on-board GoPro camera to the ground station. The transmission range for each set of transmitters is well beyond the required range of 500 meters that was set by the customer.

5. Manufacturing

5.1. Manufacturing

Shawna McGuire, Libby Hasse

The required manufacturing for the UAS was mainly centered around the chassis, rotorhead assembly, landing gear, and drive train. Other parts required for the UAS were purchased such as our engine, flight controller, rotorhead parts, servos, the camera gimbal system, and smaller items such as pulleys and wiring.

When looking at the manufacturing schedule, the chassis required the most work. We purchased carbon fiber plates and hex tubes then needed to manufacture them to the correct sizes with the appropriate slots for items such as the rotorhead assembly, drive train, and other mounting subsystems such as the engine mount. To do this, we had five mounting plates, four propeller support beams, eight joint supports, and two hexagonal tubes to support the center of the chassis. To conduct this manufacturing, all straight lines such as cutting the mounting plates and joint support outlines were done with the vertical band saw. Next, all holes or cut outs were done with the 2-axis CNC. The hex tubes were cut with a simple hack saw. All cuts were then sanded with sandpaper as well as the grinders. The most difficult chassis components were the four propeller arms. These were barely small enough to fit in the 4-axis CNC and required precise cuts for both the drive shaft cut outs as well as the rotorhead assembly to ensure optimal alignment. This was all done in the 4-axis CNC with slow feed rates, a four-flute end mill, vacuums constantly removing any debris, and compressed air to cool the bit to prevent damage.

The next difficult part of the manufacturing process was the rotorhead assembly as we needed to modify the swashplate to allow for only collective pitch control and no cyclic movement. This required us to remove the uniball bearing from the stock swashplate and replace it with a linear recirculating bearing. This modification took three weeks and three iterations due to the difficulty of working with small and complex aluminum components. The successful iteration began with the removal of the uniball with a punch and press. With the uniball removed the space remaining was much too large for the bearing. To solve this, an aluminum bushing was made and then press fit into the swashplate. The bearing could then slip fit into the bushing. In order for the bearing to sit in the right position within the swashplate a brass shim was made and added to the bottom of the swashplate around the bearing. The shim and swashplate could then be bound by two retaining clips which attach to the bearing.

Additional parts that needed to be manufactured were small items such as drilling holes into pulleys, boring the pulley diameters to a slightly larger one, drilling holes into the drive shaft, cutting the drive shaft to the appropriate size, and creating an output shaft as well as support the engine output. The drilling for both the pulleys and the drive shaft where done on the milling machines. The pulleys were bored with the lathe. The drive shaft was cut to side using the horizontal band saw. Finally, the engine output shaft was created first on the lathe. Then, we modified the clutch bell by boring it to a larger side on the lathe then drilling holes to connect the new shaft to the bell on the milling machine. Due to the bell being hardened steel, this was a difficult task to find an appropriate RPM and applied pressure to drill through the clutch bell. Finally, a bearing support was created on the CNC.

Most of the difficulty that came with manufacturing was an initial lack of experience in the shop with only one team member prepared as well as difficulty getting time on certain machines in the shop due to crowding. Later into the semester, we volunteered more team members to assist the Manufacturing lead which allowed for more work to be done. As well, there were some subsystems where necessary modifications were not introduced until later in the semester which backed up the manufacturing schedule when new components were thrown in. In the future, a better preparation of a manufacturing team in the fall semester as well as a deeper look into the details of each subsystem will allow for a smoother process.

5.2. Integration

Michael Flores, Dakota Labine

The integration of the UAS components into one system began at the rotor blades and chassis towards the electronics. Subsystems components were integrated together first, where possible, so that those subsystems could then be added to the chassis. This process manifested itself for the rotor assembly where all of the subsystem components were added together before the were added to the chassis. This left four assemblies to attach to the chassis rather than the larger sum of parts. The payload was integrated in to one assembly consisting of the camera, batteries, storage, gimbal, and transmitter. This created one simple assembly to attach to the chassis and the process was repeated for other subsystems where possible.

The chassis was assembled beginning with the rotor arms. Rotor bearing blocks were fitted to the carbon plates to produce the rotor arms. With the rotor arms properly spaced, the carbon hex tubes that constituted the main body of the UAS were then inserted into the rotor arms and attached with the chosen urethane adhesive. The rotor bearing blocks were removed to finish the subsystem assemblies. With the chassis shell assembled, the rest of the component carbon plates were adhered to the chassis awaiting subsystem integration. The drivetrain was the first subsystem integrated by using the drive shaft to align and adhere the driveshaft bearings to the carbon fiber. The drive shaft was then installed with pulleys onto the UAS. Figure 45 shows the progress of the UAS integration to this point where the integrated carbon chassis, carbon plates, and driveshaft can be clearly seen.

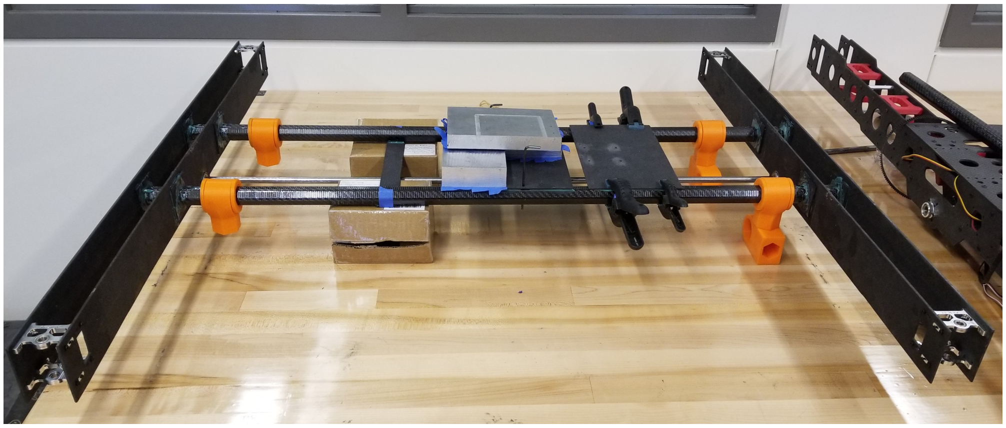

Figure 45: UAS Integration Progress Pre Landing Gear

The rest of the chassis integration was not completed but is outlined here for future integration. The next integrated components is the landing gear assemblies consisting of landing legs, spring/shock, and two 3D printed brackets. These components would be adhered to the chassis allowing for the UAS to stand on its own. Next the rotor assemblies would be bolted to the rotor arms and the quarter turn drive belts would be fitted between the driveshaft and rotor shaft. The payload will be integrated and attached to the chassis by adhering the carbon plate and components to the hex tubes. Next the flight electronics will be attached to the chassis and the electronic components will be wired to the flight computer. The final subsystem to integrate to the chassis is the power plant. This subsystem will be bolted to its component plate and wired up to the flight computer. The drive belt will also be fitted between the drive shaft and the engine output shaft. With the integration of the power plant, the UAS will be fully assembled and integrated and ready for all large scale testing.

The order of the integration outlined above is important as it allows for smaller components to be assembled parallel to each other maximizing efficiency and shortening time spent during integration. The order also is important for the verification and validation process by incrementally testing subsystems as they get more complex. This process prepares the UAS for early HITL and integration tests as quickly as possible by building up the system with regards to what metrics and processes were defined in the test outlines.

6. Verification and Validation

Nathan Castile

6.1. Test Overview

To verify that our functional requirements were met, a series of 5 testing phases were designed: electronics testing, rotor thrust testing, engine dyno testing, hardware in the loop (HITL) testing, and flight testing. These tests were designed such that major individual subsystems were validated first to ensure they met their functional requirements before integration onto the UAS. Following the completion of the subsystem tests, full scale testing began in the HITL phase by integrating all the subsystems onto the UAS chassis. HITL testing was designed to be performed incrementally, with 3 total tests that would culminate in drivetrain engagement and spinning the installed rotors. The final testing phase was flight testing, which was split into 3 incremental tests similar to in the HITL phase, with the final goal being untethered flight to verify the maximum range and ceiling requirements. Some of the testing was either completed or in progress at the time of the project termination. The remaining tests were planned, but the team did not have sufficient time to complete them.

6.2. Electronics Testing

The first goal of the electronics testing was to verify that the individual components would properly integrate with each other and with the PixHawk control unit using the wire harnessing. This included the 5200 mAh battery, power distribution board, PixHawk, receiver, transmitter, GPS, servos, and payload. The payload consisted of a dedicated 2000 mAh battery, gimbal, and video camera. Once the UAS electronics system had been wired together, use of the ground station was necessary to send it test commands and receive telemetry.

The ground station consisted of a laptop running the AP Mission Planner software equipped with a transmitter and receiver that would allow it communicate with the UAS. The communication test did not require a special facility or equipment other than what was just mentioned above. After programming the transmitters and receivers on both the UAS electronics and the ground station, short range communication success was verified within the mission planner software. Specifically, the mission planner was able to send mission commands and settings to the remote PixHawk, and telemetry, GPS data, and video was successfully downlinked. Communication between the UAS and the manual control RC transmitter was also tested and verified.

This testing verified most of functional requirement (FR) 3 (Ground Station shall communicate with the UAS). The remaining sub-requirements including autonomously launching the UAS and updating mission parameters during any phase of flight would have been verified during flight testing. This testing also verified the sub-requirements of FR 5 (UAS caries a camera payload) relating to camera control and video stream downlink. UAS to ground station communication was verified up to a range of 200ft, and max range testing at 500m was planned but unable to be completed due to time restraints.

The Pixhawk's ability to actuate the control servos was also verified by wirelessly uploading control gains from the ground station in the mission planning software. The PixHawk control module was then physically pitched/rolled to a desired angle verified with a digital pitch sensor capable of 0.1 degree accuracy. The PixHawk then sent control commands to the servos based on the internally measured orientation and the software control gains defined in ArduPilot. The output position of the control servos was verified to be at the expected values using the same digital pitch sensor.

6.3. Rotor Thrust Testing

Sufficient thrust must be provided by the rotors for the UAS to takeoff and maneuver. The developed analytical rotor thrust model indicated that the rotor selection, RPM, and pitch range would allow for a combined rotor thrust of 43 lbs. This allows the UAS to take off at its maximum weight of 30 lbs, maintain stability, and maneuver to a desired location. The physical rotor testing was designed to verify the analytical model and give confidence that the rotor blades can supply the required thrust for the mission. The rotor testing was fully completed including data analysis.

An elastically deforming beam was used to measure the thrust provided by a single rotor assembly. The beam was securely clamped at one end to a heavy, rigid structure to provide a cantilever loading scenario. The rotor attachment housing was clamped to the far end of the beam and contains the swashplate, pitch servos, electric motor, and drive shaft. The motor was controlled with an electric speed controller (ESC) which was powered by a battery pack and received commands from the operator through a quadcopter wireless receiver and transmitter. The receiver had a servo control port which was used to control the blade pitch. A set of four strain gauges in a full Wheatstone Bridge circuit measured the strain in the beam as the spinning rotor applied a lifting force at the tip of the beam. While a beam is being deformed in its elastic regime, there is a linear relation between the force applied to the tip and the strain measured in the beam. This linear relationship was characterized by loading the beam tip with various known weights and recording the strain reported by the sensors. A diagram of the test setup is shown in Fig. 46.

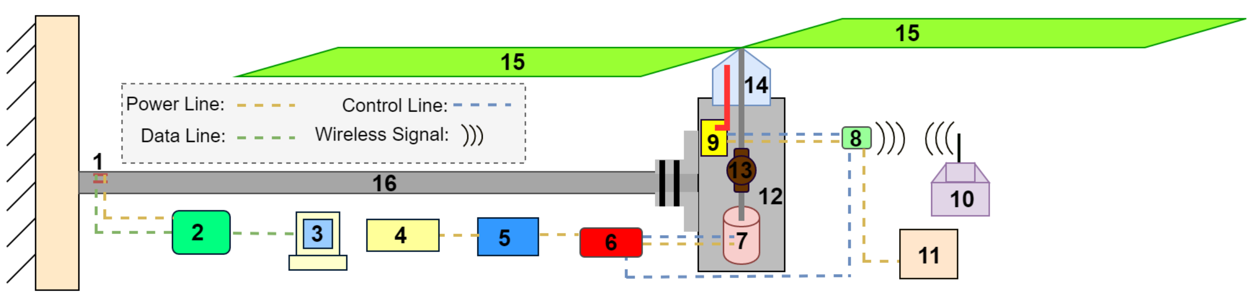

Figure 46: Rotor Thrust Test Stand Diagram

1: Strain Gauges	5: Power Monitor	9: Pitch Servo	13: Flex Couple
2: NI-9237	6: ESC	10: Transmitter	14: Swashplate
3: Computer	7: Brushless Motor	11: Power Supply	15: Rotor Blade
4: Battery	8: Receiver	12: Rotor Housing	16: Steel Beam

Table 18: Rotor Thrust Test Stand Components

The testing was performed in the hazardous engine test cell, with the test crew providing control and data acquisition from within the safe room. The primary data acquisition instruments were a digital pitch sensor, a NI-9237 (strain measurement sensor), and a photo tachometer sensor. These instruments allowed for recording the pitch of the blades, the lift provided by the sensors, and the RPM of the blades. A photo of the final test setup is shown below in Fig. 47.

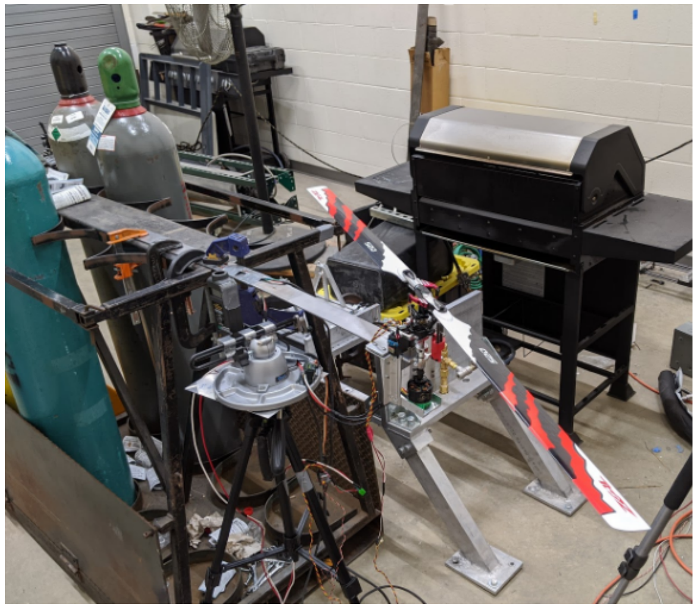

Figure 47: Image of the Rotor Test Setup

The rotor was spun at angles of attack of 5.4 and 12 degrees, and at RPM's between 500 and 1000. The RPM could not be pushed reliably past 1000 because of vibration modes that appeared in the test stand. The tested AoA's and RPM's were recorded and used as inputs into the analytical thrust model. A plot of the deviation between the model and the experimental results are shown below in Fig. 48.

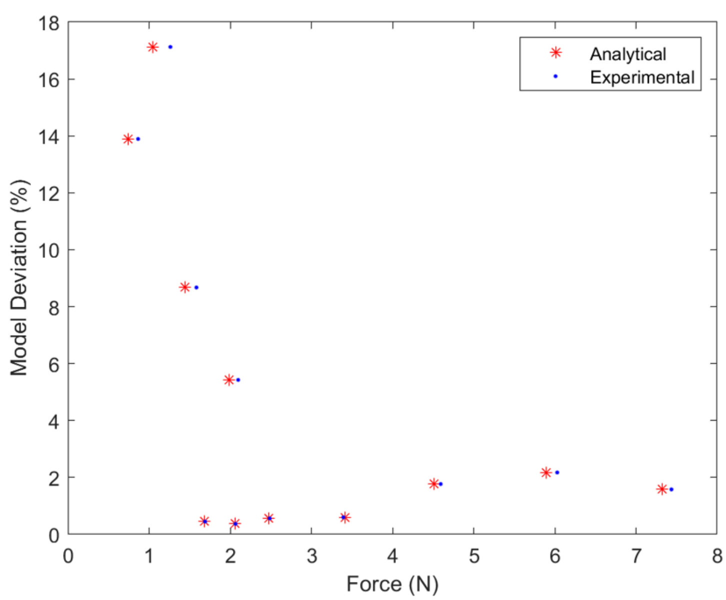

Figure 48: Model Deviation vs. Force

After removing one outlying data point, the model had a mean 4.8% deviation from the experimental data. The model also underpredicted the thrust provided by the blades, which means our blade selection should have an even larger safety factor than previously predicted. Also note that the data points with the most deviation were at low end of the tested forces, with the larger forces having a deviation of around 2% or less. This data verifies that our thrust model is accurate, and that the rotor blades will meet functional requirements 1.2.2 and 1.2.3 that state the UAS must have sufficient thrust for hover and maneuvering.

6.4. Engine Dyno Testing

Each rotor assembly requires 0.85 $ft-lb$ of torque and 0.38 hp at nominal conditions for the UAS to hover at its takeoff weight of 30 lb. Assuming the drivetrain and 1:4 drivetrain-to-motor gearing has a combined efficiency of 75%, the Zenoah G320RC motor must supply 1.133 $ft-lb$ of torque for hover. The G320RC motor has a maximum rated torque of 1.48 $ft-lb$ and a power output of 3.2 hp without modification as seen below in Fig. 49. This means that the motor only needs to supply 77% of its maximum torque to support flight. However, these performance numbers come from the manufacturer at sea level, so a drop in output torque and power is expected at Boulder's altitude. Therefore the output of the motor must be tested to verify it can supply the required performance for flight. The chosen method for determining the engine performance was using the DYNOmite eddy current dynamometer because it allows for loading the motor up to its maximum power output at its high RPM.

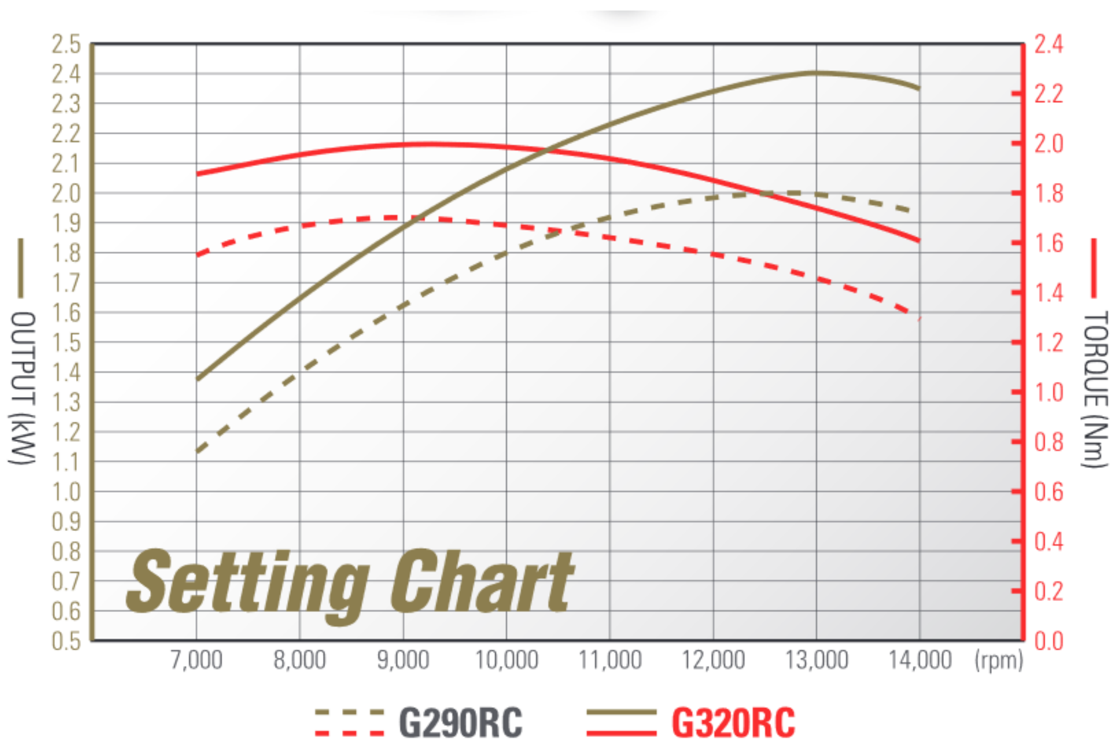

Figure 49: Manufacturer G320RC Chart

Furthermore, to achieve the maximum performance of the motor and prevent damage, it must go through a break-in process that supplies the motor with a gradually increasing load at its operational RPM of 9000. Using the dynamometer is the optimal choice to perform the break-in because it allows for variable load on the motor at high RPM's.

Due to the fuel being a significant portion of the gross weight of the UAS, it was necessary to confirm our fuel consumption estimates that were based off of manufacturer data. Having sufficient fuel is necessary to achieving the two hour hover requirement from the customer. It is expected that the manufacturer provided fuel consumption rates are a slight overprediction because at Boulder's altitude, the less dense air means that less fuel is required to achieve the optimal fuel/air ratio for peak torque. Fuel consummation would be measured during a 2 hour endurance test on the dynamometer by recording fuel weight pre and post test.

Finally, a basic temperature analysis was planned to ensure the carbon fiber motor mounting plate on the UAS would not be exposed to temperatures high enough to weaken the material (150° F) and cause a chassis failure. Thermocouple temperature data from the dyno mounting plate would confirm whether additional thermal shielding would be necessary to keep the carbon fiber safe. Due to the location of the motor standoffs in relation to the motor cylinder, safe temperatures are expected on the motor mount without needing additional shielding, but hard data was desired to confirm this hypothesis.

To perform the desired tests, the DYNOmite eddy current engine dynamometer had to be modified to support mounting the G320RC engine. CU faculty member faculty Bobby Hodgkinson sponsored the project financially and assisted with the design. At the time of the senior project suspension, the dyno parts had been fully manufactured and assembled, as seen below in Fig. 50. However, there was insufficient time to perform the live testing.

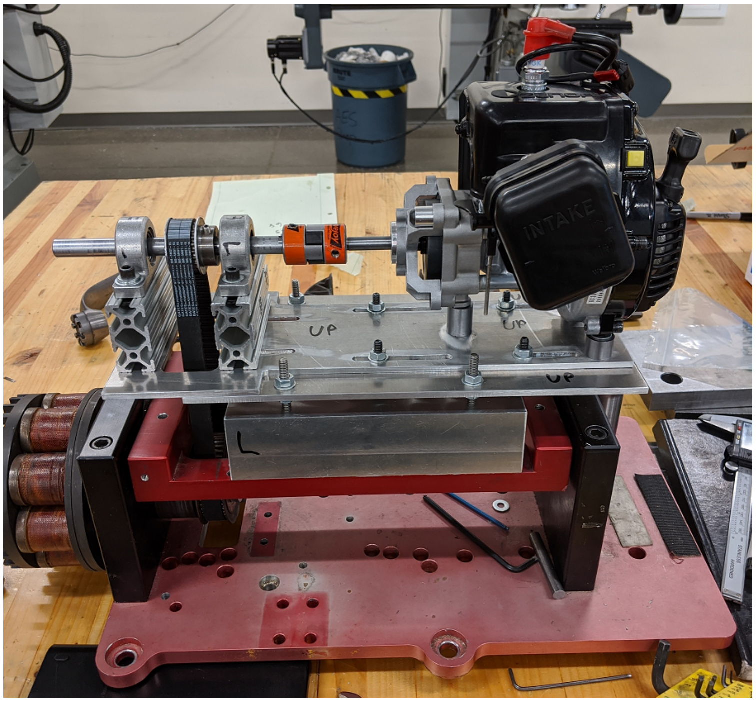

Figure 50: Assembled Dyno with Engine

The dyno test setup can be seen below in Fig. 51. The testing would be performed in the hazardous engine cell, with dyno control, data acquisition, and power supply being located in the safe room. The main instruments for the testing are the dyno tachometer and load cell, and thermocouples that would be placed on the mounting plate. Data recorded by the load cell and tachometer is converted by the DYNOmite data controller into horsepower and torque measurements that are sent to a local computer.

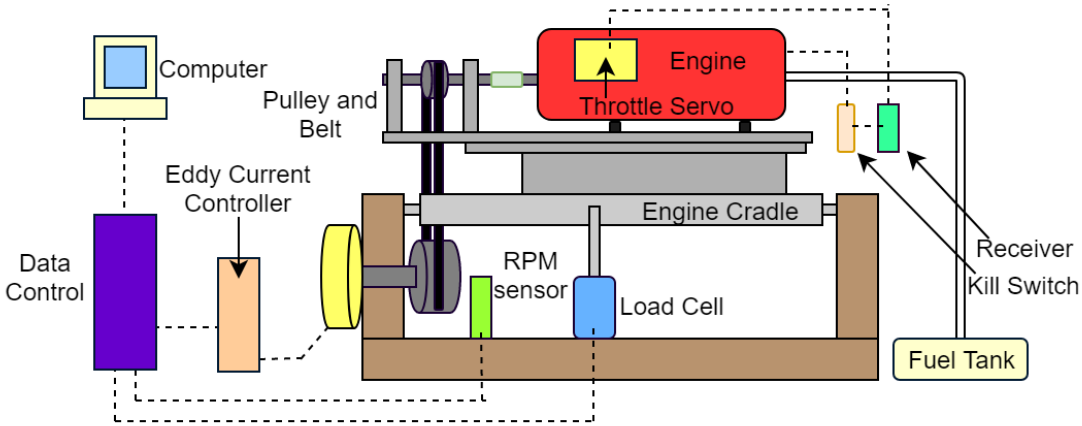

Figure 51: DYNOmite Engine Test Stand Diagram

The dyno testing would produce a HP and torque vs RPM curve that would be verify most of FR 4 (UAS shall be gas powered) was met, which states that the motor must supply enough power and torque to support the UAS's entire flight envelope. The remaining sub-requirements of FR 4, which state that the UAS must have enough fuel to support the 2 hour hover mission with a 5% fuel reserve would be verified with the fuel consumption data gathered from the endurance testing. The temperature data would partially verify sub-requirement 7.3 in FR 7 (Chassis), that states the chassis must rigidly support all components. Finally, FR 6.1 (The operator shall be able to approach the UAS when the engine is on) would be verified by confirming the motor clutch only engages above 6000 RPM.

6.5. Hardware In The Loop (HITL) Testing

Once the electronics, thrust, and power plant subsystems had been verified, the HITL testing phase would begin. Due to time restrictions, the HITL testing was unable to be performed. Had there have been time, HITL would have taken an incremental approach and be split into 3 separate tests. The UAS chassis would be fully assembled with its subsystems for these tests, with the main difference being staggered levels of power plant operation for the different tests. These tests would be used to validate cohesive operation between the multiple subsystems.

6.5.1. HITL 1

HITL test 1 would be performed without the engine being on, preventing any drivetrain engagement or rotor spinning. As such, the hazardous engine cell would not be required for this testing. The desired results of this test would be to verify UAS-to-ground station communication on the full scale vehicle, and verify pitch control accuracy with the installed rotor head mechanisms. The instruments used for verification would be a digital blade pitch sensor and the ground station, which would record downlinked telemetry from the UAS. Blade pitch measurements would verify FR 1.2.4 (UAS shall have necessary control authority for required maneuvers) by ensuring that all blades could be pitched to within 0.25° of the commanded value. The communication check would verify FR's 3.7 and 6.2, which state that the UAS functions have to be able to shut down at any time. Camera pointing tests with the gimbal would then verify FR's 3.1 and 3.2.3, which state that the ground station must be able to control the camera gimbal and receive a live video stream.

6.5.2. HITL 2

HITL test 2 would be performed with the engine on and revving to a max 7200 RPM, but without the drivetrain belts, preventing the blades from spinning. The same testing would be performed as in HITL 1, except with the inclusion of the engine vibration. This would allow for basic vibration monitoring through the Pixhawk sensor. If the Pixhawk's internal sensors become saturated by the engine vibrations, then additional vibration damping solutions would need to be explored and tested. This testing would be performed in the hazardous engine cell to ensure safety. A small, uninstalled fuel tank would be used instead of the full size integrated fuel tank. With the engine operable, HITL 2 testing would also verify FR's 3.4 (emergency commands) and 6.2 (UAS shutdown with kill switch).

6.5.3. HITL 3

HITL test 3 would be performed with both the engine on and the drivetrain engaged. This allows for verifying the smooth operation of the drivetrain and the multiple belts on the UAS. This testing would be performed in the hazardous engine cell and with a small, uninstalled fuel tank as in HITL 2. The UAS chassis would also be tightly anchored to the engine cell floor. The engine will be run up to a 7200 RPM with the engaged drivetrain. The UAS would be monitored during the testing through the engine cell window and by cameras within the cell. This will allow for observation of the drivetrain and belts during the test, and inspections would be performed between tests to verify the belt and drivetrain integrity. Completion of this testing will verify FR 7 (Chassis shall support all components on the UAS).

6.6. Flight Testing

The full scale flight testing will verify manual and autonomous flight and will be broken up into 3 incremental tests: hop, tethered, and untethered. To clarify, manual control implements a conventional handheld drone transceiver, while autonomous control is performed by entering flight commands into the ground station. All the flight tests would be performed at the NOAA Table Mountain Test Facility under the observation of Matt Rhode. A picture of the Table Mountain facility is shown below in Fig. 52. The planned flight zone is an area of approximately 2000 by 3000 feet of flat ground with no structures. We would ensure bystander safety by having a team at each of the circled intersections to stop people from driving into the flight zone area. For the hop and tethered tests, a steel braided tether will secure the UAS to redundant ground anchors to prevent flyaway scenarios. The IRISS van would be used both as a safety barrier for the test crew and as a platform for high accuracy UAS tracking equipment. An approved flight and safety checklist would be followed step by step for each test to ensure safety and streamline the operation of the tests.

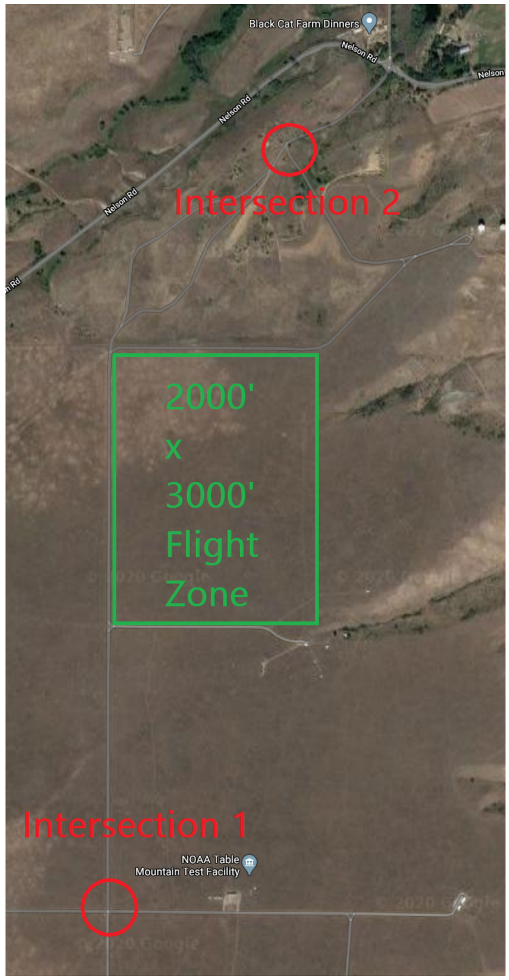

Figure 52: NOAA Table Mountain Diagram

The hop test would be performed under manual control where the motor is brought up to the operational RPM, and the blade angle of attack is raised just enough to get the UAS a few inches above the ground. The blades are then immediately dropped back to 0° angle of attack and the UAS touches down. This test verifies the drivetrain at operational RPM and that the installed thrust requirements are met. The next test is the tethered flight, where the UAS would be flow while attached to a 30 ft steel tether that has redundant ground anchors. The test will include both manual and autonomous control methods. This will allow for verification of flight stability and hover accuracy, endurance, and autonomous functionality. The final envisioned flight test would be untethered, where the max range and ceiling requirements would be verified.

The main instruments for the tethered flight testing are the onboard UAS sensors and the ground based drone tracking equipment provided by IRISS. The data of interest is the downlinked UAS telemetry and video stream as well as the high accuracy positional data from the IRISS equipment. For the flight envelope, the flight tests would show that the UAS has the ability to climb, maneuver, and hover while maintaining stability and controllability. The hover accuracy would then be tested to verify that the UAS can hold within a 5 ft cube over a 2 hour duration. These tests verify FR's 1.1, 1.2, and 1.3. Next, the UAS's ability to autonomously launch, maneuver to a set position, and later return to launch with a 5 ft accuracy would be verified. The data required for this verification is the UAS filtered GPS and inertial sensor data, along with the high accuracy positional data recorded with IRISS's instruments. This positional data would be compared with the commanded target position to ensure that the UAS can maintain its 5 ft cube hover accuracy. These tests verify all of FR 2 (autonomy).

For the power plant requirements, a 5% fuel reserve after completing a 2 hour hover mission must be verified. This will be accomplished by taking fuel weight measurements before and after the flight. Recorded fuel data can also be compare to the fuel consumption model. This test will verify FR's 4.3 and 4.3.1. The ground station's functionality has several requirements that must also be verified. This includes the ability to update mission parameters mid-flight, remotely control the camera and receive the video stream, and send RTL or kill commands to the UAS to interrupt the mission. Testing this functionality will verify FR's 3.2.2, 3.3, 3.4.1, and 5.4.

Finally, after the above functional requirements have been verified with tethered flight, the untethered flight test would be only way to verify the maximum range requirements for both the flight envelope and the payload. Customer requirements state that the UAS must have a 500 meter lateral range and a 400 ft above ground level flight ceiling. It must also be verified that the video stream maintains integrity at 720p 30fps at the maximum range. Positional data recorded from the UAS and IRISS instruments will verify that the UAS has achieved the range requirements and is still able to maintain the required 5 ft cube hover accuracy. These test would verify FR's 1.1.1, 1.1.2, 3.1.1, and 5.4.4.

6.7. Functional Requirement Summary

6.7.1. Functional Requirement 1 Validation

FR 1: UAS shall operate within the defined flight boundary.

Satisfaction: The UAS meets the 30 lb takeoff weight restriction and can maneuver to within 1640 ft (500 m) laterally and 400 ft vertically of the ground station. The UAS must also show via IMU and GPS telemetry that it can hold a hover within a five foot cube. The UAS must also demonstrate the ability to hold a hover for two hours to meet the endurance requirements.
Verified With: Rotor thrust testing, flight testing.

6.7.2. Functional Requirement 2 Validation

FR 2: UAS shall operate autonomously.

Satisfaction: The UAS must demonstrate that it can autonomously take off, travel to an operator provided location, hold a steady hover for an operator defined time, and successfully return to the launch location and land within five feet of where it took off.
Verified With: Flight testing.

6.7.3. Functional Requirement 3 Validation

FR 3: Ground Station shall communicate with the UAS.

Satisfaction: The ground station must be able to receive mission, camera pointing, and kill commands from the operator. The ground station must then successfully transmit the commands to the UAS and be able to downlink telemetry at a minimum of 1 Hz and live video at 720p, 30 fps from the UAS. The ground station must demonstrate the ability to receive and relay manual maneuver commands from the operator to the UAS.
Verified With: Electronics testing, HITL testing, flight testing.

6.7.4. Functional Requirement 4 Validation

FR 4: UAS shall be gas powered.

Satisfaction: The UAS must be gas powered and have a fuel tank capable of holding the fuel required for a two hour hover operation with a 5% fuel reserve. The endurance and remaining fuel reserve will be validated with a long duration test.
Verified With: Dyno testing, flight testing.

6.7.5. Functional Requirement 5 Validation

FR 5: UAS carries a camera payload.

Satisfaction: The UAS must demonstrate that the five pound camera payload can be securely attached without interfering with the flight operation or landing of the UAS. The gimbal must demonstrate that it can accurately point to

operator provided coordinates and stabilize the video that is downlinked to the ground station. The payload must show it can save a local copy of the video that can be recovered after landing.
Verified With: Electronics testing, HITL testing, flight testing.

6.7.6. Functional Requirement 6 Validation

FR 6: UAS shall operate safely.

Satisfaction: The UAS rotors will demonstrate that they do not rotate upon engine startup or during idle RPM's. This is ensured by the clutch which provides a physical disconnect between the motor and the drivetrain. The power kill commands must also be demonstrated to successfully power off the motor when required by the operator or during an electrical or mechanical malfunction. This will be tested on the ground to prevent loss of the UAS.
Verified With: Dyno testing, HITL testing, flight testing

6.7.7. Functional Requirement 7 Validation

FR 7: Chassis shall support all components on UAS.

Satisfaction: The chassis must demonstrate its ability to successfully house all of the components required for operation and not fail under loads experienced during flight. The chassis landing gear must survive a 1.64 ft (0.5 m) drop test at the full takeoff weight and prevent the camera, payload, and fuel tank from touching the ground.
Verified With: Dyno testing, HITL testing, flight testing

7. Risk Assessment and Mitigation

7.1. Rotor Blades

Henry Moore

Each risk is tabulated below in Table 19 along with that risk's corresponding mitigation strategy. Each risk is in Table 20 where it is assessed to be in terms of risk and consequence. Each mitigated risk is denoted by the risk number with a star.

Table 19: Propeller Blade Risk Numbering and Mitigation

Risk Number	Risk	Mitigation
1	Propeller produces insufficient thrust	Large available additional thrust
2	Aerodynamic loading is too great	Rotor will be tested before flight, analysis shows relatively low loads
3	Control authority is insufficient	5' hover box allows some tolerance in hover location, analysis shows greater than needed control authority
4	Aeroelasticity problems	Different rotation rates usable
5	Blade tensile strength insufficient for chosen rotation rate	Rotor will be tested before flight, rated by manufacturer to higher than our RPM

Table 20: Propeller Blade Risks

	Low Possibility	Med-Low Possibility	Med-High Possibility	High Possibility
High Consequence				
Med-High Consequence	3	4		
Med-Low Consequence	1	4*		
Low Consequence	2,5 1*,2*,3*,5*			

The propeller may not be able to actually hover at the exact nominal hovering conditions found by the function minimization algorithm due to real-world effects, but this will not be a problem. The propellers are not near their stall angle of attack, and thus there is significantly more thrust to be had at the same RPM. Additionally, the engine can be run at a higher RPM, which will also produce more thrust. The UAS can produce more than 35 lbs of thrust at the nominal RPM, which is enough for it to climb even at takeoff weight.

Analysis was performed on the aerodynamic loading requirements of the propellers, shown below in Fig. 63.

Though the material properties of the blade are not given by the manufacturer, the maximum shear and moment is quite small, and is easily tested by simply applying force to the blade.

The control authority is nearly a non-issue due to the high force per degree of deflection available to each rotor. Additionally, the EMU Dynamics Simulation takes into account the thrust profile of the rotors, demonstrating that the blade authority is more than sufficient for steady hover and maneuvering.

As shown in Table 20, the most significant risks after taking into account the mitigation strategies is aeroelasticity causing vibration problems for the propellers of the UAS. Analysis can be performed to ascertain whether or not the frequency of the oscillations due to the rotor aerodynamics would excite vibrational modes of the propellers, however any such calculations would involve too many assumptions due to be useful. Thus, the only way to ensure this is not a problem is thorough testing of the propeller before flight. Because the propeller is only operating at one rotation rate, testing should be able to account for any conditions that the UAS will encounter during normal operation and rule out aeroelasticity problems.

Should testing find that it may be a problem, the nominal hover can be modified to use a higher angle of attack at a lower rotation rate or a lower angle of attack at a higher rotation rate, though both would come at the cost of some wasted power.

The blade tensile strength will not be a problem, as it is rated by the manufacturer to significantly higher RPMs than will be used during flight.

7.2. Rotor Head

Libby Hasse

The rotor head risks primarily surround the assembly of the rotor head. This assembly has number of small moving parts which all have to be assembled by hand and therefore leave room for human error. Table 21 lists the risks and their correlating mitigations for this subsystem.

Table 21: Rotor Head Risk Enumeration and Mitigation

Risk Number	Risk	Mitigation
1	Swashplate misalignment during manufacturing	Follow the alignment methods outlined in the Detailed Design section
2	Set screws on pulley don't put enough force on shaft to prevent movement	Add pin to prevent pulley from detaching
3	Screws or parts come loose	Assemble everything using Loctite

The ultimate result of all three of the stated risks above end with the rotor head mechanism damaged in some way which all prevent it from being useful to the system and ultimately preventing EMU from operating the UAS. Despite each of these outcomes being detrimental to the operation of the UAS the possibility of all three risks are very low. Careful precautions are going to be taken through each rotor head assembly and additional safety mechanisms will be added as stated above in the Detailed Design description of the subsystem. Any risk number with an attached asterisk represents the risk after employing the mitigation strategy.

Table 22: Rotor Head Subsystem Risks

	Low Possibility	Med-Low Possibility	Med-High Possibility	High Possibility
High Consequence		2		
Med-High Consequence	1, 2*			
Med-Low Consequence	3, 1*			
Low Consequence	3*			

7.3. Chassis

Rebecca Rivera

The risks associated with the chassis are of generally high consequence. The risks are described in Table 23 and are evaluated in Table 24. In Table 24, the numbers accompanied by an asterisk are the corresponding mitigated risks.

Risk 1, adhesive failure has the highest possibility but can be mitigated by reinforcing adhered areas with hardware and using a larger surface area to adhere parts. Mounting hardware aides in lowering both the consequence and probability of this risk and increased surface area lowers the possibility. This risk was addressed by including holes for mounting hardware in the areas at risk of this type of failure. For example, between the engine mount and main beams. This was identified to be a high risk area because heat from the engine could potentially weaken the adhesive holding the engine plate to the main beams making an adhesive failure more likely.

Risk 2, material failure is also of extremely high consequence, any material or adhesive failure during flight could potentially be disastrous for the project. Due to the material safety factor, material failure is considered a low possibility risk. The areas most susceptible to material failure are regions in the carbon fiber surrounding holes, particularly holes close to edges. The risk of material failure at these areas was mitigated by choosing quasi-isotropic carbon fiber (meaning it contains 0 deg., 90 deg., and ±45 deg. fibers) so that any holes drilled do not completely sever all of the fibers surrounding that area. Additionally, Risk 2 was mitigated by reinforcing areas of maximum force with additional material supports. For example, joints where the main beams connect to the propeller arms were reinforced with an extra carbon fiber plate and carbon fiber cloth was going to be used to reinforce any other high risk areas.

The last major risk for the chassis is landing gear failure. Risk 3 is of medium-low possibility and medium low consequence. A landing gear failure is not likely to cause entire project failure like Risks 1 and 2, however, it could be expensive if the fuel tank, camera, or gimbal were damaged. Risk 3 was mitigated by using RC car shocks in the landing assembly to absorb the shock from a landing impact and damp out the oscillations after the initial impact. This helps to distribute the impact force and maintain more clearance between the fuel tank and camera/gimbal from the ground. The other mitigation strategy was to print the PLA landing gear components with fibers axial to the applied load so that they are in their strongest orientation. At the stopping point of the project all of these risks were determined to be mitigated and it was not anticipated that further mitigation would be required.

Table 23: Chassis Risk Enumeration and Mitigation

Risk Number	**Risk**	**Mitigation**
1	Adhesive failure	Use larger surface area between components, reinforce areas of greatest risk with hardware
2	Material failure	Reinforce with more material or supports, use carbon fiber cloth
3	Landing gear failure	Use shock absorbers, print 3D parts with fibers axial to maximum loads

Table 24: Chassis Subsystem Risks

	Low Possibility	Med-Low Possibility	Med-High Possibility	High Possibility
High Consequence	2		1	
Med-High Consequence	2*	1*		
Med-Low Consequence	3*	3		
Low Consequence				

7.4. Power Plant

Michael Flores

The power plant risks focus around issues with the performance or implementation of COTS items. Since the engine is a critical component allowing the system to fly there are high consequences associated with the failure of these components. Table 25 lists out the risks of the system and mitigation strategies. The main risks associated with this system come from engine component failures as the UAS will lose mechanical power.

Table 25: Power Plant Subsystem Risk Enumeration and Mitigation

Risk Number	Risk	Mitigation
1	Engine internal component failure.	Don't overrun the engine or run the engine past service dates.
2	Engine overheating.	Implementing a COTS external cooling system.
3	Clutch failure during engagement.	Engage the clutch slowly and purchase spare clutch assemblies.
4	Engine becomes starved of fuel.	Fly with fuel reserve and implement fuel sensing.
5	Engine vibrations damage chassis.	Implement bushings or damping engine mounts.
6	Engine creates insufficient thrust.	Install performance modifications to engine.

Of all of the listed risks, the least consequential risk comes from the failure of the clutch system. Since this failure will occur before the UAS can get off of the ground damage will be limited to the clutch assembly which is a relatively inexpensive component. The other risks present high consequences due to occurrence during flight but through mitigation, the probability can be reduced making them manageable. Table 26 shows a matrix of these risks before and after mitigation. Any risk number with an attached asterisk represents the risk after employing the mitigation strategy.

Table 26: Power Plant Subsystem Risks

	Low Possibility	Med-Low Possibility	Med-High Possibility	High Possibility
High Consequence	4, 1, 2*,6*	2, 5,6		
Med-High Consequence	5*, 4*			
Med-Low Consequence	1*	3		
Low Consequence		3*		

7.5. Drivetrain

Nathan Hetzel

The drivetrain risks center around the central drive shaft and the quarter turn belt drive configuration. Since power delivery is crucial to the projects success, mitigation of these risks are essential. Table 27 lists the different risks as well as the mitigation plan for each one. The risks associated with the drivetrain derive from drive shaft capabilities and proper installation of components.

Table 27: Drivetrain Risk Enumeration and Mitigation

Risk Number	Risk	Mitigation
1	Excessive belt wear or damage of belts	Proper alignment & proper installation for twisted configuration
2	Large bending moment on drive shaft	Additional supports to segment drive shaft
3	Low critical speed of driveshaft	Additional supports to segment drive shaft

Risk 1 was one of the highest consequence risk associated with this subsystem. The mitigation steps for this risk is to ensure proper installment of pulleys for a quarter turn belt drive is fulfilled. Documentation provided by a manufacturer online assists the EMU team on the steps to set up an optimal design for the dimensions of the UAS. Risk 2 was the least consequential risk, and is mitigated by lessening the distances between supports by adding more into the design. Although not modelled as statically determinant, the drive shaft can currently handle only two supports and adding more increases the longevity of the drive shaft. Risk 3 would cause catastrophic failure as the drive shaft would reach an excited mode, causing an infinite increase in deflections before failure. The same mitigation method for Risk 2 is employed for Risk 3, decreasing the distances between supports to increase the critical speed much beyond the operational speed of the shaft. Table 28 below shows where each risk was initially placed on a risk matrix before mitigation with their respective risk number as well as where each risk currently lies after mitigation, differentiated by the risk number accompanied by an asterisks.

Table 28: Drivetrain Subsystem Risks

	Low Possibility	Med-Low Possibility	Med-High Possibility	High Possibility
High Consequence				
Med-High Consequence	1,3			
Med-Low Consequence	1*,2,3*			
Low Consequence	2*			

7.6. Electronics

Alejandro Castillo

The Electronics subsystem presents a few risks that could potentially affect the projects' success. These, however, can mostly be mitigated by buying replacement parts as the most common failure mode is the failure of certain components or inadequate capacity of these.

Table 29: Electronics Risk Enumeration and Mitigation

Risk Number	Risk	Mitigation
1	PixHawk IMU becomes saturated by vibrations	Rubber bushings on the avionics mount
2	Battery capacities inadequate	Buy larger battery
3	Servo response time / torque inadequate	Buy new servos
4	PixHawk restarts midflight due to power interruption	Power redundancy circuit installed

Table 30: Electronics Subsystem Risks

	Low Possibility	Med-Low Possibility	Med-High Possibility	High Possibility
High Consequence	4,4*			
Med-High Consequence	3		1	
Med-Low Consequence		1*		
Low Consequence	2,2*,3*			

Risk 1 was initially very concerning to the team as there was no known data about how well the PixHawk can handle vibrations (It has built in dampers) or how intense of vibrations the engine will produce. This will remain unknown until the engine can be tested, at which time the PixHawk will be mounted close to it in order to test how it handles the vibrations. For now, though, the risk mitigation strategy includes installing rubber bushings on the avionics mount in order to dampen some of these vibrations. Furthermore, Risks 2 and 3 present no real concerns as it will be known if the components are adequate long before the UAS first takes flight. Finally, Risk 4 has been mostly mitigate by installing a power redundancy circuit that allows the pixhawk to power itself from the servo rail should the main power input port fail or should the connection be interrupted. It is highly unlikely that this will occur, however if it does it would more than likely result in total failure of the UAS.

7.7. Ground Station

Matthew Lehmann

There are not a lot of specific risks in the ground control station design that compromise the team's ability to satisfy the critical elements of this project. The main risks revolve around losing connection with the UAS in flight which could result in a multitude of problems for the aircraft. Below is an analysis of these risks and possible mitigation strategies, note that risk numbers with an asterisk represent risks after mitigation strategies have been applied.

Table 31: Ground Control Station Risk Numbering and Mitigation

Risk Number	Risk	Mitigation
1	Losing connection with the on-board flight controller	Remain within the flight envelope
2	Losing live video feed with the on-board camera	Remain within the range of TS5823
3	Way-point or firmware failure in GCS or on-board controller	Suitable landing gear for fall

Table 32: Ground Control Station Risks

	Low Possibility	Med-Low Possibility	Med-High Possibility	High Possibility
High Consequence				
Med-High Consequence	3,3*			
Med-Low Consequence		1		
Low Consequence	1*, 2*		2	

The highest priority risk with the ground control station is losing connection to the UAS flight controller mid-flight. The operator would not have any ability to command the aircraft causing the autopilot to assume full control over the flight. Now, the on-board flight controller is capable of recognizing such a loss in communication; and it reacts by immediately landing the UAS regardless of its location. While it is a great safety feature to have for the project, it can result in the UAS landing in wooded areas that make either its retrieval or safe landing an issue for the team. Granted, the likelihood of this is minimal considering that the transmission range of the RFD 900+ radio modems being used for command up/downlink to the UAS is 40 km. Therefore the actual possibility of this happening is low. There is no major concern with the ground control station that puts the entire project's success in jeopardy.

7.8. Logistical

Michael Flores, Dakota Labine

The main logistical risks for the EMU project are founded in the time delays that could occur to the project when specific. Outside of manufacturing delays, the majority of these risks have a low probability of occurring. Table 33 lists out each risk and how each risk could be mitigated. Majority of mitigation strategies for these risks focuses on scheduling to preempt these issues as well as employing detailed procedures for obtaining and handling project items.

Table 33: Project Logistic Risk Enumeration and Mitigation

Risk Number	**Risk**	**Mitigation**
1	Test days limited to poor weather.	Scheduling multiple testing periods where each outdoor period spans more than one day.
2	Manufacturing delays project completion	Creating a fast and anticipatory schedule, completing tasks between semesters, dedicating multiple people to each manufacturing task.
3	Needed COTS items are no longer available.	Each purchase requisition form must contain one alternative COTS item.
4	COTS item needs to be reordered.	Budget reserve for expediting items, inspecting each part once it arrives, testing each component before integration to identify issues early.

Of all of the listed risks, mitigating the manufacturing risk is the most necessary. For a project of this scope, these delays can severely impact project completion. To offset this, the team will complete work over the time in between semesters, and build a schedule to complete things early in case one does get set back, the project doesn't run too far behind. For personnel, multiple team members will be given portions of the manufacturing to facilitate the completion of work. The other risks do not present as high of consequence but the use of procedures can mitigate these consequences. Table 34 shows a matrix of all risks before and after mitigation. Any risk number with an attached asterisk represents the risk after employing the mitigation strategy. These mitigation strategies should prove to be effective in limiting the impact of these logistical risks.

Table 34: Logistical Risks

	Low Possibility	Med-Low Possibility	Med-High Possibility	High Possibility
High Consequence				
Med-High Consequence	4		2	
Med-Low Consequence	4*	1, 3, 2*		
Low Consequence	3*	1*		

7.9. Financial

Dakota Labine, Michael Flores

The main financial risks for the EMU project coming from the possibility of breaking or destroying a major component and needed to re-order parts. The likely hood of breaking a part of subsystem can be detailed in the subsystem specific risk matrices below. The three major risks are detailed in Table 35. All finical risks are associated with the need to buy more material and parts that could put the project over budget.

Table 35: Project Financial Risks Enumeration and Mitigation

Risk Number	Risk	Mitigation
1	Carbon chassis breaks from manufacturing, assembly, or testing.	Detailed manufacturing and assembly plan to prevent mistakes or damage, as well purchasing
2	Destroying a motor during testing and flight demonstration	Following manufacturer procedures and best practices to ensure longevity and proper function of the motor. As well as maintaining some leftover budget incase a new motor must be purchased.
3	Rotor-head assembly destroyed in testing, travel, and manufacturing.	Detailed manufacturing plan, developing a pre-flight checklist, and purchasing two extra rotor-head assemblies as back ups.

The three risks detailed in Table 35 are the most relevant as they have the highest impact on the project financially. The main methods of mitigation for all components are to develop a manufacturing plan to prevent errors in manufacturing that make to component inoperable, to create a test and safety plan to keep all components safe and low the risk of accidental breakage, and to buy spare parts for the components that are most likely to break. This is done for major components, while enough budget is left over to buy other components if needed. Introducing these methods of mitigation shift the financial risks over drastically and can be seen in Table 36. Any risk number with an attached asterisk represents the risk after employing the mitigation strategy.

Table 36: Financial Risks

	Low Possibility	Med-Low Possibility	Med-High Possibility	High Possibility
High Consequence		1	2	
Med-High Consequence		3		
Med-Low Consequence				
Low Consequence	1*,2*,3*			

8. Project Planning

Dakota Labine, Michael Flores

8.1. Organizational Chart

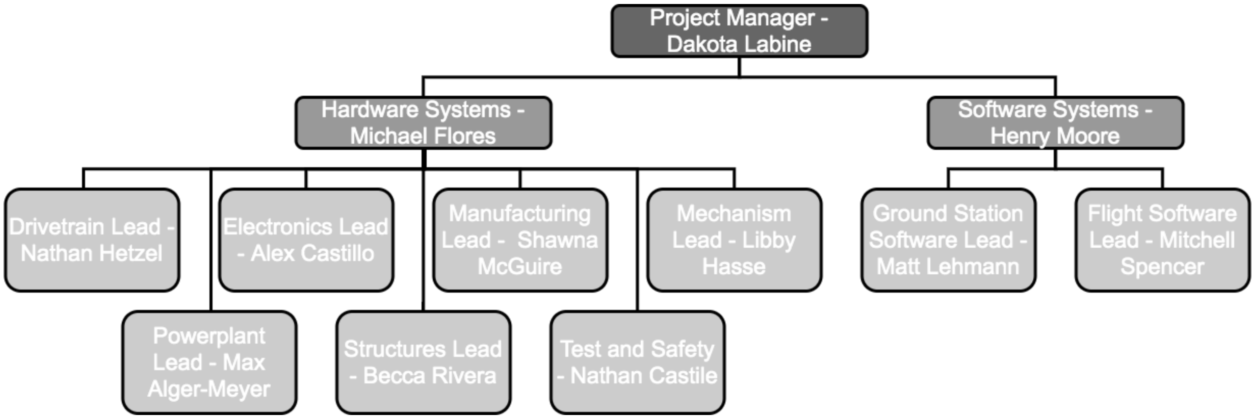

Figure 53: EMU's Team Organizational Chart

The EMU team's organizational chart is seen in Figure 53 and gives a visualisation to the team's structure. The team is lead by a project manager with two systems leads under him who are responsible for the hardware team, and the software team. The hardware systems lead's sub-team consist of the drive-train lead, the electronics lead, the manufacturing lead, the mechanism lead, the power-plant lead, the structures lead and the test and safety lead. The software systems lead's team consists of ground station software lead, and the flight software systems lead. While each lead role is filled by one person on the team, the design work, analysis, and work load is shared between multiple other leads. The following explains the role of each team member and their position

Team Roles

- **Dakota Labine - Project Manager**: Planning and overseeing of the project to ensure the completion of the project and associated tasks on time and as expected.
- **Michael Flores - Hardware Systems**: Monitoring and tracking all hardware systems to ensure compatibility and integration.
- **Henry Moore - Software Systems**: Monitoring and tracking all software systems to ensure compatibility and integration
- **Nathan Hetzel - Drivetrain**: Completing all necessary design and analysis of drivetrain components to ensure project completion.
- **Alejandro Castillo - Electronics**: Completing all necessary design and analysis of electronic components to ensure project completion.
- **Shawna McGuire - Manufacturing**: Building and executing manufacturing plan to ensure final assembly and integration of all subsystems.
- **Libby Hasse - Mechanisms**: Completing all necessary design and analysis of mechanism components to ensure project completion.
- **Matthew Lehmann - Ground Station Software**: Completing all necessary design and analysis of ground station software components to ensure project completion.
- **Mitchell Spencer - Flight Software**: Completing all necessary design and analysis of flight software components to ensure project completion.
- **Max Alger-Meyer - Powerplant**: Completing all necessary design and analysis of powerplant components to ensure project completion.
- **Rebecca Rivera - Structures**: Completing all necessary design and analysis of all structural components to ensure project completion.
- **Nathan Castile - Test and Safety**: Build and execute a test and safety plan to validate and verify all project requirements while maintaining the safety of the team and the project.

8.2. Work Breakdown Structure

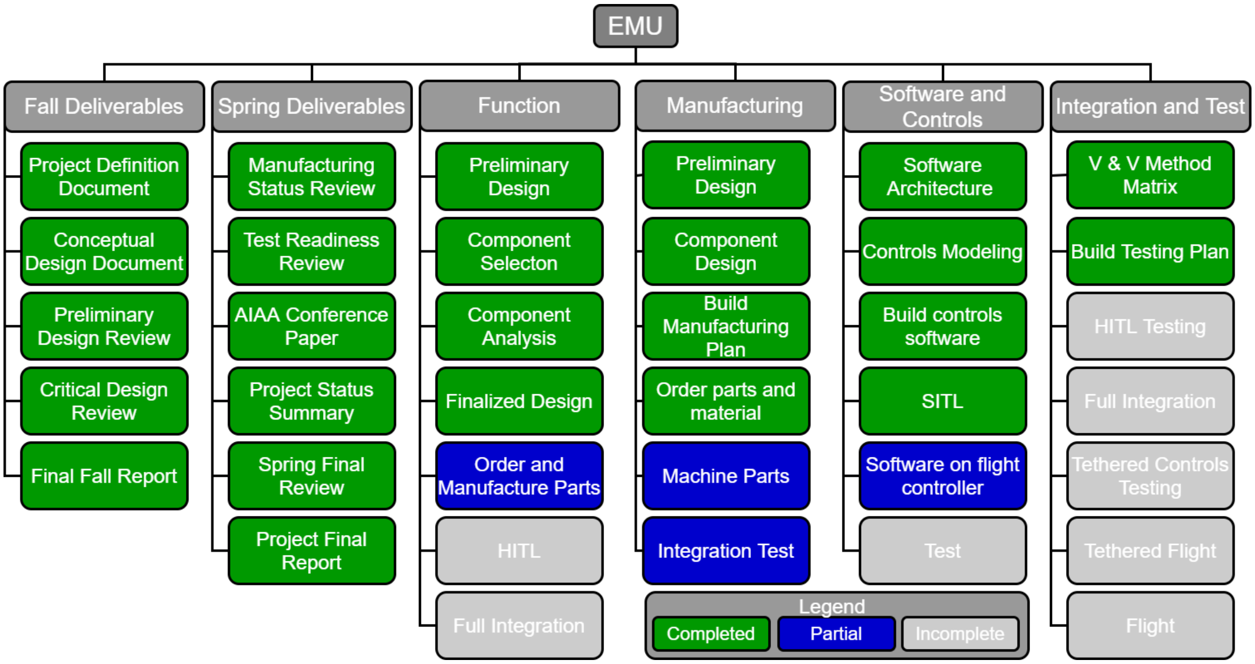

Figure 54: Work Breakdown Structure

The work breakdown structure for the EMU team can is shown in Figure 54. The work break down structure shows a high order list of the major tasks the EMU team needs to complete for the project. The major tasks can be broken down into six main sections: Fall Deliverables, Spring Deliverables, Function, Manufacturing, Software and Controls, and Integration and Test. The explanation of each section and the respective tasks can be seen below. Items represented in blue and grey were projected to be completed.

Fall Deliverable

- **Project Definition Document**: Document detailing the specific project objectives and scope.
- **Conceptual Design Document**: Document detailing the specific project requirements and high level design solution.
- **Preliminary Design Review**: Presentation on the feasibility of the baseline design.
- **Critical Design Review**: Presentation of the final design with design, analysis, and logistical feasibility.
- **Final Fall Report**: Document to give details on the design solution proposed including all necessary and associated information.

Spring Deliverable

- **Manufacturing Status Review**: Presentation on the status of manufacturing and the projects complete integration plan.
- **Test Readiness Review**: Presentation on the test and safety plan and objectives to verify design requirements.
- **Spring Final Review**: Presentation on the final project including all testing results, and verification and validation of all requirements
- **Project Final Report**: Document to give details on the final project results, lessons learned, and serves as a basis for future work.
- **Senior Design Symposium**: Presentation of final project to convey project highlights and results.

- **AIAA Conference Report**:Document to convey the project in industry standard formatting.

Function

- **Preliminary Design**: Generate a high level design solution to meet projects functional requirements.
- **Component Selection**: Select components necessary to meet design requirements.
- **Component Analysis**: Analyze and refine the component selections to satisfy requirements and integrate together.
- **Finalized Design**: Create a finalized design solution with analysis to meet all functional requirements with means and capability of verification and validation.
- **Order and Manufacture Parts**: Order all COTS parts and raw material and perform necessary manufacturing to ensure final assembly and integration
- **HITL**: Integrate all components before final assembly to check with functionality of all systems together.
- **Full Integration**: Final assembly off copter to ensure integration and function of project as one component.

Manufacturing

- **Preliminary Design**: Generate a high level design solution to meet projects functional requirements.
- **Component Design**: Create necessary models of all systems to determine manufacturability of final design.
- **Build Manufacturing Plan**: Create a manufacturing plan detailing the means and methods to create all parts.
- **Order Parts and Materials**: Order all COTS parts and raw material necessary to manufacture all components.
- **Machine Parts**: Make all custom parts and machine any COTS parts to allow for integration between systems.
- **Integration Test**: Integrate all components and test the compatibility and quality of manufacturing.

Software and Control

- **Software Architecture**: Map out the software flow and architecture.
- **Controls Modeling**: Build a controls model to determine project gains and estimate the performance of the copter.
- **Build Controls Software**: Create the flight software necessary to control the copter as expected with the predicted gains.
- **SITL**: Test the controls software in a simulation to validate the controls modeling and gain selection.
- **Software on flight controller**: Put flight software onto the flight controller to allow for flight software to control flight.
- **Test**: Test the flight software to validate control laws and verify the codes functionality.

Integration and Test

- **V & V Method Matrix**: Create a verification and validation matrix to track all requirements and the attached methods to verify and validate.
- **Build Testing Plan**: Making a testing plan to ensure proper procedures to validate and verify all requirements.
- **HITL Testing**: Integrate all systems outside of the final assembly to check functionality of systems before full integration.
- **Full Integration**: Complete final assembly off all systems to check compatibility and function or the system as a whole.
- **Tethered Controls Testing**: Perform a tethered demonstration of the fully integrate system to do a systems check
- **Tethered Flight**: Flying the copter while tethered to the ground check flight performance and proving flight feasibility.
- **Flight**: Flying the copter untethered demonstrating the functionality of the copter to meet design requirements.

8.3. Work Plan

8.3.1. Spring Semester Work Plan

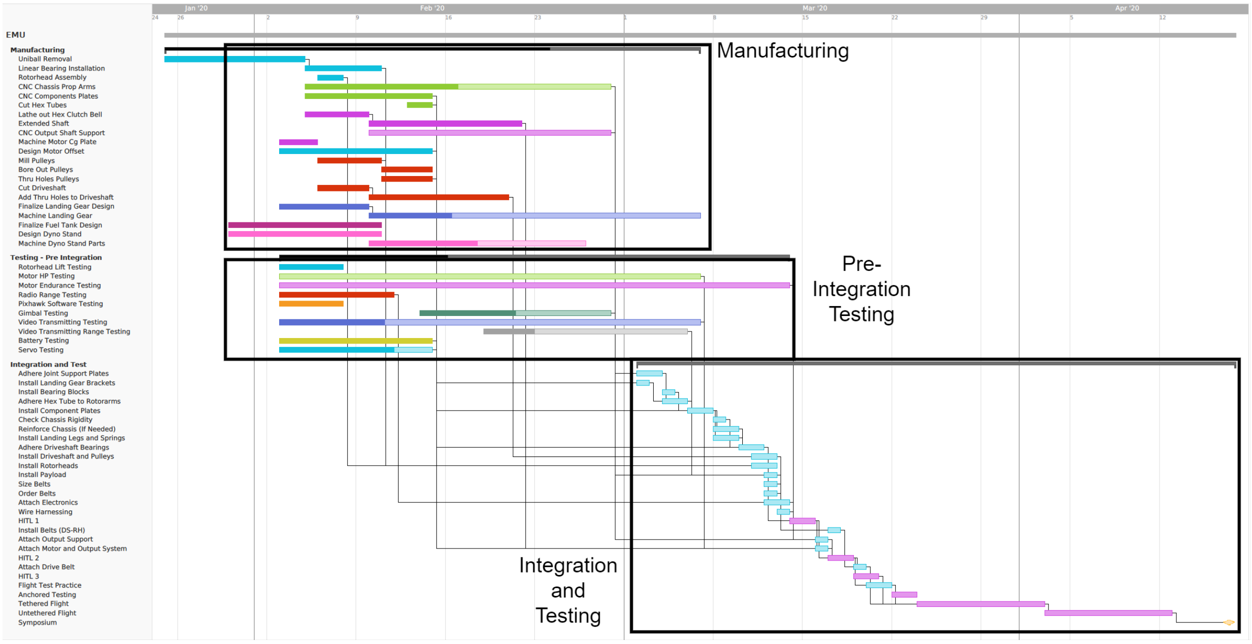

Figure 55: Spring Full Schedule

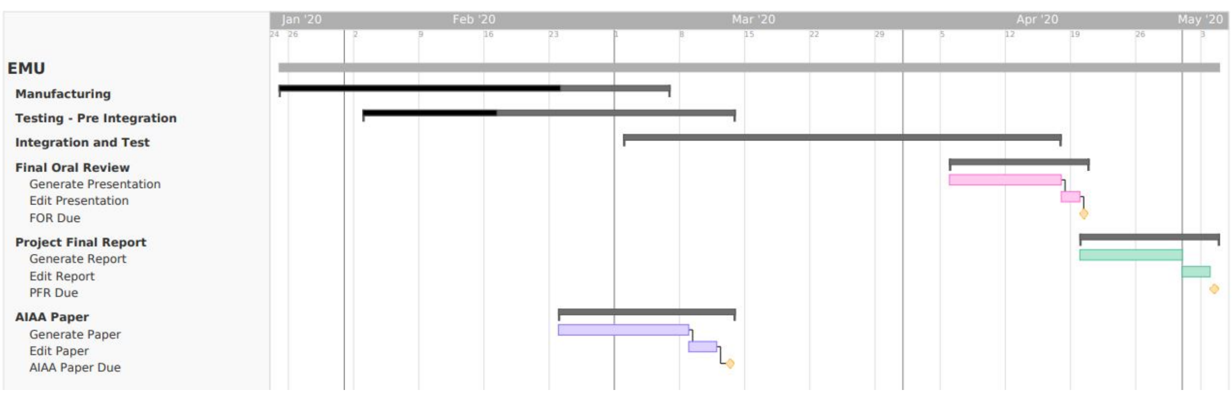

Figure 56: Reports Schedule

Figures 55 and 56 shows to work plan schedule for the EMU team over the spring semester. The main schedule can be broken down into four main sections that are manufacturing, pre-integration testing, integration and testing, and reports. The critical path leading to the project completion follows the first three main sections in order. While following the critical path the team will complete all necessary documentation and reports. The breakdown of the main sections are defined below.

Spring Semester

- **Manufacturing**: Machining and manufacturing off all system and subsystem components.
- **Pre-Integration Testing**: Verification and Validation of all subsystems flowing out of testing.
- **Integration and Test**: Integration of all components to test compatibility and functionality and verify requirement satisfaction.
- **Reports**: Generation, editing and submitting of all class deliverable reports.

8.3.2. *Manufacturing Work Plan*

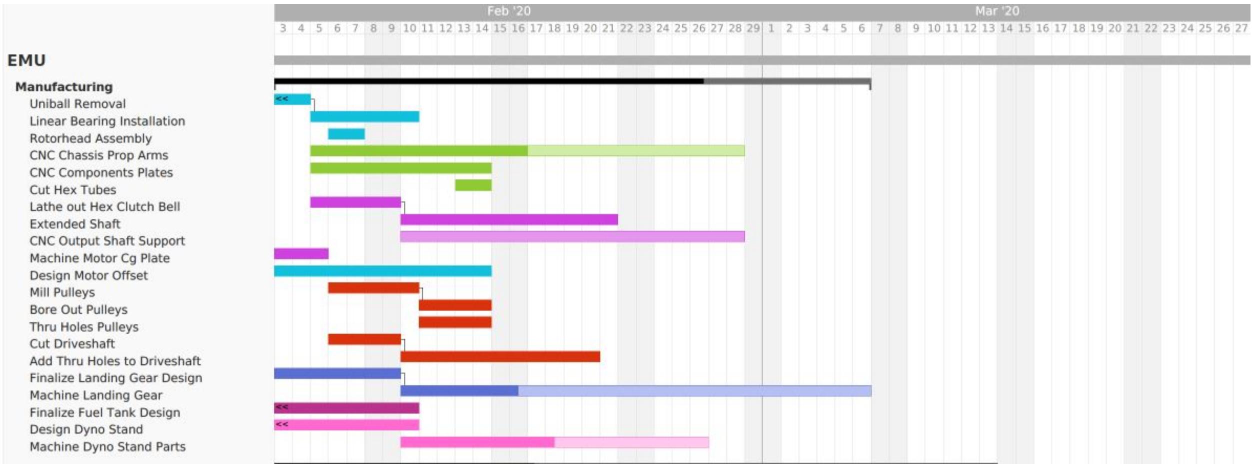

Figure 57: Manufacturing Schedule

The manufacturing schedule can be seen in Fig. 57. The schedule outlines the major components that were manufactured. A summary of major components that were manufactured can be seen below.

Manufacturing

- **Rotorhead Manufacturing**: Uni-ball removal, linear bearing installation, rotorhead assembly
- **Chassis Manufacturing**: CNC chassis prop arms, CNC component plates, cut main hex tubes, machine landing gear
- **Powerplant Manufacturing**: CNC output shaft support, lathe hex clutch bell, extended clutch output shaft
- **Drivetrain Manufacturing**: Mill pulleys, bore out pulleys, add thru holes to pulleys, cut driveshaft to length, add thru holes to driveshaft

8.3.3. *Pre-Integration Testing Work Plan*

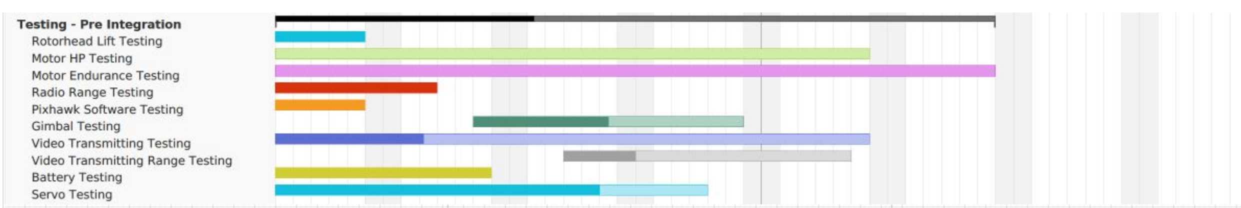

Figure 58: Pre-Integration Testing Schedule

The schedule for pre-integration testing can be seen in Fig. 58. The schedule starts with initial verification and validation of all major components and subsystems before integration into the UAS. The findings from initial V & V were used to help refine the test and safety plan to ensure final verification of all requirements. The breakdown of each task is described below.

Pre-Integration Testing

- **Rotorhead Lift Testing**: Test rotor lift capabilities to verify model
- **Motor HP Testing**: Test and verify motor for HP capabilities
- **Motor Endurance Testing**: Test and verify motor endurance capabilities

- **Radio Range Testing**: Test and verify the radio's range
- **PixHawk Software Testing**: Test and validate software function on flight controller
- **Gimbal Testing**: Test and verify gimbal and pointing functionality
- **Video Transmitting Testing**: Test and verify video streaming to ground station
- **Video Transmitting Range Testing**: Test and verify video streaming range capabilities
- **Battery Testing**: Test and verify battery power capabilities
- **Servo Testing**: Test and verify servo functionality

8.3.4. Integration and Testing Work Plan

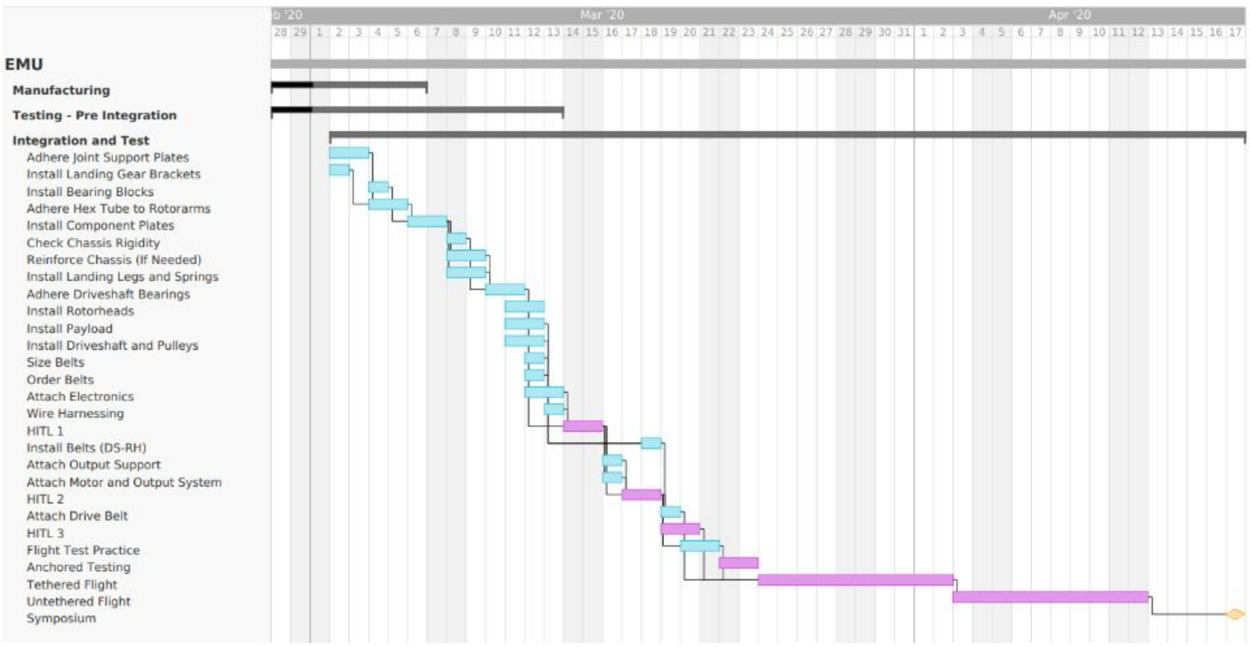

Figure 59: Integration and Testing Schedule

The schedule for integration and testing can be seen in Fig. 59. The flow for integration and testing is to integrate pre-tested components onto the chassis then perform incremental HITL tests. After full integration incremental test flights are performed to check out flight controls.

Integration and Testing

- **Integration**: Adhere joint support plates, install landing gear brackets, install bearing blocks, adhere hex tube to rotorarms, install component plates, reinforce chassis, install landing legs and springs, adhere driveshaft bearings, install rotorheads, install payload, install driveshaft and pulleys, attach electronics, wire harnessing, install belts, install motor, install drive belt.
- **HITL 1**: Demonstrate hardware and software functionality with no motor
- **HITL 2**: Demonstrate hardware and software functionality with motor but no power transfer
- **HITL 3**: Demonstrate hardware and software functionality with motor running, power transfer, non flight
- **Flight Test Practice**: Dry run procedures for running flight tests
- **Anchored Test**: Demonstrate manual flight controls and validate maneuverability
- **Tethered Flight**: Demonstrate controlled flight and hover capabilities while tethered
- **Untethered Flight**: Demonstrate autonomous unbound flight operations

8.3.5. Spring Reports Work Plan

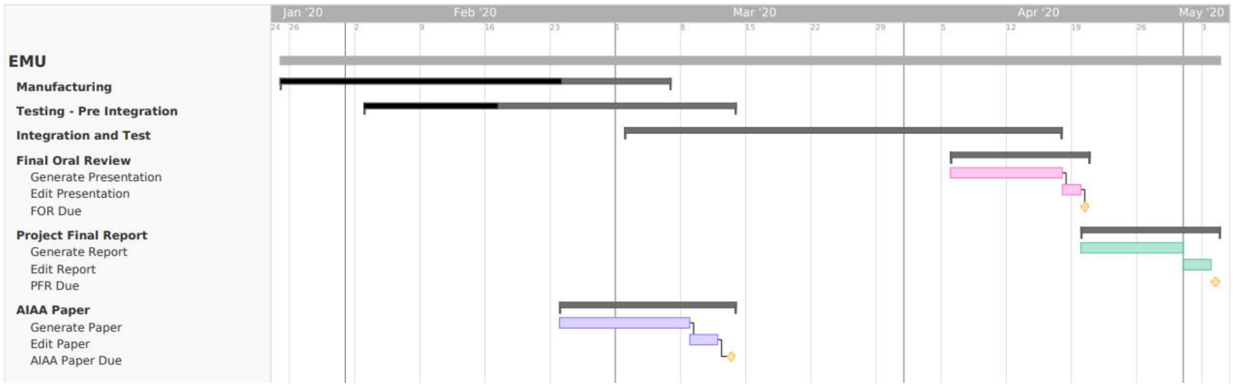

Figure 60: Reports Schedule

The schedule to prepare for submission of all springs reports can be seen in Fig. 60. Three major reports were due during the semester and are broken into three sub tasks. These three sub tasks were generating the paper, reviewing the paper and submitting the paper. The breakdown of the three major papers can be seen below.

Spring Reports

- **Final Oral Review**: Presentation on the final project including all testing results, and verification and validation of all requirements.
- **Project Final Report**: Document to give details on the final project results, lessons learned, and serves as a basis for future work.
- **AIAA Paper**: Document to explore EMU rotor thrust model in industry standard formatting.

8.4. Cost Plan

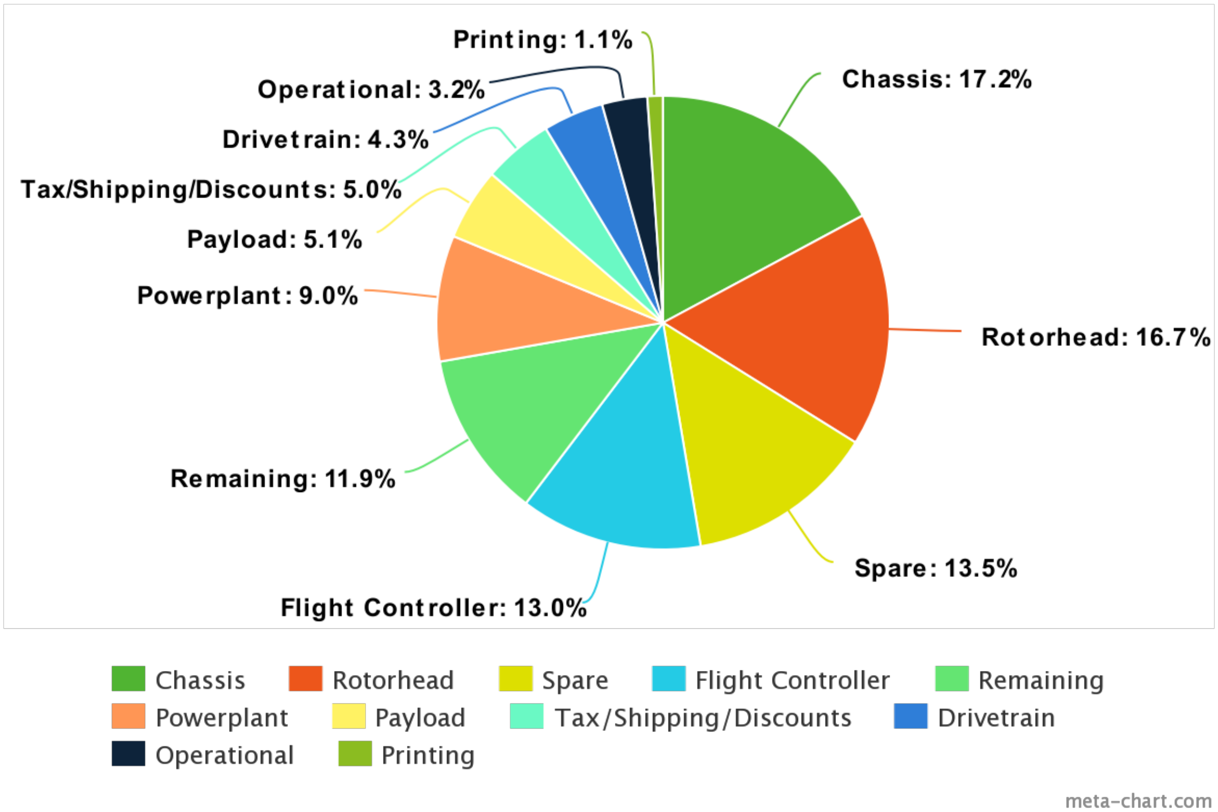

Figure 61: Cost Plan Pie Chart

Table 37: Cost Break Down Summary

System	Price
Power Plant	$ 448.94
Drivetrain	$ 215.37
Rotorhead	$ 835.27
Flight Controller	$ 650.63
Payload	$ 257.33
Chassis	$ 858.33
Operations Support	$ 162.14
Spare Parts	$ 673.42
Tax/Shipping/Discount	$ 248.91
Printing	$ 55.00
Total	$ 4,405.34
Remainder	$ 594.66

Figure 61 and Table 37 portray the cost budget plan for the EMU team. The budget can be summarized by eight major systems. These eight systems are as follows: rotorhead, chassis, drivetrain, power plant, electronics, payload, operations support, spare parts. Each system's total budget includes all necessary components to ensure full functionality and operation of the main system and can be seen in Tables 38 - 45. Each table from Table 38 - 44 has a column which takes into consideration the cost of spare parts being bought. The summation of the spare parts can be seen in Table 45 and is included in the overall budget. The pricing summarized in Table 37 is the standard price of each item and doesn't include shipping, tax and any discounts the team secured which can be seen in Table 37. The

EMU team finished the project under the $5,000 budget with roughly $600 left over.

8.4.1. Rotorhead Cost Plan

Table 38: Rotorhead Budget Break Down

Part	Description	Quantity	Quantity Spare	Price	Total Price	Spare Price
Rotorhead Housing	Main Rotor Housing	4	2	$13.99	$55.96	$27.98
Propeller Clamps	Main Rotor Holder	4	2	$23.99	$95.96	$47.98
Propellers	380 Carbon Blades	4	4	$16.99	$67.96	$67.96
Rotorhead Shaft	Rotorhead Shaft	4	2	$8.99	$35.96	$17.98
Bearing Blocks	Main Shaft Bearing Block	4	2	$22.99	$91.96	$45.98
Swashplates	Metal Swashplate	4	2	$20.99	$83.96	$41.98
Servo	Digital Servo	4	1	$33.99	$135.96	$33.99
Linear Bearing	Recirculating Linear Bearing	4	2	$18.87	$75.48	$37.74
External Retaining Rings	Hold the linear bearing in place	8	12	$0.29	$2.32	$3.48
Linkage Rods	Short and Long	4	2	$3.99	$15.96	$7.98
Control Arms	Attach swashplate to T	4	2	$17.99	$71.96	$35.98
Feathering Shaft	Goes in between the T to connect the Propeller clamps	4	2	$5.99	$23.96	$11.98
Feathering Shaft Bearing Washer	Feathering Shaft Bearing Washer	2	1	$3.99	$7.98	$3.99
Thrust Bearing	Thrust Bearing	4	2	$8.99	$35.96	$17.98
Ball Link	Ball Link	4	2	$3.99	$15.96	$7.98
Linkage Rods	Linkage Rods	3	1	$5.99	$17.97	$5.99
				Total	$835.27	$ 416.95

8.4.2. *Chassis Cost Plan*

Table 39: Chassis Budget Break Down

Part	Description	Quantity	Quantity Spare	Price	Total Price	Spare Price
Central Hex Tubes	Carbon Hex Tubes .75"x66"	2	0	$113.99	$227.98	$0.00
Rotor Arm Plates	Quasi-isotropic Solid Carbon Fiber Sheet	1	0	$453.00	$453.00	$0.00
Joint Support Plates	Included in Rotor Arm Plates Line Item	0	0	$0.00	$0.00	$0.00
Motor Plates	Included in Rotor Arm Plates Line Item	0	0	$0.00	$0.00	$0.00
Landing Gear Legs	Included in Central Hex Tubes Line Item	4	0	$0.00	$0.00	$0.00
Landing Gear Brackets	Custom Part	4	2	$0.00	$0.00	$0.00
Landing Gear Springs	Landing Springs	4	2	$5.00	$0.00	$10.00
Chassis Adhesive	Urethane Adhesive	4	2	$13.98	$55.92	$27.96
Misc Hardware	Nuts, Bults, Washer, Adhesive	1	0	$200.00	$200.00	$0.00
				Total	$936.90	$37.96

8.4.3. *Drivetrain Cost Plan*

Table 40: Drivetrain Budget Break Down

Part	Description	Quantity	Quantity Spare	Price	Total Price	Spare Price
Output Shaft Pulley	Output Shaft Pulley	1	1	$10.83	$10.83	$10.83
Drive Shaft Pulley	Drive Shaft Pulley	1	1	$13.51	$13.51	$13.51
Output Shaft to Drive Shaft Belt	156XL037G, TIMING BELT	1	2		$0.00	$0.00
Driveshaft (DS)	3/8" Alloy Steel Round Bar 4340-Normalized Cold Finish	1	1	$23.36	$23.36	$23.36
Motor Plate DS Bearing	Mounted Open Needle-Roller Bearing	2	1	$28.51	$57.02	$28.51
Rotor Arm Bearings	COTS flanged 3/8inch diameter bearing	4	2	$3.00	$12.00	$6.00
Rotor Arm Pulleys	Timing Gear Pulley	4	2	$10.80	$43.20	$21.60
Rotor Shaft Pulley	Timing Gear Pulley	4	2	$10.80	$43.20	$21.60
Rotor Arm to Rotor Shaft Belt	Timing Belt	4	4		$0.00	$0.00
Stay Collars	Clamping Two-Piece Shaft Collar	2	2	$1.38	$2.76	$2.76
Dowel Pins	Dowel Pins	1	0	$9.49	$9.49	0
				Total	$215.37	$128.17

8.4.4. *Powerplant Cost Plan*

Table 41: Powerplant Budget Break Down

Part	Description	Quantity	Quantity Spare	Price	Total Price	Spare Price
Motor	Zenoah G320RC Motor 31.88CC	1	0	$299.00	$299.00	$0.00
Ignition System	Included in motor line item	1	0	$0.00	$0.00	$0.00
RPM Sensor	RPM Sensor kit	1	0	$22.00	$22.00	$0.00
Governor	MultiGov	1	0	$0.00	$0.00	$0.00
Mufflers	Included in motor line item	1	0	$0.00	$0.00	$0.00
Clutch	Included in motor line item	1	1	$0.00	$0.00	$0.00
Clutch Bell Carrier	Universal for the 54mm clutch, COTS	1	1	$14.94	$14.94	$14.94
Clutch Bell	COTS clutch bell for 54mm Clutch Bell	1	1	$29.99	$29.99	$29.99
Clutch Bell End Mount	Custom	1	0	$0.00	$0.00	$0.00
Clutch Bell End Bearing	COTS flanged 3/8inch diameter bearing	1	0	$6.12	$6.12	$0.00
Throttle Servo	Digital Programmable Servo	1	0	$33.99	$33.99	$0.00
Fuel	Fuel Per Flight	1	0	$0.00	$0.00	$0.00
Fuel Pump	Included in motor line item	1	0	$0.00	$0.00	$0.00
Fuel Filter	Walbro ”Winged” wicking fuel filter	1	1	$3.99	$3.99	$3.99
Fuel Tank	Custom ”U” Kevlar Fuel Tank	1	0	$0.00	$0.00	$0.00
Fuel Lines	Fuel line set	1	0	$0.00	$0.00	$0.00
Motor Kill Switch	Motor Kill Switch	1	0	$31.35	$31.35	$0.00
Dowel Pins 1/16”	Dowel Pins 1/16”	1	0	$5.25	$5.25	$0.00
Shaft Collars	Shaft Collars	1	1	$2.31	$2.31	$2.31
				Total	$448.94	$51.23

8.4.5. *Flight Controller Cost Plan*

Table 42: Flight Controller Budget Break Down

Part	Description	Quantity	Quantity Spare	Price	Total Price	Spare Price
Pixhawk Damper	Damper	1	0	$7.79	$7.79	$0.00
PixHawk		1	0	$238.00	$238.00	$0.00
PixHawk Power Module	Power Module V1.0	1	0	$6.99	$6.99	$0.00
Battery - Pixhawk	Zeee 5200mAh 7.4V 2S 50C Lipo Battery	1	1	$16.99	$16.99	$16.99
Battery - Ignition	3S 2200mAh LiPo Battery	1	1	$16.99	$16.99	$16.99
GPS Module	Here 2 GNSS	1	0	$95.00	$95.00	$0.00
PixHawk Cable Set	Cabling for PixHawk	1	0	$20.89	$20.89	$0.00
Transmitter/Receiver	RFD900+ Telemetry Bundle	1	0	$230.00	$230.00	$0.00
5V Regulator	5 V Regulator	2	0	$8.99	$17.98	$0.00
				Total	$650.63	$33.98

8.4.6. *Payload Cost Plan*

Table 43: Payload Budget Break Down

Part	Description	Quantity	Quantity Spare	Price	Total Price	Spare Price
Camera	GoPro Hero3+ Black	1	0	$89.99	$89.99	$0.00
Gimbal	Tarot T-2D Brushless Gimbal	1	0	$119.00	$119.00	$0.00
Transmitter	Eachine TS5823 Transmitter	1	0	$9.69	$9.69	$0.00
Gimbal Battery	Tenergy NiMH Battery Pack 12V 2000mAh	1	0	$21.99	$21.99	$0.00
Receiver	Eachine RC832 5.8G 40CH AV Receiver with Raceband	1	0	$16.66	$16.66	$0.00
Gimbal Mount	Custom	1	0	$0.00	$0.00	$0.00
Make Up Mass	Custom	1	0	$0.00	$0.00	$0.00
				Total	$257.33	$0.00

8.4.7. *Operations Support Cost Plan*

Table 44: Operations Support Budget Break Down

Part	Description	Quantity	Quantity Spare	Price	Total Price	Spare Price
Servo Programmer	Servo Programmer	1	0	$16.99	$16.99	$0.00
Fuel Can	Fuel Can	1	0		$0.00	$0.00
Fuel	Fuel (Gallon)	5	0		$0.00	$0.00
Oil	2-Stroke Oil 25:1	8	0	$9.00	$72.00	$0.00
End Mill		1	0	$12.40	$12.40	$0.00
RCA to HDMI Adapter	Ground Station	1	0	$14.89	$14.89	$0.00
Shaft Coupling	Dyno Test Stand	1	0	$4.03	$4.03	$0.00
Key Stock	Dyno Test Stand	1	0	$4.14	$4.14	$0.00
M5 Hex Bolts	Dyno Test Stand	1	0	$4.81	$4.81	$0.00
Adhesive Gun		1	0	$11.01	$11.01	$0.00
Adhesive Nozzle		1	0	$12.72	$12.72	$0.00
Flanged Bearings		1	3	$3.00	$3.00	$9.00
Plastic Main Rotor Holder		2	1	$6.99	$13.98	$6.99
				Total	$162.14	$0.00

8.4.8. *Spare Parts Cost Plan*

Table 45: Spare Parts Budget Break Down

System	Price
Rotorhead	$416.95
Chassis	$27.10
Drivetrain	$128.17
Powerplant	$51.23
Flight Controller	$33.98
Payload	$0.00
Operations Support	$15.99
Total	$673.42

8.5. Test Plan

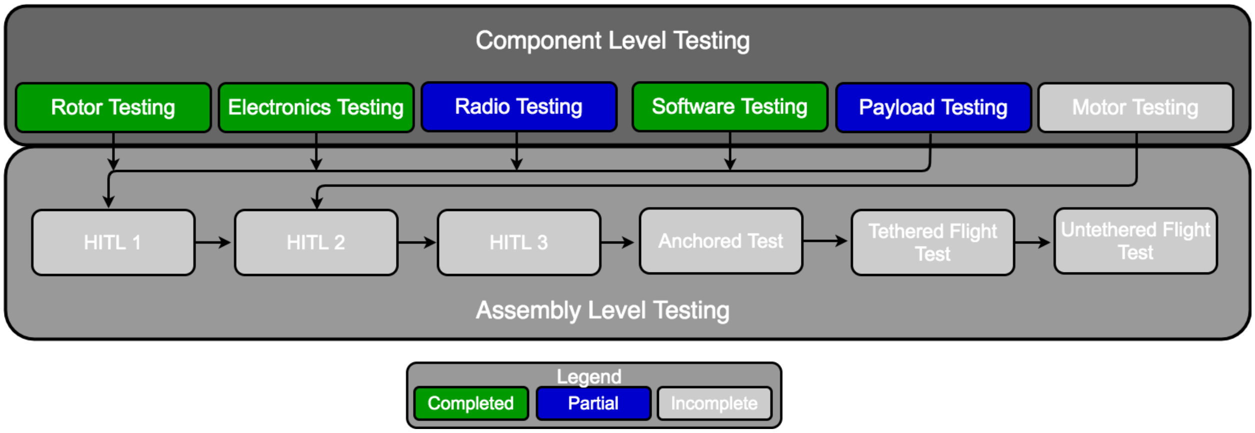

Figure 62: Test Plan

Figure 62 shows an over arching flow of the testing plan for the EMU project. The testing flow can be broken down into two major categories; component testing and assembly testing. Component level testing is testing on a component/subsystem pre-integration, and assembly level testing is testing with integrated components. Testing was planned to flow where all tests, besides motor testing, was to be completed before Hardware in the Loop test 1 (HITL 1), to verify and validate component/subsystem metrics that are independent of other components of the UAS. To move into HITL 2 testing and continue through the testing flow, motor testing needed to be completed. It's worth noting that each test box represent multiple test that were/to be conducted. For example, motor testing encompasses motor hp testing and motor endurance testing. The test flow was designed to allow for the most logical validation of design requirements, ensure safe operations, and prove flight worthiness. Scheduling of these tests can be seen in the work plan section, with details about each test being outlined in more detail above. A breakdown of each over arching test can be seen below.

Component Level Testing

- **Rotor Testing**: Which includes testing the propellers to validate rotor lift model and confirm rotor sizing.
- **Electronics Testing**: Which includes battery testing to validate battery selection.
- **Radio Testing**: Which includes radio range testings to validate transmission range.
- **Software Testing**: Which includes software in the loop to validate the control laws.
- **Payload Testing**: Which includes gimbal testing, video transmission testing, and video range transmission testing to validate the payload.
- **Motor Testing**: Which includes motor hp and motor endurance testing to validate motor metrics and power consumption.

Assembly Level Testing

- **HITL 1**: Testing with all components besides the motor and main drive belt integrated to test all hardware functionality.
- **HITL 2**: Testing with all components besides the main drive belt integrated, but with the motor running to test all hardware functionality and check the motor vibrations don't saturate the flight controllers IMU's.
- **HITL 3**: Testing with all components besides integrated to test all hardware functionality and check the system operates as intended.
- **Anchored Test**: Performing small hop test's to check thrust capabilities, demonstrate quadcopter control and check system functionality.

- **Tethered Flight Test**: Incrementally perform more autonomous flight operations while remaining tethered to validate all system operations.
- **Untethered Flight Test**: Test system functionality and verify full system functionality while UAS is allowed free to roam.

9. Lessons Learned

Michael Flores, Dakota Labine

Lessons learned presented here will outline important advice to early engineers or major aspects of the EMU team's experience that would have proved beneficial had they been implemented or understood at the beginning of the project. These will represent real issues faced and addressed throughout this project but will be described broadly in order to be applicable to future and different projects.

1. **Overall Project**
   - **Requirement Derivation**: The most important phase of the project is deriving design requirements that are clear and precise. This will drive the design process and should clearly constrain the engineering work to what is necessary and agreed upon. A good practice is an internal System Requirements Review (SRR) to ensure that all system level requirements accurately capture the functional objectives of the system. The team should also review all derived requirements to make sure they are well written.
   - **Centralized Model/Database of Information**: Centralized model that allows access to the most current design and metrics should be implemented. Setting the precedent of using this model and updating it minimizes wasted time designing components for an outdated system and removes model owner dependencies.
   - **Clear Definition of Mission Profile**: Clearly defining a mission profile will help with the development of requirements and avoid scope creep. It also will define the ideal mission operation and performance even when system capabilities allow for the mission to develop differently.
   - **TIMs/Technical Checkups**: Technical Interchange Meetings (TIMs) and technical checkups are useful in order to update the team on system developments. These should be held often and after big milestones in order to keep everyone on the same page. They should focus on specific technical parameters and should include all changes or aspects of the current design. Doing this will minimize the lack of misinformation between subsystems.
   - **Organize Trade Studies by Impact**: Often trade studies will yield a solution that will flow down and affect the design options that are used in other trade studies. An example for the EMU team was the rotor number trade affecting what options were used in the chassis configuration trade. In this case, develop the trades with a larger impact first and then follow up with trades that have options affected by the larger study.
   - **System Functional Flow Block Diagram**: Development of this diagram early on is crucial to defining the essential functions the system will perform and how those will interact. A good FFBD won't present any design solutions and will express how systems will interact to perform overall function and how the system will behave. Doing this will specify what functions are necessary and will make it easier to define which subsystems will be performing those functions to avoid confusion and duplicate design work.
   - **Challenge Everything**: It's beneficial to the project to challenge all aspects in an appropriate and efficient manner. Challenging design decisions, problem solutions, and procedures will help solidify answers and bring to surface potential future problems. Doing so should be done before finalizing a design solution at a minimum. Good decisions and solutions will be easily defended and mitigate any concern.
2. **Team Dynamic**
   - **Task Adaptability**: When one design engineer becomes a choke point for the design work of the system due to an overload of tasks, it becomes the responsibility of that design engineer to make this issue known and relinquish tasks. Other design engineers must be available to volunteer efforts or be tasked by the project manager to help with the design. In small teams such as the EMU team, this is critical to project workflow.

- **Consistent Engineering Understanding**: A pitfall encountered came from engineers not understanding the big picture approach to the design. It is important to very explicitly state how the design will proceed and confirm that all of the engineers understand this. One engineer not understanding the approach can cascade into wasted design efforts and confusion between subsystems. Clearly lay these out and make them accessible for all engineers to see. While each individual is assigned a certain role, everyone should act as a system engineer for the entire project.
- **Project Commitments**: Each team members personal commitment to the project varies. Learning to assign tasks accordingly can help prevent project delays and keep the project moving. It's recommend to understand each persons schedule and commitment to the project to help build out a plan that is realistic to the team. Design engineers must also present honest commitments to be scheduled for.

3. **Project Management**

- **Project Benefit Vs. Team Benefit**: The needs for the team and the needs for the project don't always match. Being able to react to the changing need of both the project and the team. Doing so will help set expectation accordingly to help with project flow.
- **Code of Conduct**: Developing a code of conduct that outlines the expectations of everyone on the team will help manage the team member's accountability. The code of conduct should reflect the expectation on meeting attendance, task due dates, professionalism, and general respect for each-other and faculty members. Ensure that the code of conduct reflects repercussions for breaking the code of conduct. It's recommend to do this in a strike system where each strike has increasingly more impacting repercussions.
- **Time Commitment**: The average weekly time commitment of each team member averaged sixteen hours a week, which was less than initially indicated by the team. It is beneficial to the project to set expectation based on this average weekly commitment. Using this information the project critical path can be projected out and true expectations can be set for the project.
- **Quad Chart Update**: The project manager and systems engineer should collect and track weekly quad chart style updates. The quad chart should have sections: top 5 accomplishments for the current week, top 5 challenges for the current week, top goals 5 goals for the following week, and top 5 issues or concerns for the following week. Tracking these items help with tasking and predicting future problems.
- **Anonymous Communication Platform**: As a project manager, a system should be in place where team members may anonymously state their opinion about manners related to the project. Some members of the team may find it best to speak out about the project privately. Allowing them to do so can bring light to major issues that are being over looked.
- **Develop Communication Channels**: Creating messaging/meeting rooms for individuals to discuss and share the evolution of the design is important. This allows for smaller, quicker conversations to occur with out the whole team and for any updates to be shared across the project. Set the precedent early that these channels must be used.
- **Automate Where Applicable**: Use resources such as Google Calendar, Slackbot, auto email, and any other self notification systems to inform team of deadlines and deliverables. The more the project manager can automate mundane tasks like the ones mentioned previously, the less likely deadlines will be over looked, and the more free time the PM can dedicated to other aspects of the project.

4. **Systems Engineering**

- **Perform Skill Assessments**: Skill assessments of the system design and the team are an important step to be conducted by the systems engineer, manufacturing engineer, or production engineer. Skill assessments will result in consultations determining what kind of skills the team must have in order to complete design/manufacturing tasks. Performing an audit of available skills of the team members will determine the teams capacity to complete the tasks necessary. Improving team skills to shrink this gap as early as possible is crucial to minimizing skill based manufacturing delays.
- **Requirement Allocation**: Systems engineer must properly allocate requirements to appropriate subsystems to guide the design and ensure that the design engineers are aware of their responsibility regarding satisfying requirements.
- **Verification and Validation Tracking**: Each requirement will have an attached means of verification. It is crucial that the subsystem lead engineer, that the requirement is allocated to, becomes responsible for its

satisfaction and tracking. Keeping a constantly updated list to track requirement verification is necessary for project status and tasking.

- **Assigning Area Managers**: In projects similar to this, there was not an engineer specifically in charge of the payload as a subsystem and instead requirements and functions were delegated across multiple subsystem lead engineers. By assigning a manager to different areas, such as the payload, they are responsible for correct trajectory of the design in this area. Major tracking, integration, and direction will still be headed by the systems engineer but it provides an extra check that the area is progressing in the correct direction. Areas in this project that used or could've used this were the payload, landing gear, ground station hardware, and fuel.
- **Develop Design Schedules With Engineers**: The systems engineer or the project manager should set the design schedules for the program. When the schedules are designed, it is important to consult with the design engineers in order to agree upon the deadlines. Doing this will ensure that the design engineers agree to be held responsible for this deadline and will appropriately reach out regarding concerns. Should deadlines need to be negotiated, the systems engineer or project manager will have the ability to reassess with regards to the completion of tasks in other subsystems.

10. Individual Report Contributions

10.1. Alejandro Castillo

Design Work: Power Budget & Battery Selection, Electronics Diagram, Electronic Component Selection, Electronics Mount
Report Work: Flight Controller Conceptual Design, Electronics Detailed Design, Proofreading/Editing

10.2. Dakota Labine

Design Work: Initial camera and gimbal research, clutch research/design/analysis, driveshaft pulley analysis/selection, manual labor, scheduling, integration, landing gear design, bill of material tracking, purchasing, part procurement, budgeting, over arching design, mass budgeting, team management.
Report Work: Project Purpose, Project Planning, Project Objectives and Functional Requirements, Requirement Development, Integration, Power Plant Risks, Logistical Risks, Financial Risks.

10.3. Henry Moore

Design Work: Rotor simulation GUI, EMU dynamics simulation and preliminary control system, rotor blade selection, landing gear design and COTS selection
Report Work: Rotor blades conceptual design, detailed design, and risk assessment, EMU Dynamics Simulation section of controls detailed design, risk matrix enumeration and risk matrix creation

10.4. Libby Hasse

Design Work: rotorhead design concept and SolidWorks models, rotorhead analysis, rotorhead component selection, rotorhead test stand design and manufacturing
Report Work: rotorhead conceptual design, detailed design, and risk assessment

10.5. Matthew Lehmann

Design Work: Ground control station and software in the loop development, hardware selection for telemetry and command communication as well as hardware selection for audio and visual feed from UAS
Report Work: Conceptual design and detailed design report sections as well as risk assessment for the ground control station

10.6. Max Alger-Meyer

Design Work: Preliminary power and fuel analysis, engine sizing, engine selection and power plant component determination, research, clutch bell output support bracket design and modeling
Report Work: Powerplant Conceptual Design, Powerplant Detailed Design, Powerplant risk assesment, Proofreading/Editing

10.7. Michael Flores

Design Work: Requirements development, requirement allocation and tracking, verification tracking, fuel system design, landing gear bracket design, chassis adhesive selection, flight emergency checklists, system integration, rotor head analysis, purchase order requisition system development, fall semester design schedule, integration schedule.
Report Work: Project Purpose, Project Objectives and Functional Requirements, Requirements Development, Integration, Project Planning, Lessons Learned, Power Plant Risks, Logistical Risks, Financial Risks.

10.8. Mitchell Spencer

Design Work: Control law development and testing, GCS research and software implementation, SITL simulation and verification, GitHub management and revision control, MATLAB gain determination analysis
Report Work: Flight Controller Conceptual Design, Control Law Detailed Design

10.9. Nathan Castile

Design Work: Rotor thrust test procedure/test stand assembly/running test, power plant test procedure and DYNOmite modifications and assembly, electronics and software test plans, hardware integration test plans, full-scale flight test plans/procedure, flight safety checklist, FAA safety research, campus safety research.
Report Work: All of section 6 (V and V), formatting and editing document

10.10. Nathan Hetzel

Design Work: Drivetrain configuration selection, Drivetrain SolidWorks modeling, Drivetrain component selection, Drive shaft analyses such as critical speed and fatigue, Rotor guard safety research, Machine shop assistance with CNC machining and component sanding
Report Work: Drivetrain Design Process and Outcome, Drive Shaft Selection, Engine Engagement write up, Drivetrain Risk Mitigation, Drivetrain appendix, PFR edits including proofreading and section continuity for entire document

10.11. Shawna McGuire

Design Work: Assistance with Chassis design including: conceptual designs, models, SolidWorks, SolidWorks simulations. Drivetrain assistance with SolidWorks model and component selection. Manufacturing schedule for next semester as well as SolidCAM files.
Report Work: Manufacturing, Proof Reading: Project Purpose, Conceptual Design

10.12. Rebecca Rivera

Design Work: Chassis design, chassis SolidWorks model, chassis SolidWorks simulations, 3D printing for landing gear, manufacturing
Report Work: Chassis Design Process and Outcome, Chassis Risks, Chassis Appendix, Formatting, Editing

References

[1] Achtelik, Michael. Doth, Klaus-Michael. Gurdan, Daniel. Stumpf, Jan. "Design of Multi Rotor MAV with regard to Efficiency, Dynamics and Redundancy" Ascending Technologies GmbH. 13-16 August 2012. from

[2] Borenstein, Steve. "IRISS MultiRotor", University of Colorado–Boulder, Retrieved August 29, 2019, from https://canvas.colorado.edu/

[3] "Clutch: 9 Different Types of Clutches: How They Works [Automobile Engg]." The Engineers Post, 2 Sept. 2019, www.theengineerspost.com/9-different-types-of-clutches/.

[4] Cutler, M., Ure, N.-K., Michini, B., and How, J., "Comparison of Fixed and Variable Pitch Actuators for Agile Quadrotors," AIAA Guidance, Navigation, and Control Conference, 2011.

[5] Dimitriadis, Theys. Hendrick, P. De Schutter, J. "Influence of propeller configuration on propulsion efficiency of multi-rotor Unmanned Aerial Vehicle." KU Leuven. June 7-10, 2016.

[6] Explained, Engineering. "Centrifugal Clutch - Explained." YouTube, Engineering Explained, 15 Apr. 2015, www.youtube.com/watch?v=D9d4qXreb8Q.

[7] Frank, Greg. "Project Definition Document - SPECS", University of Colorado–Boulder, Retrieved September 9, 2019, from https://www.colorado.edu/aerospace/current-students/undergraduates/senior-design-projects

[8] Hinchliffe, Mark. "Chain versus Belt versus Shaft Drive." Motorbike Writer, 17 Oct. 2018, motorbikewriter.com/chain-versus-belt-shaft/.

[9] "Include ." Perl, Python, Ruby, PHP, C, C++, LUA, Tcl, Javascript and Java Comparison, 8 Mar. 2011, raid6.com.au/~onlyjob/posts/arena/.

[10] Jackson, Jelliffe. "Project Definition Document (PDD)", University of Colorado–Boulder, Retrieved August 29, 2019, from https://canvas.colorado.edu/

[11] Jefferson, Alex. "The Pros and Cons of Different Engine Types." Proctor Cars Magazine, 19 Mar. 2018, www.proctorcars.com/the-pros-and-cons-of-different-engine-types/.

[12] Kuantama, E., Craciun, D., Tarca, I., and Tarca, R., "Quadcopter Propeller Design and Performance," *New Advances in Mechanisms, Mechanical Transmissions and Robotics*, Proceedings of The Joint International Conference of the XII International Conference on Mechanisms and Mechanical Transmissions (MTM) and the XXIII International Conference on Robotics (Robotics '16), Springer International Publishing.

[13] McCloud, Peter. "Goliath - A Gas Powered Quadcopter." Hackaday.io, hackaday.io/project/1230-goliath-a-gas-powered-quadcopter.

[14] McKay, M.E., Niemiec, R., and Gandhi, F., "Performance Comparison of Quadcopters with Variable-RPM and Variable-Pitch Rotors," Journal of the American Helicopter Society, 2018.

[15] McKelvy, Aubrey. "Project Definition Document - RAPTR", University of Colorado–Boulder, Retrieved September 7, 2019, from https://www.colorado.edu/aerospace/current-students/undergraduates/senior-design-projects

[16] Media, Donut. "TORQUE CONVERTERS — How They Work." YouTube, Donut Media, 4 July 2018, www.youtube.com/watch?v=PI2RPGcKdPA.

[17] Mejia, Marcos. "Project Definition Document - HERMES", University of Colorado–Boulder, Retrieved September 7, 2019, from https://www.colorado.edu/aerospace/current-students/undergraduates/senior-design-projects

[18] "MN701-S KV135 -2PCS/SET." T-Motor, Retrieved September 24, 2019, from http://store-en.tmotor.com/goods.php?id=459

[19] Tao, Pang. "DESIGN, PROTOTYPING AND AUTONOMOUS CONTROL OF GASOLINE-ENGINE VARIABLE-PITCH QUADCOPTER." National University of Singapore. 2016.

[20] Udris, Aleks. “How Does A Radial Engine Work?” Online Flight Training Courses and CFI Tools, 2015, www.boldmethod.com/learn-to-fly/aircraft-systems/radial-engine/.

[21] Kuantama, E., Craciun, D., Tarca, I., and Tarca, R., ”Quadcopter Propeller Design and Performance,” *New Advances in Mechanisms, Mechanical Transmissions and Robotics*, Proceedings of The Joint International Conference of the XII International Conference on Mechanisms and Mechanical Transmissions (MTM) and the XXIII International Conference on Robotics (Robotics ’16), Springer International Publishing.

[22] McKay, M.E., Niemiec, R., and Gandhi, F., ”Performance Comparison of Quadcopters with Variable-RPM and Variable-Pitch Rotors,” Journal of the American Helicopter Society, 2018.

[23] Cutler, M., Ure, N.-K., Michini, B., and How, J., “Comparison of Fixed and Variable Pitch Actuators for Agile Quadrotors,” AIAA Guidance, Navigation, and Control Conference, 2011.

[24] Leishman, J. G., Principles of helicopter aerodynamics, Cambridge: Cambridge University Press, 2006.

[25] XFOIL - Subsonic Airfoil Development System Available: http://web.mit.edu/drela/Public/web/xfoil/.

[26] Knight, M., and Hefner, R. A., Static Thrust Analysis of the Lifting Airscrew, Washington D.C.: National Advisory Committee for Aeronautics, 1937.

[27] Gibiansky, Andrew. “Quadcopter Dynamics, Simulation, and Control”. http://andrew.gibiansky.com/downloads/pdf/Quadcopter%20Dynamics,%20Simulation,%20and%20Control.pdf

[28] U.S. Department of Energy. “Replace V-Belts with Notched or Synchronous Belt Drives.”. U.S. Department of Energy - Energy Tips: MOTOR SYSTEMS, 2012, www.energy.gov/sites/prod/files/2014/04/f15/replace_vbelts_motor_systemts5.pdf.

[29] Selby, Darin, et al. “Darin Selby.” x-engineering, x-engineer.org/automotive-engineering/drivetrain/transmissions/drivetrain-losses-efficiency/.

[30] BESTORQ, “Belt Theory.” BESTORQ, www.bestorq.com/Library/TechInfo/techinfo/theory.pdf.

[31] U.S. Department of Defence, ”Military Handbook-5: Metallic Materials and Elements for Aerospace Vehicle Structures”. Defense Technical Information Center, 1997.

[32] Budynas, Richard G., et al. ”Shigley’s Mechanical Engineering Design”. Vol. 9, McGraw-Hill Education, 2011.

[33] Schroeder, R., Jonathan, ”Demystifying the 2:1 Ratio and the Stick-Slip Phenomenon”, PCB Linear, 2019. https://pages.pbclinear.com/rs/909-BFY-775/images/White-Paper-Demystifying-the-2-1-Ratio-and-Stick-Slip-Phenomenon.pdf

[34] Donovan, Rachel, Fortune, Rose, and Trout, Robert, ”Elevated Temperature Effects on the Mechanical Properties of Age Hardened 6xxx Series Aluminum Alloy Extrusions”, California State University, San Luis Obispo, 2015. https://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1132&context=matesp

[35] “Mechanical Properties of Carbon Fibre Composite Materials, Fibre / Epoxy Resin (120°C Cure).” Mechanical Properties of Carbon Fibre Composite Materials, www.performance-composites.com/carbonfibre/mechanicalproperties_2.asp.

[36] 3M Scotch-Weld Multi-Material and Composite Urethane Adhesives DP6310NS and DP6330NS . Dec. 2018, multimedia.3m.com/mws/media/1279477O/3m-scotch-weld-dp6310ns-and-dp6330ns-technical-data-sheet.pdf.

[37] “Tube - Hex - Fabric - 0.75 x 0.85 (+Length Options).” Rock West Composites, www.rockwestcomposites.com/shaped-tubing/hexagonal-tubing/carbon-fiber/tube-hex-0-75-x-0-86-options.

[38] “Quasi-Isotropic Solid Carbon Fiber Sheet 2.5mm x 24’ x 48.’” DragonPlate, dragonplate.com/Quasi-isotropic-Solid-Carbon-Fiber-Sheet-25mm-x-24-x-48.

[39] ”Torsion Spring, 90 Degree Left-Hand Wound.” Mcmaster Carr, https://www.mcmaster.com/9271k598

Appendix A: Simulation Results

Rotor Blades

Henry Moore

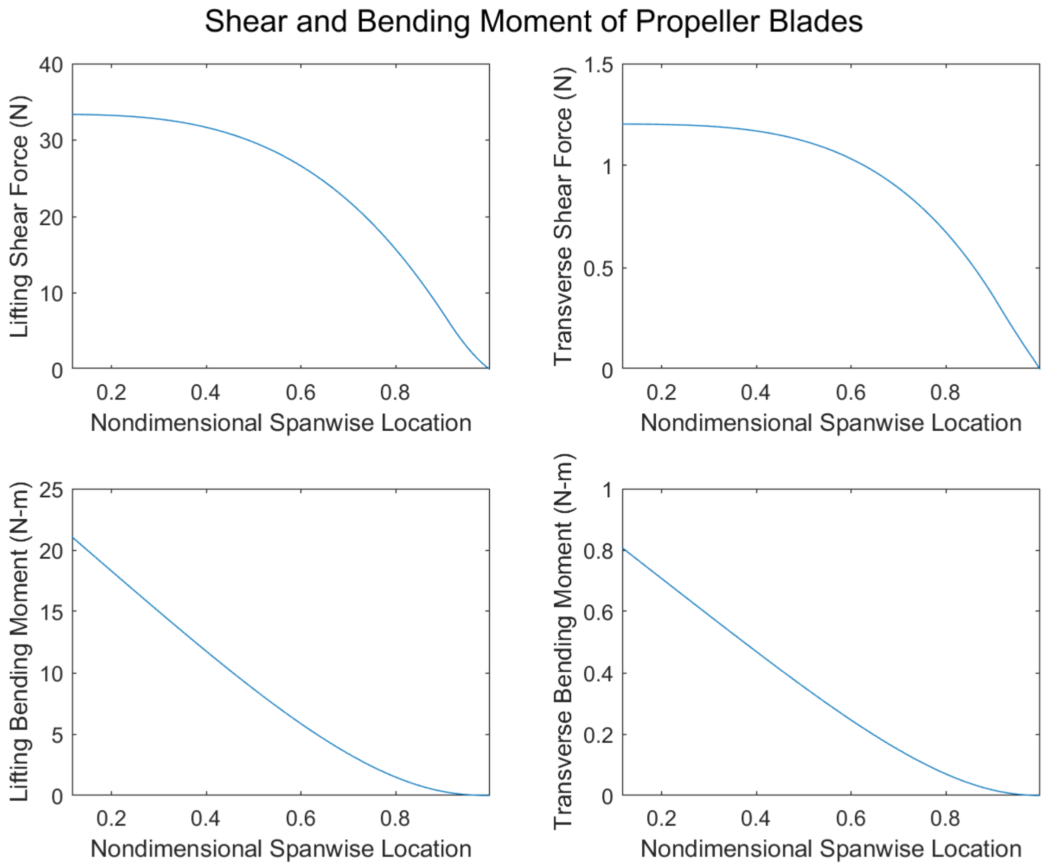

Figure 63: Blade Structural Analysis

Chassis

Rebecca Rivera

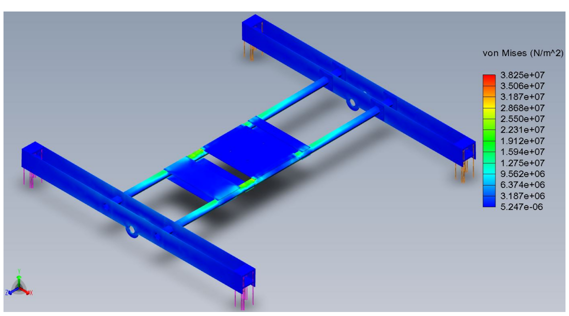

Figure 64: Roll Simulation Isometric View

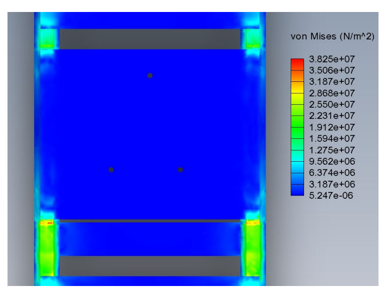

Figure 65: Roll Simulation Zoomed View

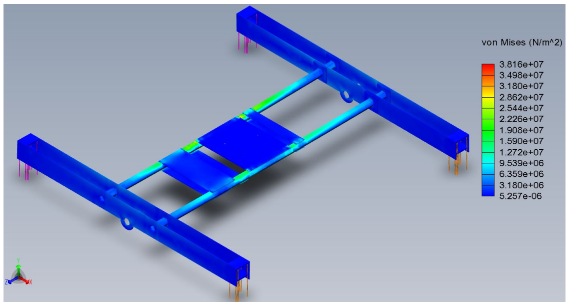

Figure 66: Pitch Simulation Isometric View

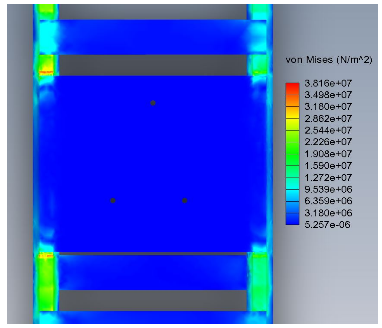

Figure 67: Pitch Simulation Zoomed View

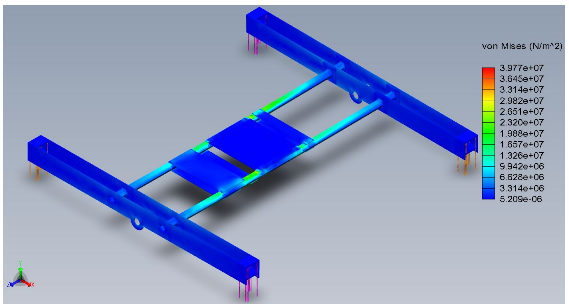

Figure 68: Yaw Simulation Isometric View

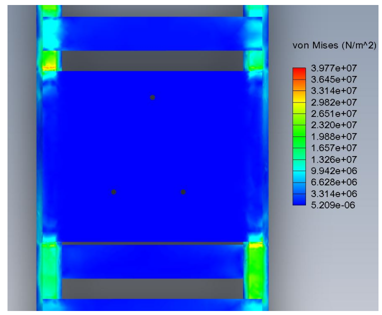

Figure 69: Yaw Simulation Zoomed View

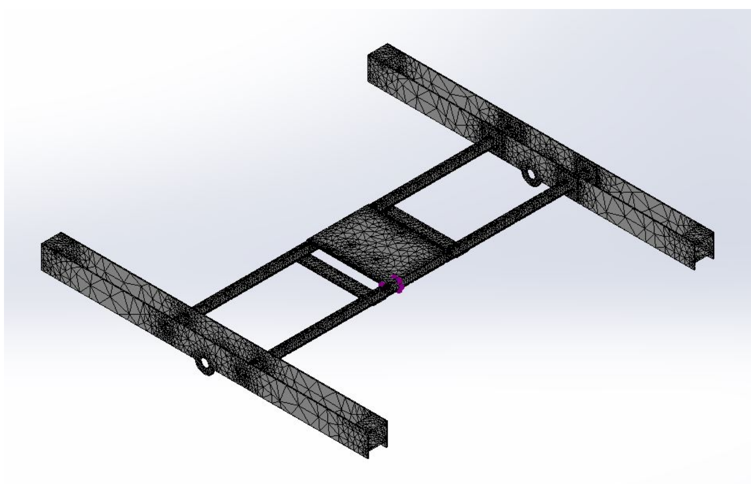

Figure 70: Mesh Used in SolidWorks Simulations

Appendix B: Trade Studies

Rotor Blades

Henry Moore

Table 46: Pros and Cons of Variable Speed Propellers

Description	Pro	Con
Relatively simple control system possible	x	
Rotors can be optimized for hover	x	
Rotors can be optimized for relatively low rotation rate	x	
Requires electric power, alternator, and ESCs instead of mechanical power transmission		x
Prohibitively expensive		x

Table 47: Pros and Cons of Variable Pitch Propellers

Description	Pro	Con
Greatly increased thrust rate of change and control response	x	
Direct mechanical power transmission from engine possible	x	
Autorotation possible	x	
Off-the-shelf rotors not able to be optimized for hover		x
Requires complex drive train		x
Thrust requires careful characterization		x

Table 48: Pros and Cons of Variable Speed, Variable Pitch Propellers

Description	Pro	Con
Extremely optimal performance both maneuvering and hovering	x	
Extremely high control authority	x	
Extremely high cost		x
Extremely high mass		x
Prohibitively difficult and complex drivetrain required		x
Little usage outside technical demonstrations		x

Table 49: Propeller Blade Selection Weighting

Criteria	Weight (%)	Driving Requirement(s)	Rationale
Hover Efficiency	35	FR 1, DR 1.2	The propeller's hover efficiency is extremely important with regards to achieving our mission endurance goal.
Cost	22	FR 7	Lower cost allows greater spending in other subsystems.
Drivetrain Simplicity	25	FR 6	Greater drivetrain simplicity means a lower chance of failure
Mass	15	FR 7	Lower mass allows greater mass budget for other subsystems.
Maneuver Efficiency	9	DR 1.2.1	The maneuver efficiency of each propeller ensures that the UAS can support the two hour mission.
Control Capability	7	FR 1, DR 1.2, DR 1.2.2	Control capability is required to maintain flight within the bounding hover box.
Total	100		

Propeller Criteria Standards					
Criteria	**1**	**2**	**3**	**4**	**5**
Mass	Extremely high mass	High mass	Average mass	Low mass	Extremely low mass
Hover Efficiency	Extremely inefficient hovering	Inefficient hovering	Average hovering efficiency	Efficient hovering	Extremely efficient hovering
Maneuver Efficiency	Extremely inefficient maneuvering	Inefficient maneuvering	Average maneuver efficiency	Efficient maneuvering	Extremely efficient maneuvering
Drivetrain Simplicity	Required drivetrain is extremely complex	Required drivetrain is complex	Required drivetrain is of average complexity	Required drivetrain is simple	Required drivetrain is very simple
Control Capability	Extremely low control authority and response	Low control authority and response	Moderate control authority and response	High control authority and response	Extremely high control authority and response
Cost	Extremely high cost	High cost	Average cost	Low Cost	Extremely low cost

Table 50: Scale Assessment of Propeller Type

Criteria	**Weight (%)**	**Options**		
		Variable Speed	**Variable Pitch**	**Variable Speed and Pitch**
Hover Efficiency	35	5	3	5
Cost	22	2	4	1
Drivetrain Simplicity	15	3	4	1
Mass	12	3	4	2
Maneuver Efficiency	9	4	4	5
Control Capability	7	3	4	5
Total	**100**	**3.57**	**3.65**	**3.16**

Table 51: Trade Matrix for Propeller Type

Chassis

Rebecca Rivera

Table 52: Pros and Cons of Pusher Configuration

Description	**Pro**	**Con**
Increased efficiency by 3%	x	
Limits propeller surface area		x
Limits camera field of view		x
Downwash affects camera stability		x
Increased complexity in chassis design		x

Table 53: Pros and Cons of Puller Configuration

Description	Pro	Con
Decreased efficiency by 3		**x**
No restriction on propeller surface area	**x**	
No restriction camera field of view	**x**	
No wash to affect camera stability	**x**	
Simple chassis design	**x**	

Table 54: Rotor Configuration Weighting

Criteria	Weight (%)	Driving Requirement(s)	Rationale
Propeller Surface Area	35	FR 1, DR 1.2.2	In order to produce the maximum power output, the configuration needs to allow for the largest propeller surface area.
Manufacturing Complexity	25	DR 1.4, FR 5, FR 7, DR 7.2	The rotor configuration must allow for the simplest assembly possible to decrease weight. The rotor configuration should cause minimal complexity when assembling landing gear and the payload attachments
Payload Interference	25	FR 5	The mission of the UAS relies on the performance of the payload camera. The rotor assembly must avoid interfering with the camera mission as best as possible
Efficiency	15	DR 1.2.1	The overall efficiency of each configuration should be accounted for to ensure that the UAS can support the two hour mission.
Total	100		

Table 55: Scale Assessment of Pusher vs. Puller Configuration

Rotor Configuration Criteria Standards					
Criteria	**1**	**2**	**3**	**4**	**5**
Propeller Surface Area	N/A	N/A	Configuration restricts the allowable size of propeller surface area.	N/A	Configuration allows for maximum size of propeller surface area
Manufacturing Complexity	N/A	N/A	Configuration will require a more complex landing assembly	N/A	Configuration does not interfere with landing assembly
Payload Interference	N/A	Configuration will cause downwash over the payload. Payload will also need to be configured to avoid propellers.	N/A	Configuration will cause minimal downwash on payload. Payload configuration will not be affected by rotor configuration	N/A
Efficiency	N/A	N/A	Configuration results in a slightly lower efficiency.	N/A	Configuration allows for the highest possible efficiency.

Table 56: Pros and Cons of Quadcopter Configuration

Description	**Pro**	**Con**
Greatest efficiency due to greater propeller surface area	**x**	
Good stability to support stable hover conditions	**x**	
Simplest design	**x**	
Cannot safe a rotor failure		**x**
Decreased safety for flight testing		**x**

Table 57: Pros and Cons of Coaxial, Triangular, Six Rotor Configuration

Description	**Pro**	**Con**
Limited efficiency due to smaller propeller surface area		**x**
Difficult design integration with chassis		**x**
Good stability to support stable hover conditions	**x**	
Can save a rotor failure with limited thrust	**x**	
Increased safety for flight testing	**x**	

Table 58: Pros and Cons of Hexagonal Configuration

Description	Pro	Con
Limited efficiency due to smaller propeller surface area		x
Difficult design integration with chassis and drive train		x
Good stability to support stable hover conditions	x	
Can save a rotor failure with 73% thrust	x	
Increased safety for flight testing	x	

Table 59: Number of Rotors Weighting

Criteria	Weight (%)	Driving Requirement(s)	Rationale
Weight	25	DR 1.4	The overall TOW must be no more than 30 pounds. This significantly limits the weight that individual components can take up within the overall system. Increasing the weight of each part will also negatively affect the efficiency of the aircraft.
Efficiency	25	DR 1.2.1	In order to support a two hour mission, the UAS needs to maintain the highest efficiency. A combination of the propeller surface areas and the number of drive units will either positively or negatively influence the efficiency.
Manufacturing Complexity	15	DR 1.4, DR 7.4.1	The UAS can only be successful with the construction of each component and successful assembly of the system. The propellers need to receive power from the power plant through the drivetrain. The complexity of this assembly will increase with each rotor and will also increase the weight of the assembly.
Maneuverability	15	FR 1, DR 1.1, DR 1.2 DR 1.2.3, DR 1.3	The configuration needs to provide enough maneuverability to travel to an LOI and maintain steady, stable hover. The aircraft also needs to be able to adjust to changing wind conditions.
Cost	10	halp	The entire project has a budget of $5000 that will include not only the components of the final assembly, but all testing equipment and spare parts that support the final design. This restriction must be tracked and therefore design decisions must include cost analysis.
Safety	10	DR 1.3, FR 6, DR 6.1	The safe operation of the aircraft is paramount to a successful mission. Propellers are a large safety concern as they have the potential to cause serious harm. Safe landing must also occur in order to maintain the aircraft functionality and safety by not falling from the air.
Total	100		

Table 60: Scale Assessment of Rotor Configuration

Number of Rotors Criteria Standards					
Criteria	**1**	**2**	**3**	**4**	**5**
Weight	N/A	N/A	Adds a significant amount of additional material to the overall assembly.	Will require an increased amount of material in order to assemble.	Will limit the amount of additional material required in the assembly
Efficiency	N/A	N/A	Assembly has small propellers and multiple drive units.	Assembly has average sized propellers with multiple, complex drive units.	Assembly allows for large propellers and minimal drive units.
Manufacturing Complexity	Assembly has multiple drive units that will require complex components to support.	N/A	Assembly has multiple, simple drive units with difficult drivetrain access.	N/A	Assembly has limited, simple drive units with easy drive train access and simple drive units.
Maneuverability	N/A	Components will require difficult control laws due to the number of rotors.	Components will require complex control laws due to the complexity of the drive units.	N/A	Components will allow for intuitive control laws due to limited, simple drive units.
Cost	N/A	Large number of rotors will require more spending on additional propellers,drive units, and servos.	Rotors with complicated drive units and multiple propellers will require a large budget to afford multiple propellers and complex drive units.	N/A	Limited propellers with simple drive units will result in the lowest cost.
Safety	N/A	N/A	Largest propellers will have the highest probability of injury.Less than five propellers will result in a total failure in the case of a single-rotor failure.	Middle-range propellers will decrease the likelihood of injury. More propellers will increase survivability in a single-rotor failure.	Smaller propeller length will have the lowest probability of injury. Maximum number of propellers will have the highest survivability in a single-rotor failure.

Table 61: Pros and Cons of X-chassis

Description	**Pro**	**Con**
Little space for hardware		**x**
Good stability and control	**x**	
Higher drivetrain complexity due to lack of mounting space		**x**
More weight due to sandwiching and mounting structures		**x**

Table 62: Pros and Cons of H-chassis

Description	**Pro**	**Con**
Sufficient space for hardware	**x**	
Good stability and control	**x**	
Low drivetrain complexity	**x**	
Less weight due to simple design	**x**	

Table 63: Pros and Cons of XH-chassis

Description	**Pro**	**Con**
Sufficient space for hardware	**x**	
Good stability and control	**x**	
Higher complexity		**x**
More material due to sandwiching		**x**

Table 64: Chassis Shape Weighting

Criteria	**Weight (%)**	**Driving Requirement(s)**	**Rationale**
Mounting Space	30	FR 7, DR 7.3	The chassis must have sufficient space to hold all of the UAS components including the motor, fuel, flight controller, payload, mechanisms, etc.
Weight	20	DR 1.4	Weight must be minimized for two reasons: to fit the project requirement of 30 lbs TOW and to create a more efficient design. The goal is not to make the UAS weigh 30 lbs but to minimize weight as much as possible. More weight also brings the disadvantage of higher cost.
Mechanisms Complexity	20	DR 7.4, DR 7.4.1	The difficulty required for the power delivery system to the rotors will directly depend on the chassis shape. Therefore, a more simple design is desired to minimize mechanical setbacks.
Manufacturing Complexity	15	DR 1.4, FR 7	The chassis must be manufacturable with the team's available resources and not have too many parts to assemble because assembling more parts means more weight due to screws/nuts/washers.
Stability & Control	15	FR 1, FR 2	The UAS must be able to take off, travel, hover, and land autonomously making good stability and control are essential for a successful project.
Total	100		

Table 65: Scale Assessment of Chassis Shape

Chassis Criteria Standards					
Criteria	**1**	**2**	**3**	**4**	**5**
Mounting Space	Not enough space for all components	Components must be stacked to fit	Some components stacked to fit	No stacking but components clustered	Ample space for all components and mechanisms
Weight	Excessive material required	Borderline excessive material required	Unnecessary weight can be avoided at expense of other design choice	Acceptable weight	Minimal material required
Mechanisms Complexity	Very complicated	Complicated	Neither simple nor complicated	Simple	Very simple
Manufacturing Complexity	Comprised of only small parts to assemble	Many small parts to assemble	Limited small parts to assemble	Few small parts to assemble	No small parts to assemble
Stability & Control	Inherently unstable and difficult to control	Unstable and easier to control	Stable and difficult to control	Stable and moderate to control	Stable and easy to control

Drivetrain

Nathan Hetzel

Table 66: Clutch: Pros & Cons

Description	Pro	Con
Can run motor w/o spinning rotors	x	
Lightweight	x	
Different options of clutches	x	

Table 67: Direct Drive: Pros & Cons

Description	Pro	Con
Rotors spin right when engine starts		x
Lightweight	x	
Simple system	x	

Table 68: Torque Converter: Pros & Cons

Description	Pro	Con
Can run motor w/o spinning rotors	x	
Heavy		x
Complex system		x

Table 69: Alternator: Pros & Cons

Description	**Pro**	**Con**
Can run motor without spinning rotors	**x**	
Does not require clutch	**x**	
Heavier		**x**
Requires additional power conditioning		**x**
Expensive		**x**
Efficiency loss from mechanical to electric		**x**

Table 70: Driveshafts: Pros & Cons

Description	**Pros**	**Cons**
Requires low maintenance	**x**	
Remains clean while running	**x**	
Most expensive option		**x**
Heaviest option		**x**

Table 71: Belts: Pros & Cons

Description	**Pro**	**Con**
Requires low maintenance	**x**	
Cheapest option	**x**	
Remains clean while running	**x**	
Lightest option	**x**	

Table 72: Chains: Pros & Cons

Description	**Pro**	**Con**
Requires high maintenance		**x**
Cheap option	**x**	
Heavy weight		**x**
Shoots oil while operating		**x**

Table 73: Electric: Pros & Cons

Description	**Pro**	**Con**
Requires low maintenance	**x**	
Low mechanical complexity	**x**	
Physically smallest	**x**	
Requires electric motors (heavy, costly)		**x**
Efficiency loss from electrical to mechanical		**x**

Gimbal & Camera Configuration

Dakota Labine, Michael Flores

Criteria	Weight (%)	Rationale
Pointing Control	40	The camera and gimbal most be capable of point at a set locations by the user for the duration of the hover state, as well as be able to adjust point locations mid flight.Control of the camera plays the largest role in the selection process.
Video Stability	35	The camera most be capable of streaming clear video during its hovers state.The gimbal and camera must be capable of providing stable video to ensure video quality meets streaming requirements
System Complexity	15	The chosen gimbal and camera configuration should be rather simple, and easy to interface with. Gimbal controls must integrate with flight controller
Weight	10	The combined weight of gimbal and camera must below the payload weight of 5 lbs. Ensuring that the weight of the camera and gimbal is less than 5 lbs is crucial to the requirements
Total	100	

Table 74: Gimbal & Camera Weighting

Gimbal & Camera Configuration Criteria Standards					
Criteria	**1**	**2**	**3**	**4**	**5**
Pointing Control	Gimbal offers no pointing control	Gimbal offers one degree of point control	Gimbal offers two degrees of point control	Gimbal offers three degrees of point control	Gimbal offers three degree of point control and tracking capability
Video Stability	Configuration offers no stability	Configurations offers one principle axis of stability	Configurations offers two principle axis of stability	Configurations offers three principle axis of stability	Configurations offers three principle axis of stability and vibration stability
System Complexity	System uses a completely custom configuration or is not able to integrate with UAS	System uses a partially custom configuration, with some off the shelf components	System uses a mix between off the shelf and custom parts	System uses mostly all of the shelf components	System uses a completely off the shelf solution
Weight	Weighs above 3 lbs payload limit	Weighs under 2.5 lbs payload limit	Weighs under 2 lbs	Weighs under 1.5 lbs	Weighs under 1 lbs

Table 75: Scale Assessment of Gimbal & Camera Configuration

Power Plant

Max Alger-Meyer

Table 76: Single Piston Engine: Pros & Cons

Description	Pro	Con
Reliable Design	x	
Inexpensive	x	
Significant vibrations		x

Table 77: Dual Piston Engine: Pros & Cons

Description	**Pro**	**Con**
Reliable Design	**x**	
Inexpensive	**x**	
Semi-counteractive vibrations	**x**	

Table 78: Radial Engine: Pros & Cons

Description	**Pro**	**Con**
Reliable Design	**x**	
Cost efficient	**x**	
Moderate vibrations		**x**

Table 79: Turbine Engine: Pros & Cons

Description	**Pro**	**Con**
Low vibrations	**x**	
Shorter lifespan		**x**
Expensive		**x**

Table 80: Hybrid Electric Power Plant: Pros & Cons

Description	**Pro**	**Con**
Can run motor without spinning rotors	**x**	
Does not require clutch	**x**	
Heavier		**x**
Requires additional power conditioning		**x**
Expensive		**x**
Efficiency loss from mechanical to electric		**x**

Table 81: Integrated Clutch: Pros & Cons

Description	**Pro**	**Con**
Prevents Misalignment	**x**	
Affordable	**x**	
Mitigates Clutch Failure Risk	**x**	
Limits Engine Size		**x**
Limits Piston Configuration		**x**
Few Commercial Options Available		**x**

Table 82: Power Plant Weighting

Criteria	Weight (%)	Rationale
Efficiency	25	Efficiency is crucial in a fuel system. More efficient engines allow better use of the liquid fuel meaning the the UAS can fly for a longer duration.An engine with a higher efficiency will allow the UAS to decrease its fuel weight and operational cost. This dual effect means that the engine's efficiency is the largest weighted criteria in engine choice due to its larger effect on the UAS as a whole
Weight	20	The weight of the motor directly effects the overall system weight. Whereas engines are traditionally compared using a power to weight ratio, here we have decided to focus solely on weight as only motors with sufficient power will be considered.
Reliability & Maintainability	10	Due to the long duration component of the flights that will be performed, the UAS requires an engine that is reliable and can be used multiple times. Missions performed by the UAS can last up to two hours meaning that the system needs an engine that won't fail. The testing performed in developing the UAS will also add flight hours that they system must be able to handle in order to complete all the necessary testing. Since duration is a larger aspect of the mission, the reliability of the engine becomes a middle weighted criteria.
Cooling	15	Cooling the engine system ensure that it runs at optimal condition for the duration of the mission. Although important, additional cooling options can be implemented.
Vibrations & Balancing	10	Vibrations caused by the engine can effect the UAS dynamics and structural integrity. Even when important,vibration dampening can be added in many different ways to counter act this phenomena.
Cost	10	Cost is an important factor in order to create a replicable system that is within the provided budget. Engine cost will be a large portion of the budget but most engines fall within a fairly similar area. Though cost is a consideration, the idea behind a smaller weighting is to rule out any options that are out of budget while evenly weighting a range of engines that are within a reasonable price
Drive Train Integration	10	Ease of drive train integration is an important factor to take into consideration when analyzing which motor should be selected. Motors with built in clutches avoid potential problems of misalignment between the engine and the clutch, and breaking of the clutch bell.
Total	100	

Table 83: Scale Assessment of Power Plant

Power Plant Criteria Standards					
Criteria	**1**	**2**	**3**	**4**	**5**
Weight	Very low power per unit weight	Low power per unit weight	Typical power per unit weight	High power per unit weight	Very high power per unit weight
Cooling	Very high temp, active cooling required	High temp, potential need for active cooling	Moderate temperature	Air cooling effective	Low temp, no active cooling system required
Vibrations & Balance	Severe vibrations	Heavy vibrations, dampening required	Moderate vibrations, some dampening required	Mild vibrations, light dampening required	No vibrations, no dampening required
Efficiency	Very low efficiency	Low efficiency	Moderate efficiency	High efficiency	Very high efficiency
Reliability & Maintainability	Very hard to maintain/source replacement parts	Hard to maintain/source replacement parts	Neither easy nor hard to maintain/source replacement parts	Easy to maintain/source replacement parts	Very easy to maintain/source replacement parts
Cost	Very expensive (\$1500+)	Expensive (≤\$1500)	Fair pricing (≤\$1200)	Affordable (≤\$1000)	Very affordable (≤\$700)
Drivetrain Integration	Engine not designed to integrate with a clutch				Engine is designed to integrate with a clutch

Ground Station Software
Matthew Lehmann

Table 84: Pros and Cons of APM Planner 2.0

Description	Pro	Con
Open Source	x	
ArduPilot Compatible	x	
SITL and HITL Capabilities	x	
Black box of a GUI		x

Table 85: Pros and Cons of UgCS

Description	Pro	Con
Not open Source		x
ArduPilot Compatible	x	
SITL and HITL Capabilities	x	
Black box of a GUI		x

Table 86: Pros and Cons of a Custom GUI

Description	Pro	Con
Open Source	**x**	
Custom Autopilot		**x**
Learning Curve for Team		**x**
Control over GUI Design	**x**	

Table 87: Ground Station Software Weighting

Criteria	Weight (%)	Driving Requirement(s)	Rationale
Manual Control Delivery	25	DR 3.2.4, DR 3.3	The software must be able to send individual commands to the UAS manually prior to any autonomous flight for safety and functionality verification
Autopilot	25	DR 3.2.1, DR 3.2.2	The software must have the ability to autonomously monitor and control the UAS during its flight to avoid any crashing or unstable behavior
Cross-platform Capability	15	FR 3	The software should be transferable between computers so that the customer has the ability to operate the UAS once the project finishes. Otherwise the legacy of the project beyond the EMU team is nonexistent.
GUI Development Resources	15	FR 3, FR 5	The GUI resources available for each option should be considered to ensure that the skill set of the team does not inhibit the production of the ground control software in any way
Development Time	10	FR 3, FR 5	The development time for the software has to be taken into account when it comes to generating the GUI since the mechanical aspects of the UAS are where the team expects to focus most of its time
Cost	10	FR 3, FR 5	The cost of the software should still be considered to ensure that the team can focus available funds on mechanical pieces that are at risk of breaking during the testing phase
Total	100		

Table 88: Scale Assessment of Ground Station Software

Ground Station Software Criteria Standards					
Criteria	**1**	**2**	**3**	**4**	**5**
Manual Control Delivery	N/A	N/A	Programmatically capable of sending interpretable commands to on-board flight controller	N/A	Capable of sending built-in flight controller commands to on-board controller without any user signal programming
Autopilot	Steep learning curve to implement and no team experience in programming such a thing	Steep learning curve, a few team members with experience in programming and flight mission planning	Mild learning curve, a few team members with experience in programming and development	Built-in mission planning but still requires learning on behalf of the team to fully and properly implement	Completely built-in autopilot with minimal required inputs or design changes from the team
Cross-platform Capability	Not possible without paying for IDE on both machines	N/A	N/A	N/A	Simple to transfer freely between machines
GUI Development Resources	Minimal resources for GUI development available	N/A	GUI development resources available and requires minimal programming skills	N/A	No GUI development required
Development Time	Requires extensive training time and potential to detract heavily from mechanical assembly of UAS	N/A	Requires a noticeable amount of training depending on team experience and detracts from time being spent on mechanisms	Requires minimal training and detracts noticeably from mechanical assembly of UAS	Requires no training and fails to detract from mechanical assembly of UAS at all
Cost	\$1000+	\$500+	\$250+	\$100+	Free

Appendix C: Design Details

Rotor Blades

Henry Moore

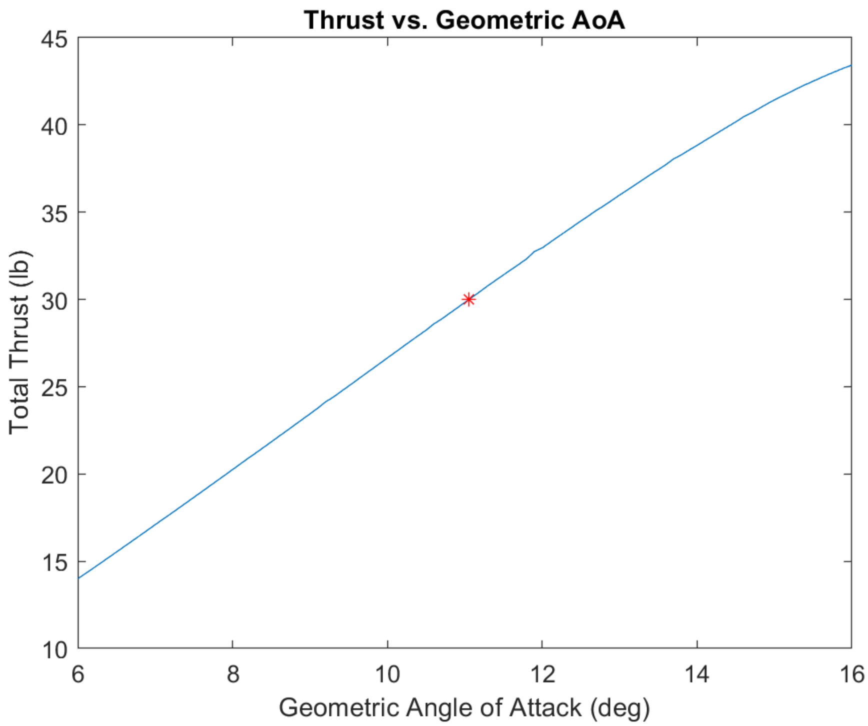

Figure 71: Total Thrust vs. Angle of Attack

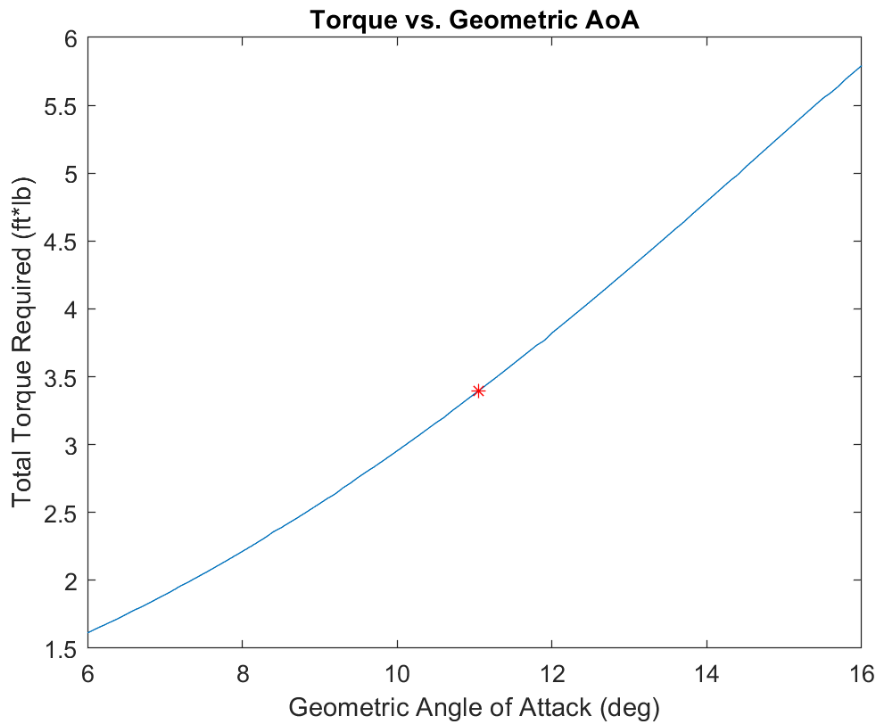

Figure 72: Total Required Torque vs. Angle of Attack

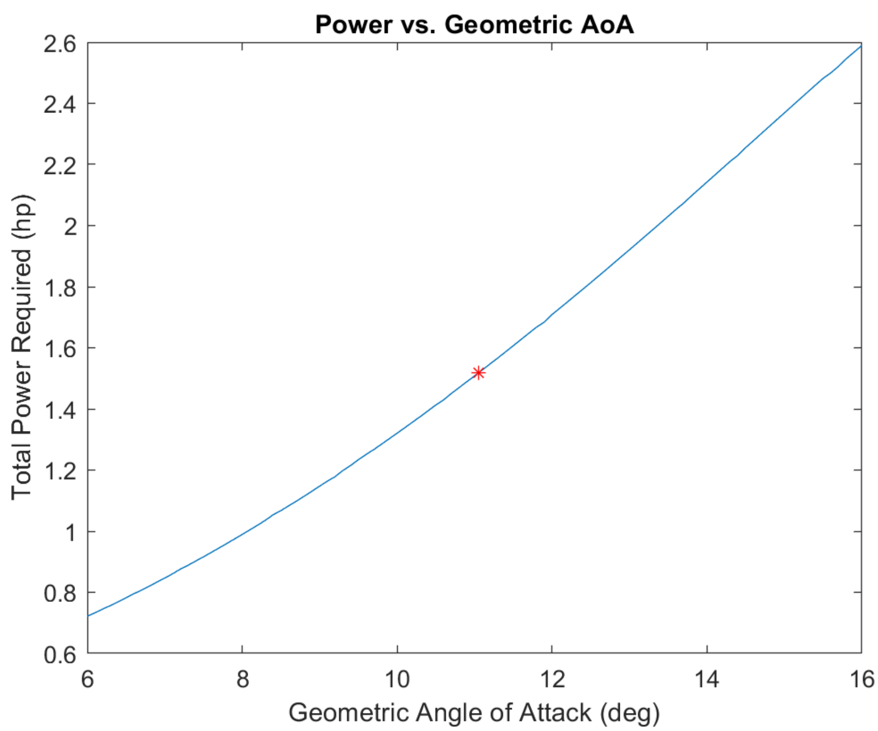

Figure 73: Total Required Power vs. Angle of Attack

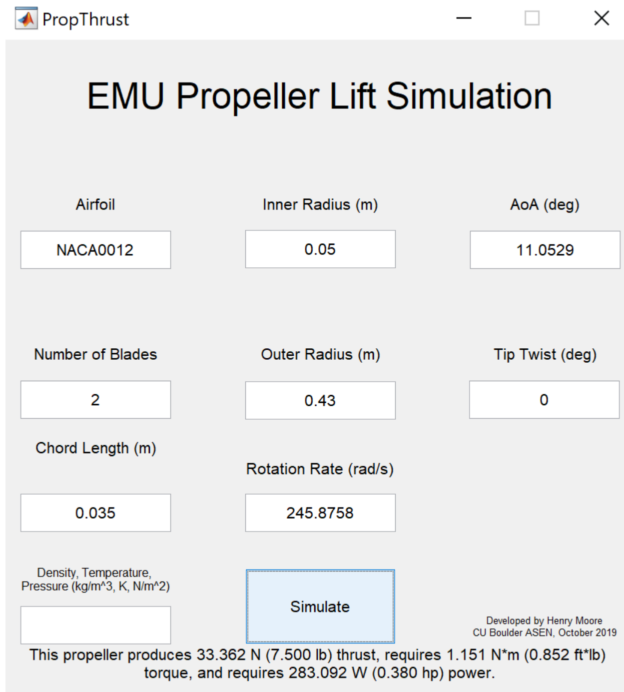

Figure 74: Propeller Simulation GUI

Chassis

Rebecca Rivera

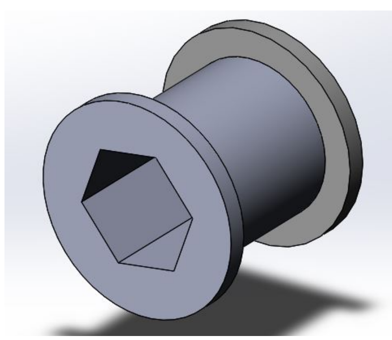

Figure 75: Landing Gear Inner Rotation Surface

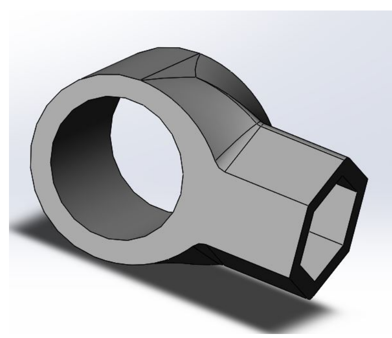

Figure 76: Landing Gear Outer Rotation Sleeve

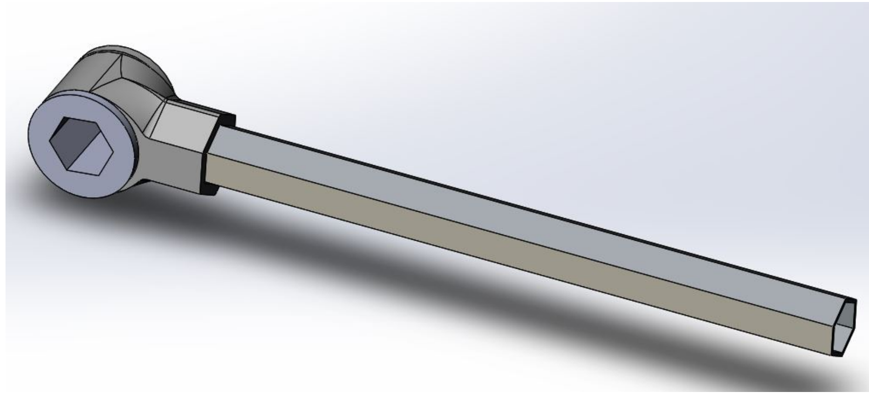

Figure 77: Landing Leg Assembly

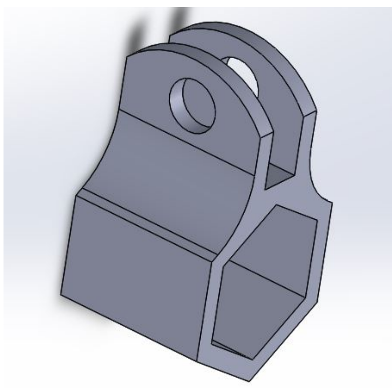

Figure 78: Landing Gear Lower Shock Mount

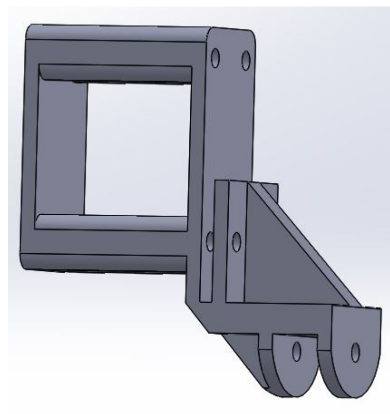

Figure 79: Landing Gear Upper Shock Mount

Figure 80: Landing Gear Shocks