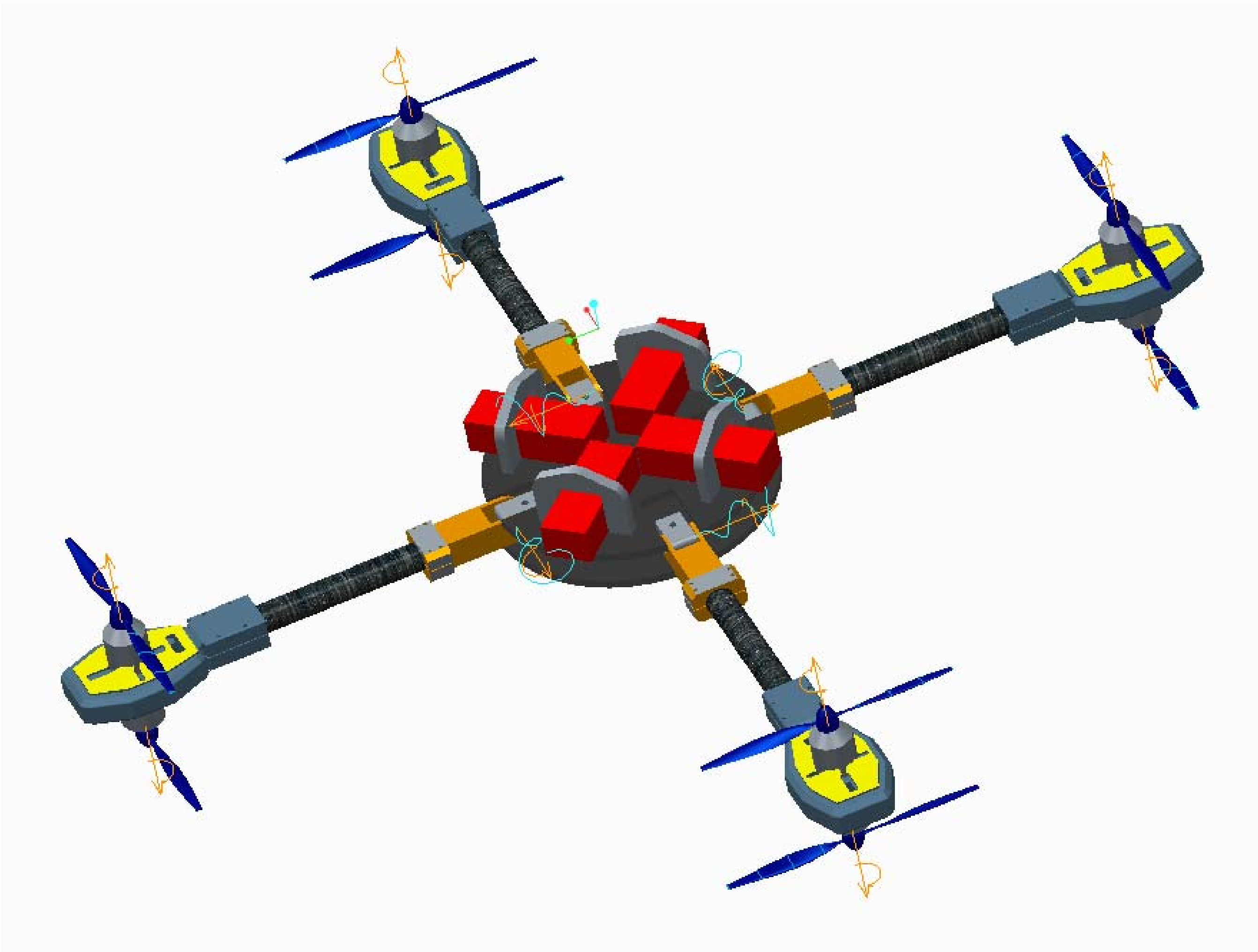
Design and Manufacture of a Rotorcraft

Measure Phase Report



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3 Abstract

This paper represents an overview of the second of five phases in this project. This phase is known as the Measure phase, in which measurement systems and assumptions are validated and numerical data is gathered or calculated. This report will review the project definition established in the Define phase report before discussing the obstacles faced by the team during the Measure phase and the decisions made based on those obstacles.

Rotorcraft vehicles typically fall into two categories: high portability with a low payload capacity or low portability with a high payload capacity. Despite these categories, there exists a need for highly portable rotorcrafts with a high payload capacity, particularly in military applications. As such, this paper presents further investigation into the design and manufacture of a rotorcraft that meets this need.

Three possible rotorcraft designs are described and examined within this paper, including the components required by each design and the weight and cost of each design. Models of each design built in Creo Parametric PTC demonstrate the physical rotorcraft design and how the rotorcraft fits within a military backpack and analyses performed in Creo Parametric PTC verifies the assumptions and calculations performed during the Define phase and the beginning of the Measure phase.

In the Measure phase, the project team used a measurement tool recommended by professors within the Department of Mechanical Engineering. This tool is used to validate the team's design decisions and measure key metrics such as flight time, throttle, and efficiency without having physical prototypes of each design.

4 Introduction

Rotary unmanned aerial vehicles often fall into one of two classifications: high portability with a low payload capacity or low portability with a high payload capacity. However, there is a need for rotorcrafts that are capable of transporting heavy payloads while still maintaining high portability, and that need is increasing over time due to the military applications of an unmanned aerial vehicle capable of carrying large payloads while being portable by a single soldier on the ground. The objective of this project is to design and build a rotorcraft with high portability and high payload capacity. Such a device would be beneficial in situations requiring quick deployment of a device carrying a payload up to fifty pounds, such as in battle or during covert military operations.

The advantages of using a rotorcraft flying machine include an ability to take off and land vertically. Some rotorcrafts already exist that can carry fifty pounds, but these rotorcrafts have low portability due to their size. One of the heaviest loads carried by a rotorcraft was 129.4 pounds; however, the rotorcraft could only hover a few feet off the ground [1].

Major design considerations and potential problems include the rotor number and configuration, the raw materials, folding/transport ability, and specifications of the electrical controls that will influence the overall performance of the device. In order to be useful to the Air Force, the sponsoring organization for this project, the vehicle must meet several requirements. More information on these requirements can be found in Figure 4. The most common application for these needs would likely be delivering explosive devices to enemy territory.

This report presents an overview of the Define phase report and an in-depth examination of the work accomplished by the team during the Measure phase. A major accomplishment during the Measure phase is the use of eCalc (a web-based service designed to calculate, evaluate and design electric motor driven systems for remote controlled models) to measure the capabilities of the three designs proposed in this report without having to build three physical prototypes and test the prototypes [2].

5 Team Organization

For this senior design project, the team consists of three industrial engineers, three mechanical engineers, and two electrical engineers. The team reports to the department of Industrial and Manufacturing Engineering and to Dr. Okenwa Okoli, who is also the contact between the team and the sponsor.

The team aims to work together in creating a positive, productive, and professional learning environment. This environment is established through mutual trust and respect, integrity and ethics, and open communication among all members. The team aims to work together in a timely yet careful manner to ensure that the project is completed properly and on time. Figure 1 illustrates the roles delegated to each team member for the Measure phase and who each team member reports to.

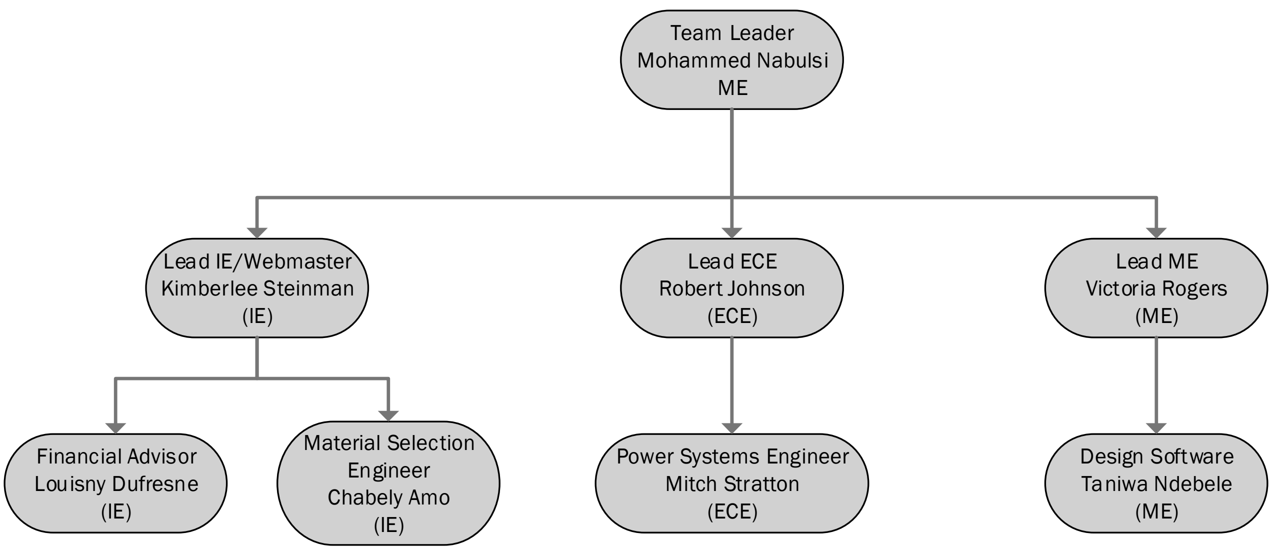

Figure 1. Organizational Chart of Team

- The Measure Phase Team Leader is responsible for setting reasonable goals and managing project completion. The Team Leader assures that workload is distributed evenly between the team members. The Team Leader also sets meeting agendas and keeps the communication flowing between team members, faculty members, and the sponsor.
- The Mechanical Engineering Lead is responsible for managing mechanical engineering members of team and scheduling meetings with the mechanical engineering advisor. The Mechanical Engineering Lead maintains constant contact with the Electrical and Computer

Engineering Lead to ensure compatibility between mechanical and electrical components of the project and is in charge of maintaining the documents created by the Software Designer.

- The Industrial Engineering Lead is responsible for managing industrial engineering members of team, scheduling meetings with the industrial engineering advisor, and ensuring that the team meets deliverable deadlines.
- The Electrical and Computer Engineering Lead is in charge of scheduling meetings with the electrical and computer engineering advisor. The Electrical and Computer Engineering Lead is also in charge of selecting electrical components of the project and programming the rotorcraft.
- The Material Selection Engineer is in charge of researching all the possible materials required for the design and manufacturing of the rotorcraft. The Material Selection Engineer is responsible for selecting the manufacturing process required to manufacture the parts.
- The Financial Advisor is responsible for the group finances as well as keeping track of purchased parts and overall inventory. The Financial Advisor maintains appropriate expenses and plans for funding and ensures the group stays in budget.
- The Webmaster is responsible for maintaining the team project website with up to date information and media and for facilitating the sharing of research with all team members.
- The Power Systems Engineer is responsible in particular for all power systems components of the project.
- The Software Designer is in charge of the creation of all drawings, reports, and all other necessary documents regarding the design of the project.

6 Project Definition

6.1 Background Research

In 1907, Louis Breguet designed the earliest rotorcraft [1]. The four-rotor helicopter was only able to fly a few feet above the ground. Since then, unmanned aerial vehicles (also known as UAVs) have become commonly used for many applications. There are several programs working on improving these rotorcrafts including [1]:

- Bell Boeing Quad TiltRotor
- Aermatica Spa’s Anteos
- AeroQuad and Ardu Copter
- Parrot AR.Drone

However, all these programs have not come up with a design that meets this senior design project. These programs have a variety of uses including world-class engineering research laboratories, military and law enforcement, and as well as commercial use for aerial imagery [3]. The primary difference between this senior design project and the rest of these programs is the rotorcraft’s portability. Most of these rotorcrafts are designed with no limitation on size. So an essence having a rotorcraft capable of lifting 50+ lbs. and still being small enough to fit in a military size backpack has never been done before.

Over this past summer, FAMU-FSU College of Engineering have took on the task of building a rotorcraft with the same requirements as this senior design project has. However, Dr.Okoli has decided to keep the literature about the design concept and journals of calculations on the rotorcraft the school is building confidential until our senior design team comes up several new ideas. Based on the next meeting with Dr.Okoli, he will decide if we will continue with the new designs proposed, or if our team will continue the project FAMU-FSU COE started this past summer.

Reviewing the various configurations available for rotorcrafts is necessary before an optimal platform can be designed. A rotorcraft is a heavier than air flying machine that uses lift generated by wings called rotor blades that revolve around a mast [1]. An example of a rotorcraft is a quad rotor. A quad rotor generates lift by four set of rotors vertically oriented propellers [1]. A rotorcraft which is capable of being quickly deployed and carrying a large payload has several applications, including the transportation of equipment to remote areas where the terrain is unsuitable for ground-based vehicles.

As seen in Figure 2, a quad rotor uses four rotor blades. A quad-rotor is a useful example to show how these rotorcrafts perform because of its simplicity [3]. The Ω_2 and Ω_4 rotate in the clockwise direction, while the Ω_3 and Ω_4 pair rotate counter clockwise. This allows the rotorcraft to fly because it creates a balance for the drag created by each spinning rotor pair. Additionally, varying the number of rotations per minute for each rotor blade individually allows the user to control the lift and torque forces.

In this report, several configurations of rotorcrafts are explored. In particular, this report examines a Hexa-copter (six rotors) and an Octo-copter (eight rotors) designs. The relationship between the number of rotors and the rotor size determines how much thrust is needed per rotor to lift the vehicle and its payload.

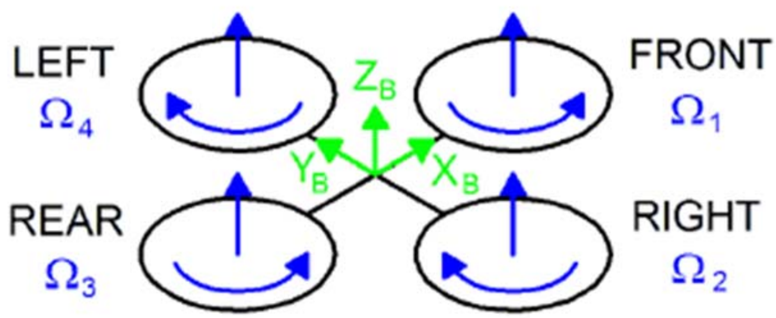

Figure 2. Quadrotor [5]

6.2 Business Case and SIPOC

Current rotorcrafts on the market prioritize either payload capacity or rotorcraft size. However, there are applications where both payload capacity and rotorcraft size are desired, such as equipment delivery in the military or more martial and offensive deliveries. By designing a rotorcraft with the given specifications (must carry at least 50 pounds and must fit in a military backpack), along with designing the processes required to manufacture the rotorcraft and building a prototype, this project will result in a revolutionary product in the rotorcraft field. It will initiate a market for rotorcraft that carry large loads while being small.

Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis can be a good starting point for analyzing an organization. The SWOT analysis for this project team can be seen in Table 1 below. For this team, the greatest strengths lie in communications and scholastic backgrounds. There is open communication among all team members and all members agree to maintain this level of communication, preventing any miscommunication before it has a chance to occur. The team members are divided among three different majors in the College of Engineering, so each team member has different training and experience to use as tools in solving any problem encountered during the course of the project.

Weaknesses lie in group size and management ability. Managing and organizing eight people and their unique schedules is a challenge in and of itself, even without involving outside resources or advisors and their schedules. The team must work together to keep each other accountable and work around difficult schedules in order to make this project successful.

Table 1. SWOT Analysis Quadrants

STRENGTHS	WEAKNESSES
• Interdisciplinary group means that there are several diverse outlooks on problems encountered during the course of the project. • A group text message (GroupMe) allows for open communication for discrete questions, while weekly meetings and email allow for in-depth progress reports and assistance. This open communication prevents problems from falling through the cracks. • Our advisors and resources (primarily Dr. Okoli, Dr. Dickens, Margaret, Emily, and Cameron) are reliable in their communication and availability to the team.	• It is more difficult to maintain order in a group of 8 students, which is one of the largest groups this year. • Finding published literature for rotorcraft carrying high payloads at a small size is difficult, as normally researchers and hobbyists prioritize one over the other. This leads to a higher need for synthesis of several vehicles instead of one or two that suit our needs. • Enforcement of internal deadlines is difficult with eight members, but it is not impossible.
OPPORTUNITIES	**THREATS**
• War or other military action in areas known for volatile terrain might lead to a spike in demand for unmanned aerial vehicles instead of unmanned terrain vehicles.	• Another military body or another funded group also developing a rotorcraft similar to the one described in this report might devalue the results of our project.

Another organizational tool is Suppliers, Inputs, Processes, Outputs, and Customers (SIPOC) analysis, which as the name implies allows an organization to explicitly identify suppliers, inputs, processes, outputs, and customers. The SIPOC analysis for this project can be seen in Table 2.

Identifying all the elements in SIPOC analysis helps to define the scope of the project. For this project, half of the process is the design of the rotorcraft and manufacturing processes, while the other half of the process is building a prototype for design chosen. Splitting this process into its two halves lets the team identify the input for each part and the supplier for that part. For instance, designing the rotorcraft and manufacturing processes requires the team's collective knowledge and training in engineering as an input, which has been supplied by the College of Engineering and its various departments, while building the prototype requires the team to build a frame for the rotorcraft using materials and process knowledge provided by HPMI.

Table 2. SIPOC Analysis Chart

<table>
<tr><th>Suppliers</th><th>Input</th><th>Process</th><th>Output</th><th>Customers</th></tr>
<tr><td>College of Engineering departments (Industrial and Manufacturing, Electrical and Computer, and Mechanical)</td><td>Group member's knowledge and training in design and manufacturing</td><td>Design a rotorcraft that meets the customer's requirements and the manufacturing processes required to create the rotorcraft</td><td rowspan="3">A rotorcraft that can fit in a military backpack (23x14.5x15), can carry a payload of at least 50 pounds, is made with commercial off the shelf components, has a range of approximately 1 mile, and is easy to maintain and use in the field, along with the manufacturing processes and data required to produce this rotorcraft.</td><td>The Department of Industrial and Manufacturing Engineering at FAMU/FSU</td></tr>
<tr><td>Online retailers</td><td>Rotorcraft components: rotors, propellers, battery, IMU sensors, microcontroller, RC transmitter</td><td rowspan="2">Build a prototype rotorcraft</td><td rowspan="2">Military bodies</td></tr>
<tr><td>HPMI</td><td>Materials for the frame for the rotorcraft</td></tr>
</table>

The SIPOC and SWOT analysis allows the team to define the scope of the project and the need for the project. The main end consumer of the rotorcraft described in this report is the United States Air Force and other military bodies. This rotorcraft could help improve soldier safety and effectiveness if utilized in battle or in training. As such, our team is undertaking this project because of the value of such a rotorcraft to military bodies. This martial value is translated into monetary value for the Department of Industrial and Manufacturing Engineering and for Dr. Okoli as the head of the department via the transfer of this rotorcraft design to the United States Air Force.

6.3 Goal Statement & Objectives

Using the SIPOC, SWOT, and other analyses described in the Define phase report, our goals are as follows:

1. Design a rotorcraft that can:
    a. Fit in a military backpack (23”x14.5”x15”)
    b. Carry a payload of at least 50 pounds
    c. Be made with commercial off the shelf (COTS) components
    d. Travel up to approximately 1 mile
    e. Be easily maintained and used in the field
2. Design the manufacturing processes to be used in creating the rotorcraft described in Goal 1.
3. Build a prototype of the rotorcraft described in Goal 1.

These three goals together are the overall goals for this project. Variables in these goals include the customer requirements and the deadlines for each phase of the Six Sigma project process associated with this project.

Depending on the level of success achieved in this project, the outcome of this project (the rotorcraft design, manufacturing processes, and possibly the prototype) could be utilized by the Air Force or by the College of Engineering as a means to further future projects or goals. The projects or goals desired by the Air Force that might be built from the success of this project are unforeseeable and potentially classified, but the College of Engineering and the Department of Industrial and Manufacturing Engineering could design further senior design projects intended to improve on the performance achieved in this project.

7 Analysis of Customer Requirements

7.1 Meeting CCR

Meeting critical customer requirements includes predicting and preventing problems that may arise. To this end, a cause and effect diagram (also known as a fishbone diagram) was created to predict any potential causes of an overall failure in terms of project completion or meeting the requirements of this project. This fishbone diagram can be seen below in Figure 3 and each cause is explained by category.

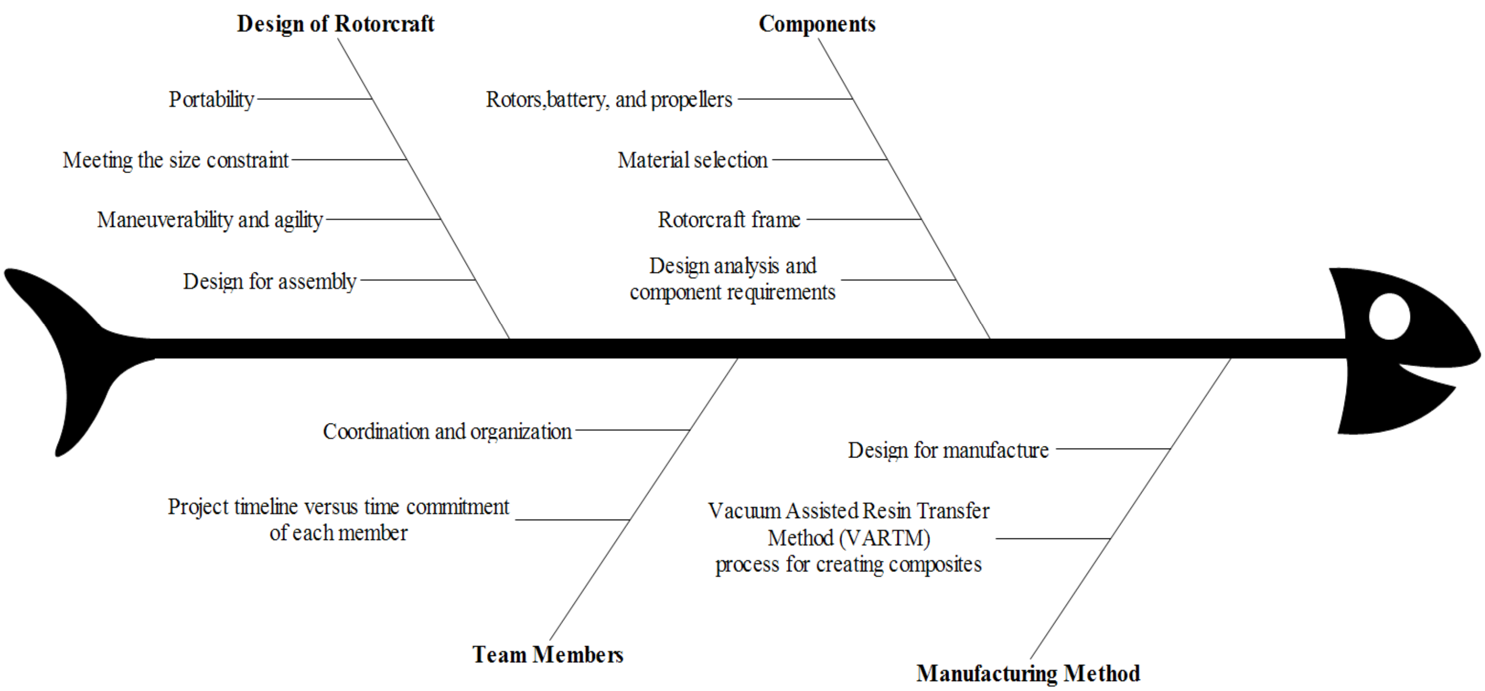

Figure 3. Fishbone Diagram

Design of rotorcraft

This category refers to problems caused within the actual design of the rotorcraft. In order to be useful to the project sponsor, the rotorcraft must be portable, meet the given size constraint of fitting in a military backpack, and be maneuverable and agile during flight. Failing to consider these aspects during the design phase will result in a failed project, as the designed rotorcraft will not meet the customer requirements.

Principles of design for assembly must be considered during design, otherwise the user will not be able to easily assemble the rotorcraft in the field. Again, failing to consider this aspect will result in a failed project.

Components

This category refers to problems caused by the specifications of the components or in component and material selection. Design analysis and component requirements must be strictly and carefully calculate and considered. An unchecked error in these calculations might snowball into selecting, purchasing, and using a component that does not sufficiently meet the actual requirements. These sorts of errors might result in a failed project, depending on how large the error is and how large the margin of error between the calculated requirements and selection component specifications are. In particular, the components with the largest potential to cause a problem are the rotors, batteries, and propellers, as they have the greatest effect on the lift and thrust forces. Additionally, quality control issues on the part of the suppliers of these components could have an effect on the final rotorcraft and could result in a failed project if the quality is poor enough.

Similarly, incorrect material selection could result in a failed project because of the failure of individual pieces of the rotorcraft. The rotorcraft frame holds all the other components and as a result, a faulty frame could lead to a failed project.

Team members

This category refers to problems caused by the team members themselves. A project team of this size requires a large degree of coordination and organization. A failure in this area, such as losing project documentation or not properly coordinating schedules, could lead to an incomplete and failed project.

Each of the eight team members have unique commitments outside of this project, such as other coursework or outside employment. The time commitment of each member must be coordinated and the overall project timeline must be factored into this time commitment or else the project will be incomplete or failed at the end of spring semester.

Manufacturing method

This category refers to problems caused by the manufacturing methods. Failing to consider principles of design for manufacturing during the design process could result in a design that is incredibly difficult or even impossible to manufacture. If these difficulties are not caught early enough, the manufacture of the rotorcraft could be delayed significantly and result in an incomplete project.

A common method for creating composite materials is the Vacuum Assisted Resin Transfer Molding (VARTM) method and this method has several quality control concerns, such as using a consistent and correct amount of resin and adequately creating a vacuum during the process. A quality control issue during the creation of the composite materials needed for this project could result in a failed project.

To avoid the incompletion of the project the team will use the voice of the customer and the house of quality matrix to analyze and determine all the factors that will enable the portability, meeting size constraint, maneuverability and agility, and design for assembly. Then, intensive analyses and calculations will be performed to make sure all the selected components and materials are capable of meeting customer requirements and are compatible with each other. Further, the team already attended a composite layout demonstration by Mr. Jerald Horne at the High Performance Material Institute (HPMI), where the necessary materials, steps, and critical considerations for the vacuum resin infusion process were explained. The team will implement the knowledge acquire on the demonstration and further assistance will be requested, if required, to ensure the quality of the parts meet with specifications. Finally, a Gantt chart is currently used to schedule meeting and set term goals. The team has been following the critical path generated by the chart to make sure all steps are completed and avoid the failure of the project.

7.2 Critical Customer Requirements (CCR)

The Voice of the Customer tree is a diagram used to capture the customer requirements in depth. The customer requirements for the rotorcraft were determine after several discussions between the stakeholders and the team and taking into consideration the cause and effect diagram (Fishbone) created by the team. Figure 4 illustrates the rotorcraft customer requirements and the approaches to achieve the design and manufacture of the rotorcraft. There are eight critical requirements the design of the rotorcraft must meet. These requirements are:

- The rotorcraft must lift a payload of fifty pounds
- The rotorcraft must fit in a military backpack
- The rotorcraft should be easy to carry
- Safety to the user should be considered
- The rotorcraft design must use off the shelf electrical components
- The rotorcraft must have a flight range of one mile
- The project’s budget is $2,500
- The rotorcraft must be easy to assemble and use in the field.

In order to lift the desired payload, the rotors, batteries, and propellers must be capable of providing the necessary lift and thrust forces. Additionally, the list and thrust forces must account for both the weight of the rotorcraft and the weight of the payload. Since the weight of the payload is fixed, the only way to minimize the required lift and thrust forces is to minimize the weight of the rotorcraft. Therefore, the body of the rotorcraft will be made out of composite materials to reduce weight while maintaining strength and the electrical and mechanical components will be lightweight as well.

The rotorcraft must fit in a military backpack, which is 23 inches in length by 15 inches in width by 14.5 inches in height. Foldable arms will help to achieve this requirement and make it possible to fold and unfold the arms when necessary. These arms fold at a hinge located at one end of the arm.

Since this project is for a military application, the rotorcraft must be easy to carry, quickly assembled for takeoff, and safe for the user. An ergonomic analysis will be performed to determine the most efficient folding mechanism the user can accomplish in the field and the electrical wires will be insulated to avoid any electrical shock.

Off the shelf electrical components will be used to facilitate replacement if needed. Additionally, using commercial off the shelf (COTS) components is more feasible than using custom components due to cost and time investment.

The rotorcraft has to have a flight range of one mile. Therefore, the battery needs to provide enough power to keep the rotorcraft in the air for the amount of time required to travel one mile and the range of the RC transmitter must be adequate to maintain user control of the rotorcraft over the entire flight range.

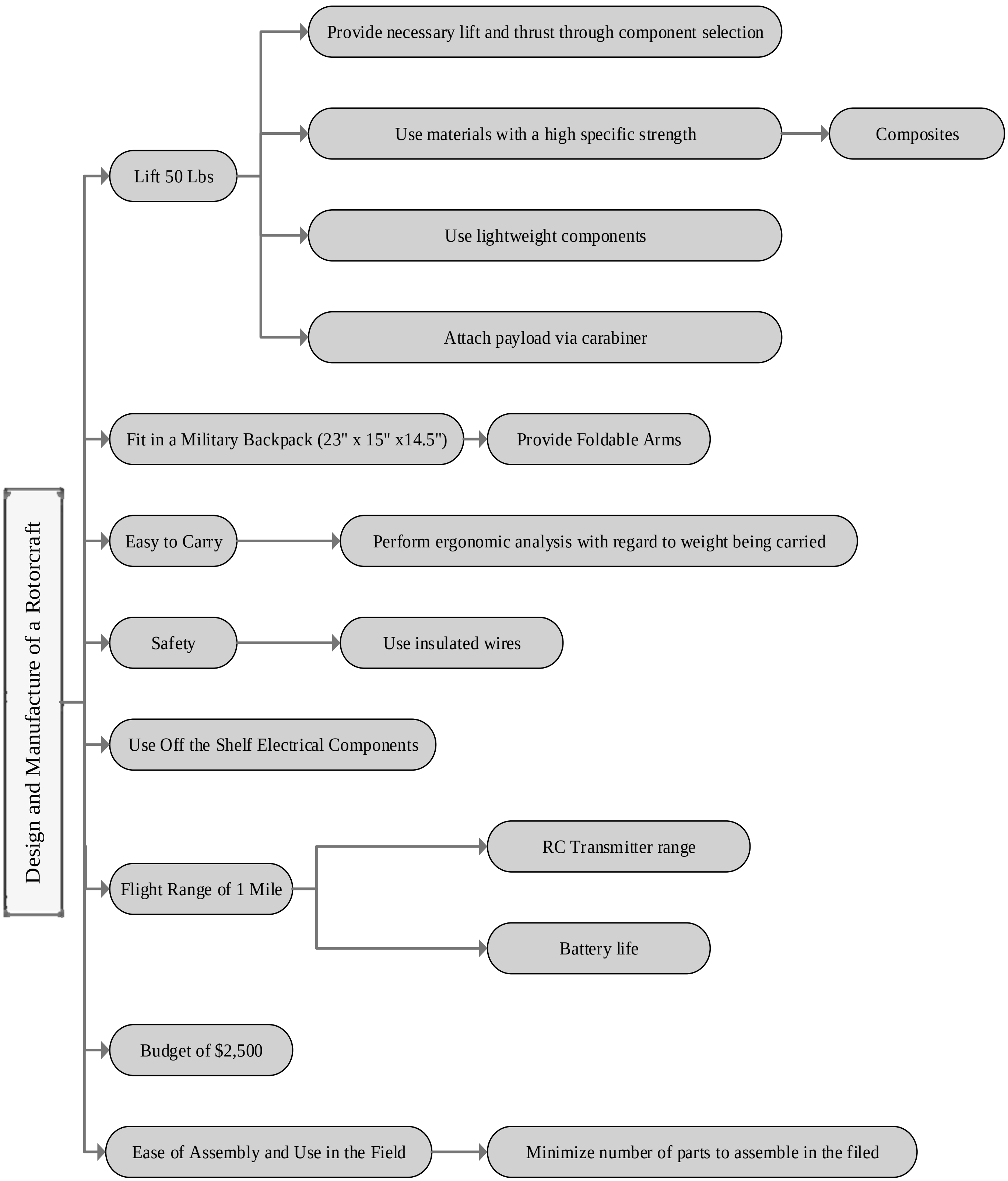

Figure 4. Voice of the Customer Tree

The House of Quality matrix uses the voice of the customer to define a relationship between customer requirements and how the team is going to achieve those requirements. Figure 5 shows the House of Quality matrix created for this project. The left side of the House lists what the customer requirements are. Importance ratings from one to five were assigned to each of these requirements via discussions between the stakeholders and the team about the importance of each requirement. The top side of the House contains the technical requirements that represents how the team will meet the customer requirements.

7.2.1 House of Quality Matrix

The box located at the center of the House of Quality is a matrix used to provide a connection between the customer requirements and the technical requirements. The customer requirements and technical requirements are paired together using symbols that indicate if the relationship is strong, moderate or weak. The symbols are assigned with indexes of nine for a strong relationship, three for a moderate relationship, and one for a weak relationship. For example, providing the necessary lift and thrust forces is strongly related to the customer requirement of lifting a fifty pound payload, while the number of rotors is only moderately related. The relationship between the lift and thrust forces and the payload is assigned an index of 9, while the relationship between the number of rotors and the payload is assigned an index of 3.

The technical weights located at the right of the quality matrix determine the most critical customer requirements. The weights were calculated by adding all the products resulting from multiplying the customer requirement ranking by the index number assigned to the relationship between the technical and the customer requirement. For example, there is a strong relationship between providing the necessary lift and thrust forces and lifting fifty pounds. Since lifting fifty pounds has a customer index rating of five and a strong relationship represents an index of nine, multiplying five and nine will give a portion of the technical weight. This calculation is performed for each relationship and all the products for each requirement are added together. Based on the weights for the customer requirements, the most important requirement is that the rotorcraft is able to lift fifty pounds. Equation 1 shows how the technical weights for the technical requirements were calculated.

$$Technical\ Weights\ for\ Customer\ Requirements = \sum_{i=1}^{n} (R_i)(I_i) \qquad \text{Eq. (1)}$$

$$n = total\ \#\ of\ relationships\ between\ a\ customer\ requirement\ and\ technical\ requirements$$

$$R = Requirement\ Rating\ (1 - 5\ )$$
$$I = Relationship\ Index\ (9\ , 3, or\ 1)$$

The technical weights located at the bottom of the targets list determine the most critical technical requirement. The weights were calculated in a method similar to that for the customer requirements, except the sum is along each column instead of along each row. For example, having foldable arms is strongly related to fitting in the military backpack and a moderate relationship with ease of assembly and use in the field. The relationship index between foldable arms and fitting in the military backpack is nine (strong) and for the relationship index between foldable arms and ease of assemble and use in the field is three (moderate). Additionally, the rating for both fitting in the military backpack and ease of assemble and use in the field is four. Therefore, multiplying nine and four and adding it to the product of three and four will result in the technical weight for that technical requirement. The necessary lift and thrust forces and number of rotors have the highest technical weights and thus are the most critical technical requirements. Equation 2 shows how the technical weights for the customer requirements were calculated.

$$Technical\ Weights\ for\ Technical\ Requirements = \sum_{i=1}^{n}(R_i)(I_i) \qquad \text{Eq. (2)}$$
$$n = total\ \#\ of\ relationships\ between\ a\ technical\ requirement\ and\ customer\ requirements$$
$$R = Customer\ Requirement\ Rating\ (1 - 5\ )$$
$$I = Relationship\ Index\ (9\ , 3, or\ 1)$$

The technical weights can also be described via a weight percentage, which is merely each customer requirement or technical requirement technical weight divided by the sum of all weights for either the customer requirements or the technical requirements and multiplied by 100.

7.2.2 Correlations among Technical Requirements

As can be seen in the roof of the House of Quality, there are twelve different correlations among the technical requirements. The reasons for these correlations are as follows, with the correlated technical requirements highlighted in bold text:

1. **Provide necessary lift and thrust forces** and **Use materials with high specific strength**: Materials with a high specific strength have a high strength relative to their weight. Using materials with a high specific strength reduces the weight of the craft without sacrificing component strength, which reduces the lift and thrust forces that must be provided.

2. **Provide necessary lift and thrust forces** and **Use lightweight components**: As in correlation 1, using lightweight components reduces the weight of the craft and thus reduces the lift and thrust forces that must be provided.
3. **Provide necessary lift and thrust forces** and **Number of rotors**: Increasing the number of rotors decreases the lift and thrust that must be provided by each rotor, and thus the number of rotors is positively correlated with the total lift and thrust forces that can be provided.
4. **Provide necessary lift and thrust forces** and **Battery life**: The power supplied by the battery and the time over which this power is supplied affects the rotorcraft's ability to provide lift and thrust forces. If the battery is dead, the rotorcraft no longer works and is no longer providing lift and thrust forces.
5. **Use materials with high specific strength** and **Method of attachment**: The method of attachment must be made of a material with a high specific strength in order to hold the payload without breaking.
6. **Use materials with high specific strength** and **Foldable arms**: The arms must be made with lightweight materials that are strong enough to survive the stresses incurred during flight, especially at the hinges or other potential weak points.
7. **Use lightweight components** and **Method of attachment**: The method of attachment adds to the total weight of the rotorcraft and thus the heavier the method of attachment, the less lightweight the rotorcraft is.
8. **Use lightweight components** and **Insulate wires**: Insulating wires adds to the weight of the rotorcraft as compared to wires that are not insulated, but not by a large amount.
9. **Use lightweight components** and **Use of off the Shelf Electrical Components**: The electrical components used in the project must be commercial off the shelf components and must be lightweight.
10. **Insulate Wires** and **Battery life**: Insulating the wires extends the battery life, as there is less loss to the environment.
11. **Number of parts to assemble in field** and **Number of rotors**: Generally speaking, more rotors leads to more actions to be performed in the field.

12. **RC transmitter range** and **Use of off the Shelf Electrical Components**: The RC transmitter range depends heavily on the ranges available in commercial off the shelf transmitters.

7.2.3 Technical Requirements Objectives and Targets

The box below the roof represents the objective of each technical requirement. This objective can be to minimize, maximize or hit the target. The technical requirements that need to be maximized are “provide necessary lift and thrust forces”, “use materials with high specific strength”, “use lightweight components”, “RC transmitter range”, “battery life”, and “use of off the shelf electrical components”. The technical requirement that needs to be minimized is “number of parts to assemble in the field”. Finally, the technical requirements that needs to be met are “method of attachment”, “foldable arms”, “insulation of wires”, and “number of rotors”. Further, the box above the technical weights of the methods and below the matrix itself lists the components that will be used to fulfill the technical requirements.

The House of Quality created for the design and manufacture of the rotorcraft serves as a path for the team to follow and meet project objectives. According to the results, the most important customer requirements to be taken into account are lifting fifty pounds, staying within budget, ease of assembly and use in the field and ease of carry. The team will also prioritize the requirement that the rotorcraft fit in a military backpack because of its level of importance specified by the stakeholders.

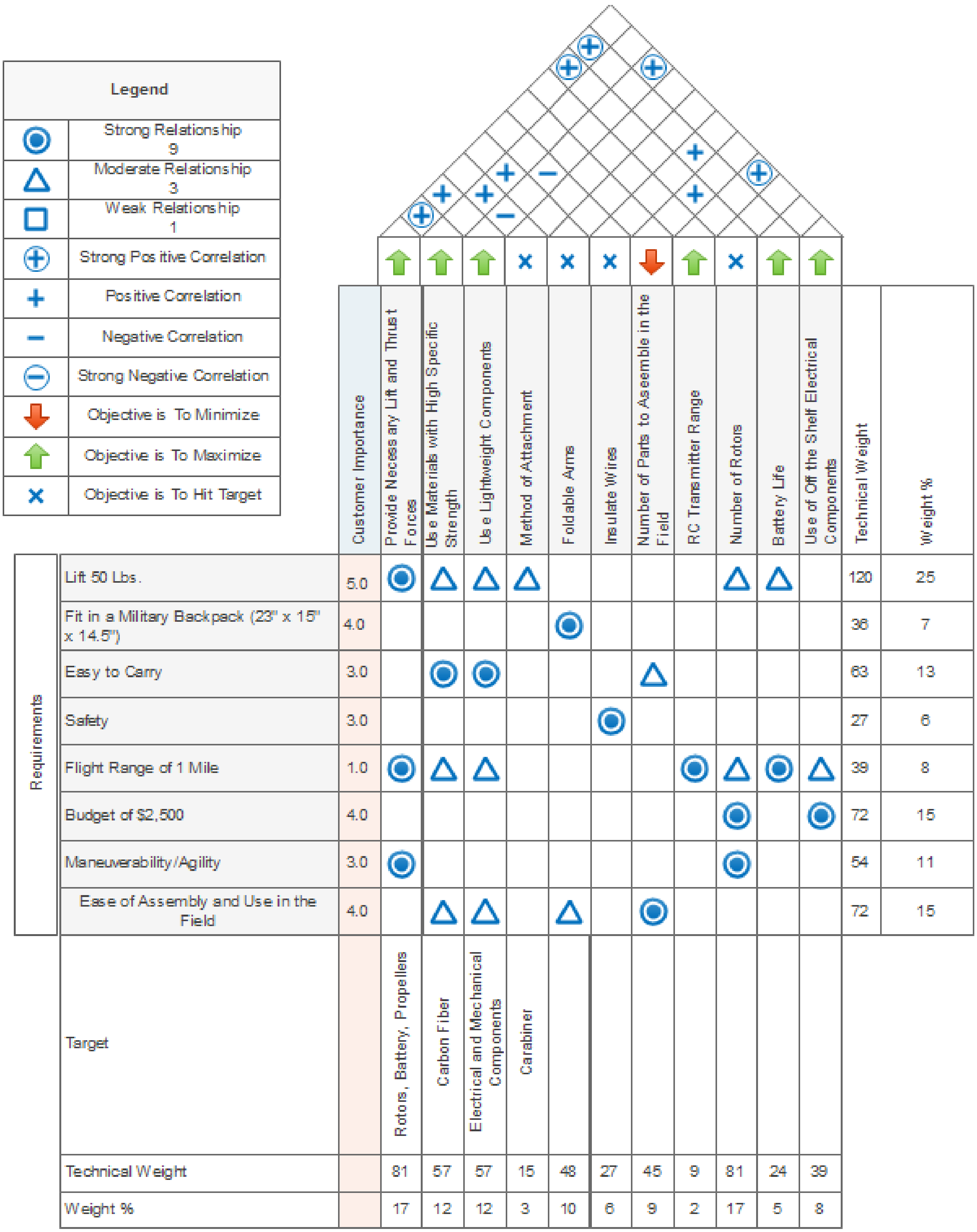

Figure 5. House of Quality

8 Design and Analysis

8.1 Carbon Fiber and Glass Fiber Comparison

Some of the customer requirements for the rotorcraft's frame include minimizing both weight and price of the rotorcraft, while maximizing its strength. Composite materials offer these characteristics as they are lighter and less expensive than alternative materials, such as aluminum, used in rotorcrafts. Composites are defined as two or more constituent materials combined by an interface. This combination results in a material with better properties that cannot be achieved by either of the constituents on their own [4]. Composite materials typically have a lower density, and so are lighter for a set amount of material than other materials used in rotorcrafts. For example, the density of carbon fiber is about 1.55 g/cm^3 while aluminum's density is 2.7 g/cm^3.

There exist different types of composite materials that can be distinguished depending on the type of matrix and reinforcement used. The particulate reinforced material that will be used for the frame is a polymer matrix. Carbon fiber or Glass fiber will be used as the reinforcement material in an **epoxy resin** matrix. The following paragraphs include comparisons between carbon fiber and glass fiber, a brief explanation of epoxy resin properties, and the process that will be used to manufacture the frame of the rotorcraft.

First, a comparison of carbon fiber and glass fiber is necessary to select the better material for the frame of the rotorcraft. The rotorcraft has to tolerate a wide range of stresses from changing frequency vibrations, heat, centrifugal forces, hard landings, and many more. Therefore, the material has to be strong and stiff to endure all those factors. Tables 3 compares properties and characteristics of carbon and glass fiber.

Table 3.Mechanical Properties and Price of Carbon Fiber and Glass Fiber

Material	Tensile Strength (MPa)	Young Modulus (GPa)	Density (g/cm^3)	Price/Yard ($)
Carbon Fiber [4,5,6]	4127	125 – 181	1.58	30 - 40
Glass Fiber [7,8]	3450	30 – 40	2.66	5

It should be mentioned that the numbers shown in Table 3 are estimations and actual values vary from sample to sample. Because there are many types of carbon and glass fibers, including E-glass and S-glass, the manufacturing process and after treatments can affect the properties displayed in Table 3, even for a particular type of glass fiber. However, the values in Table 3 are suitable to make comparison between carbon fiber and glass fiber.

Table 3 shows that carbon fiber is stronger than glass fiber. Carbon fiber has a tensile strength of 4127 MPa, while glass fiber has a tensile strength of 3450 MPa. The difference between their strengths is nearly 18 percent. The stronger the material the greater the durability of the rotorcraft. Also, carbon fiber presents a young modulus of 125-181 GPa and glass fiber of 30-40 GPa. As such, carbon fiber is much stiffer than glass fiber, which is another important factor enabling the resistance of stresses in the rotorcraft.

Another aspect to be taken into consideration is density. The rotorcraft needs to be as light as possible in order to minimize the thrust and lift forces needed to maintain flight. Because carbon fiber has a density of 1.58 g/cm3 while glass fiber of 2.66 g/cm3, it is favorable to use carbon fiber because a higher amount of strength can be obtained for a lesser weight of material. The denser a material is the heavier it will feel for an equal sized chunk. Calculations showing exactly how much heavier glass fiber will be versus carbon fiber can be seen in **Appendix A.** If glass fiber was chosen as the material to move forward with this project, then the components chosen for the different designs discussed in the following sections would not be able to carry the payload.

Finally, budget is an important constraint in this project. Carbon fiber price per yard ranges from $ 30-40 while glass fiber price is between $3 and $6 for the same amount. Carbon fiber is significantly more expensive than glass fiber, however its greater strength and lower density make the difference in price worth the expense so long as the remainder of the project's material remain within budget. Because of all these factors, carbon fiber was selected for the frame of the rotorcraft.

8.1.1 VARTM Manufacturing Process

To manufacture the carbon fiber, the vacuum-assisted resin transfer molding (VARTM) is utilized. VARTM is one of the processes use to manufacture composites and is the one that will be used to create the frame of the rotorcraft. The VARTM process was selected because there are resources available in Tallahassee to learn and perform the process. The team met with Mr. Jerald Horne in order to better understand the VARTM process. This process consists of using pressure to vacuum seal a flexible bag that encloses the reinforcement and the matrix together until the resin cures. The process occurs in three steps: the creation of the mold (based on the design of the rotorcraft), the manufacturing, and post processing.

The manufacturing process of the vacuum bag can be seen in Figure 6 and the materials and equipment required in the process include [9]:

- Mold Release → prevents sticking between the matrix and the mold
- Release Fabric → separates the flow medium from the composite and leaves a good surface finish
- Flow Medium → allows the resin to flow with ease
- Vacuum Bag → seals the reinforcement and matrix together and increases the permeability of the process
- Mastic Sealant → sticks the bag, the tubes, and the mold together
- Plumbing System → two tubes are used: the gate and the vent. The gate tube filtrates the resin and the vent tube is used to control the vacuum pressure
- Pump → use to apply the vacuum

The vacuum bagging process consists of six basic steps. These steps are to:

1. Prepare the area where the composite will be manufactured.
2. Cut, clean, and prepare all the materials require for the process.
3. Place all the materials and equipment in their respective order, as illustrated in Figure 6.
4. Prepare the resin. Add curing agent and stir as necessary.
5. Start the vacuum bagging process. Connect the pump to the correct tube, infiltrate the resin, and let it cure.
6. Apply post processing to the composite.

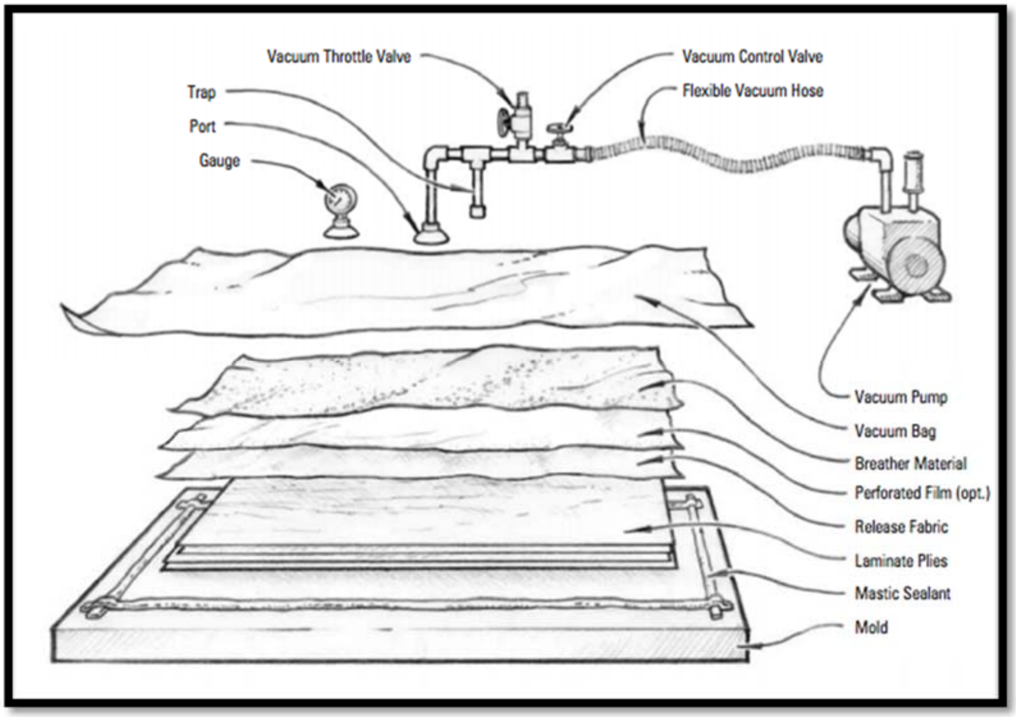

Figure 6. Materials and equipment for the Vacuum Bagging Process [12]

8.2 How an Octo-copter Operates

To maintain balance, the Octo-copter must be continuously taking measurements from the sensors and making adjustments to the speed of each rotor to keep the body level. Usually these adjustments are done autonomously by a sophisticated control system on the Octo-copter in order to stay perfectly balanced. These rotors are aligned in a square. Four rotors on opposite sides of the square rotate in a clockwise direction and the other four rotors rotate in a counterclockwise direction. If all the rotors were to turn in the same direction, the craft would spin. This spin can also be seen in normal helicopters that are without a functional tail rotor. Yaw is induced by unbalanced aerodynamic torques [10]. The aerodynamic torque of the clockwise rotors cancel out with the torque created by the counterclockwise rotors, so if all eight rotors apply equal thrust the Octo-copter will not spin. An Octo-copter has four controllable degrees of freedom: Yaw, Roll, Pitch, and Altitude [10]. These degrees can be seen in Figure 7. Each degree of freedom can be controlled by adjusting the thrusts of each rotor.

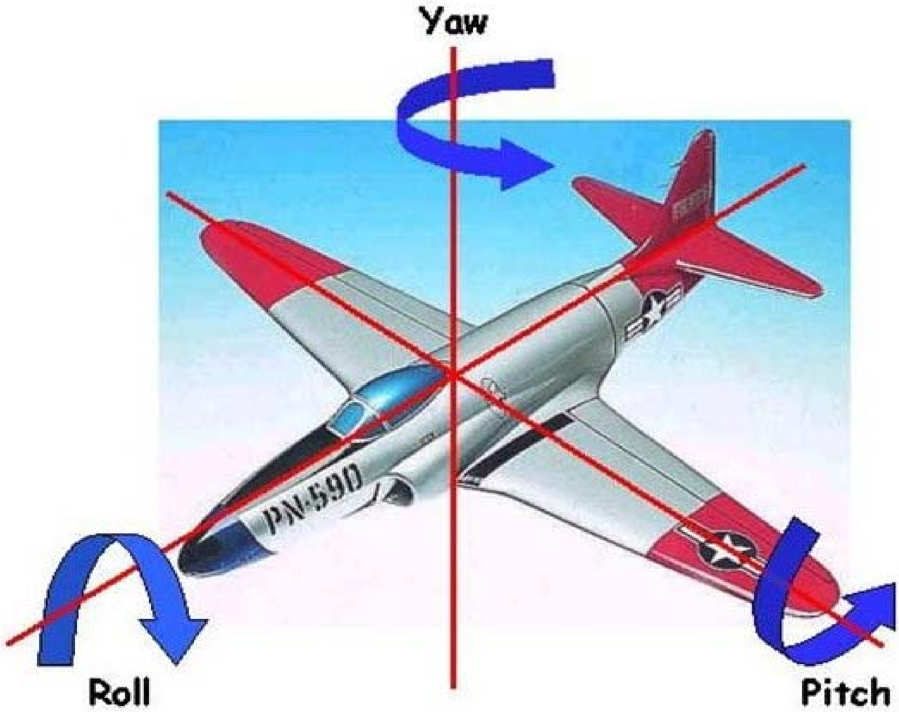

Figure 7. Rotorcraft's Orientation is Described By Using Three Angles: Roll, Pitch, and Yaw

- Yaw is controlled by turning up the speed of the clockwise rotating motors and taking away power from the counterclockwise rotating motors. The yaw angle of the Octo-copter describes its bearing or rotation of the craft as it stays level to the ground. Rotation about the yaw axis is like when you shake your head to say "no". Controls becomes a matter of which motors get more power and which motors get less.
- Roll is controlled by increasing speed on one motor and lowering on the opposite one. The roll angle of the Octo-copter describes how the craft is tilted side to side. Rotation about the roll axis is like tilting your head towards one of your shoulders. Rolling the Octo-copter causes it to move sideways.
- Pitch is controlled the same way as roll, but using the second set of motors. This may be kind of confusing, but roll and pitch are determined from where the "front" of the rotorcraft is, and in an Octo-copter they are basically interchangeable but the "front" must be clearly and consistently defined or control of the rotorcraft may be lost. The pitch angle of the Octo-copter describes how the craft is tilted forwards or backwards. Rotation about the pitch axis is like tilting your head in order to look up or down. Rotation about the pitch axis

is similar to nodding “yes”. Pitching the Octo-copter causes it to move forwards or backwards.

- Altitude is simply controlled by throttle. The more throttle applied to the Octo-copter the higher the altitude becomes.

For example, to roll or pitch, two rotors’ thrust is decreased and the opposite rotors’ thrust is increased by the same amount. This causes the Octo-copter to tilt. When the Octo-copter tilts, the force vector is split into a horizontal component and a vertical component. This causes two things to happen: First, the Octo-copter will begin to travel opposite the direction of the newly created horizontal component. Second, because the force vector has been split, the vertical component will be smaller, causing the Octo-copter to begin to fall. In order to keep the Octo-copter from falling, the thrust of each rotor must then be increased to compensate.

There are a whole host of multi-rotor types. There is an equal amount of reasons for going for each of the specific setups. Essentially it boils down to number of booms and single or coaxial engine mounting. The choice of frame will affect many aspects of the multicopter, including efficiency, lifting power, flight times, and stability. The number of physical engines present is also important, and this can affect the ability for the aircraft to cope should one engine be lost. Figure 8 shows the radial and coaxial configuration for an Octo-copter [11]:

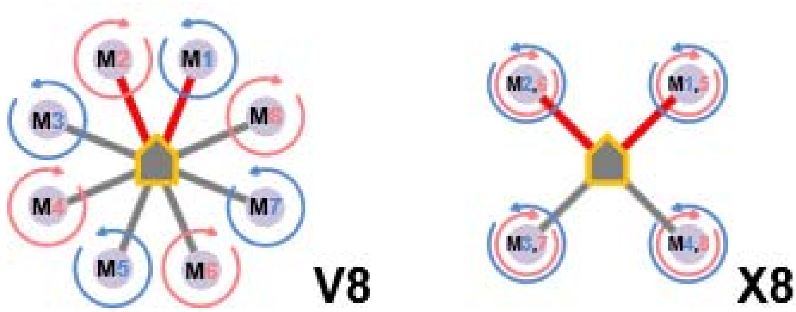

Figure 8. Quadrotor Loaded Force Diagrams

Taking a look at the above diagram, the key components are the number of booms, which in most cases equals the number of motors. However, there are also the coaxial set ups, such as the X8 in Figure 8. These have two engines mounted co-axially on the ends of each boom: one up and one down, with one tractor and one pusher prop to keep the thrust vector downwards. The vast majority of rotorcraft are designed with non-coaxial setups, as the coaxial rotorcrafts have a few drawbacks. Specifically, these drawbacks are poor efficiency and a tendency to overshoot on the yaw in one direction. However, coaxial rotorcrafts excel at their lifting power and stability. The reason they excel is straightforward: since there are four booms instead of eight, there is more room to fit larger props and motors, which allows more thrust and lifting capacity. Another positive for using the coaxial frame is ease of transport because there are less booms involved.

When considering the force diagrams in static condition, it will be considered in two dimensions. The actual system will be experiencing motion in three dimensions. The actual system will experience more complicated dynamic forces. However, two dimensions should be satisfactory when assuming the simple takeoff forces of lift and weight. When the lift forces are appropriately resolved, choosing motors that will produce lift forces greater than the equilibrium lift forces is essential. Since the equilibrium forces are static forces, the actual lift forces generated by the motors must be greater to achieve lift otherwise the system will not move. An additional assumption to be made is that the frame which houses the entire system is sufficiently rigid to all of the imposed forces. The lift forces may be modified and resolved as shown below.

Force Equilibrium:

$$\sum F_y = Lift\ Forces + System\ Weight = 0$$

$$\sum F_y = 8L + (-W_s) + (-W_p) = 0 \qquad \text{Eq. (3)}$$

Where L is lift generated, W_s is the weight of system, and W_p is the weight of the payload

Moment Equilibrium:

$$\sum M = Forces \times Distance\ from\ Reference\ Point = 0$$

$$\sum M = (L \times x_1) + (L \times x_2) + (L \times x_3) + (L \times x_4) + (W_h \times x_o) + (W_p \times x_o) = 0 \qquad \text{Eq. (4)}$$

Where L is lift generated, X is the distance from the center plate to the end of the arms

Force equilibrium calculations for the three designs discussed in the coming sections can be seen in **Appendix B**. As for the Moment Equilibrium equation, x_o is zero because the payload and housing is going to be placed directly in the center of the system. The reason for this decision is because if this is true, then there will be minimal moment acting on the system.

The placement of the motors/propellers is symmetrical. The motors/propellers that are paired up rotate in the same direction. For example, in Figure 8, motors 1 and 5 form a pair and both rotate clockwise, as do motors 3 and 7. Conversely, motors 2 and 6 as well as motors 4 and 8 rotate in the counter-clockwise direction. An assumption to be made is that each of the motors were manufactured to be identical. Therefore, under steady-state conditions each of the motors should be outputting the same amount of torque to produce the same amount of lift. Due to the counter-rotating nature of the two motor/propeller pairs, the net torque at steady-state equilibrium should equal zero.

Torque Equilibrium:

$$\sum T = Net\ System\ Torque = 0$$

$$\sum T = T_1 + T_2 + T_3 + T_4 + T_5 + T_6 + T_7 + T_8 = 0 \qquad \text{Eq. (5)}$$

Assuming: $T_1 = T_2 = T_3 = T_4 = T_5 = T_6 = T_7 = T_8 = T$

$$\sum T = (-T) + (-T) + (-T) + (-T) + T + T + T + T = 0 \qquad \text{Eq. (6)}$$

The simple force and torque diagrams are observed under static conditions. Designing and constructing a mechanical system as generally described here to takeoff from the ground and maintain steady-state flight (hovering) is one of the team's primary concern. To achieve steady-state flight, observing static conditions should be satisfactory. However when achieving flight past hovering, the forces will dynamically change. Consequently, the system will require motors capable of achieving much more than the specified conditions by the static forces. Since distance and flight time are an important consideration, energy consumption and capacity are very important. The battery selection is essential here. Once these limitations have been surpassed, dynamic control of the system becomes the primary focus of modification.

8.3 Components Analysis

In order to help with the components selection, a membership with eCalc was acquired. Since 2004, eCalc has provided web-based quality services to calculate, evaluate and design electric motor driven systems for remote controlled models [2]. In essence, eCalc provides the outcome of the rotorcraft based on the combination of the battery, speed controller, motor, and propeller chosen. It will alert the user if there are any errors based on the components chosen, such as if the motor is drawing too much current, if the battery needs to be larger, or if the pitch needs to be increased. This membership was recommended by Dr. Chuy (Mechatronics professor) and

Dr. Kumar (Fundamental of Aerodynamics professor) from the Mechanical Engineering department. Both Dr. Chuy and Dr. Kumar informed the team that eCalc was ninety percent accurate from firsthand experience. They continued to tell the team that the mechanical engineering department previously worked on building a rotorcraft that needed to carry five pounds and the test data gathered from their project as far as flight time, motor efficiency, current drawn, revolutions per minute of the propeller, and other characteristics matched identically to the eCalc website. Furthermore, eCalc guarantees all data has a margin of error of no greater than ±10% [2]. In the coming sections 3 different designs will be considered. Designs # 1 was proposed by intern Cameron Alexander, and design # 2 and design # 3 are proposed by the team.

Motor - Electric powered model rotorcrafts has gained popularity, mainly because the electric motors are more quiet, clean and often easier to start and operate than the combustion motors. The selected motor must be lightweight and capable of rotating the propeller at the desired angular velocity. Selecting the correct motor is essential in producing the required thrust to lift the rotorcraft off the ground. The motor selection was based on several desired characteristics: low weight, high efficiency, and high power. In order to get these characteristics two classes of motors were examined. These classes are brushless motors and brushed motors. Brushless motors spin at a much higher speed and use less power at the same speed than brushed motors [12]. In addition, brushless motors don’t lose power in the brush-transition like the brushed motors does, so it’s more energy efficient [12].

These motors are slightly more expensive but they have a higher efficiency. This efficiency is typically between 80 and 90%. Due to these characteristics as well as the fact that brushed motors require some maintenance due to both the brushes and the commuter wearing after a while due to friction, a brushless motor was chosen moving forward. Brushless motors required an electronic speed controller (ESC) specially designed for the brushless motors, which converts the battery's DC voltage into three pulsed voltage lines that are 120^{o} out of phase [12]. The brushless motor's maximum RPM (rotations per minute) is dependent on the 3-phase's frequency and on the number of poles:

$$RPM = \frac{2\ x\ frequency\ x\ 60}{number\ of\ poles} \qquad \text{Eq. (7)}$$

Increasing the number of poles will decrease the maximum RPM but increase the torque of the motor. A brushless motor's direction of rotation can be reversed by swapping two of the three phases. An important specification when considering brushless motors is the “Kv-rating”. The Kv-rating shows how many RPMs the motor will achieve if provided with v-number of volts (RPM/volt).

In Table 4, a comparison of the E-Flite Power 110, E-Flite Power 360, and E-Flite power 52 motors can be viewed. The E-Flite Power 110 and E-Flite Power 360 are the motors proposed by the team, while the E-Flite power 52 motor is the motor proposed by intern Cameron Alexander. The E-flite Power 110 motor has a 295Kv value as compared to 590Kv for the E-Flite Power 52 motor and 180 Kv for the E-flite Power 360 motor. This is very significant because in order to generate more thrust, lower Kv values and larger prop sizes is required. For the rotorcraft, the mass of the motors should be minimized. Since 8 motors are going to be used the Power 110 motors would weigh 4kg (8.8 lbs.), the Power 360 motor would weigh 9.81 kg (21.6 lbs.), and the Power 52 motor would weigh 2.8kg (6.16 lbs.). Further the Power 110 and the Power 52 have the same max current, while the Power 360 has a max current of 130 amps. An important characteristic is the maximum voltage for each motor. The more voltage the motor can accept from the battery, the more thrust it will be able to generate to lift the required payload. The Power 360 motor accepts 44.4 volts, which is the most out of any motor under consideration. The cost of using eight E-Flite Power 110 motors is $1,112 as compared to $872 for the E-flight 52 power motor. The most expensive motor is the Power 360, which costs a total of $2,872 and puts the project over budget by itself. Although the E-Flite power 360 motor is the most expensive motor, it is able to generate the necessary power required to lift this rotorcraft, which is demonstrated in section 8.4. Another indication that the motor can generate the necessary lift is the propeller range, which is an outstanding 24”x10” to 25”x12”. The motor that seems to have the least amount of lift capability is the Power 52 motor which only has a propeller range of 12”x 8” to 14”x 7”.

Table 4. Motor Comparison for Each Design

Design	Motor	Kv (RPM/V)	Prop Range	Mass (lbs.)	Max Current (A)	Max Voltage (V)	Power (W)	Cost ($)
Design # 1	**E-Flite Power 52 Brushless Outrunner [13]**	590	12”x 8” to 14”x 7”	0.77	65	22	1650	109
Design # 2	**E-Flite Power 360 Brushless Outrunner [14]**	180	24”x10” to 25”x12”	2.7	130	44.4	6000	359
Design # 3	**E-Flite Power 110 Brushless Outrunner [15]**	295	17”x8” to 19”x10”	1.1	65	38.4	2000	139

Battery Pack - The selected battery needs to be lightweight and provide the necessary power to the motor to run the propellers. The propulsion battery pack must supply high voltage per unit weight in order to minimize the required current draw by the motor [16]. With this in mind, the battery cells will be oriented in series to maximize the battery pack voltage and must be composed of cells with an appropriate electric charge. The battery pack must be composed of several individual cells oriented in a desired configuration to allow for easy installation and removal. The batteries which possess both a higher current capacity and electric charge typically have a higher weight and lower voltage. Battery packs with lower current capacity are lightweight with high pack voltage but have limited life time. The Pulse 5,000mAh (milli-ampere hour) 7S Lipo Pack battery has higher capacity during heavy discharge, longer cycle life, and faster charge capability compared to other batteries with low current capacity, which is a good fit for this project [16]. The second battery under consideration is the E-Flite 3,200 mAh 6S Lipo pack battery. This battery will have a high capacity during heavy discharge and charges relatively quickly. The last battery under consideration is the Thunder Power 5,000 mAh 9S Lipo pack battery. This battery supplies the highest voltage and the most power of all three batteries under consideration. There will be four batteries used, with each battery pack supplying power to two rotors.

Keeping the motor decision in mind, Table 5 shows the specifications on the Pulse battery proposed by the team, the Thunder battery also proposed by the team, and the E-Flite battery proposed by intern Cameron Alexander. The most important thing here as far as generating enough power to have enough thrust to lift the aircraft is the capacity and the voltage supplied. The Pulse battery supplies 25.9 volts as compared to the E-Flite battery which supplies 22.2 volts. The Thunder battery however supplies an outstanding 33.3 volts. The Pulse battery has seven cells in series as compared to the E-Flite battery which has six cells in series and the Thunder battery has nine cells in series. Comparing the capacity, the Pulse battery and the Thunder battery have a capacity of 5,000 mAh as compared to the capacity of 3,200 mAh for the E-flight battery. The current capacity measures how much current a battery will discharge over a specified period of time. Higher mAh ratings do not necessarily reflect how fast current can be drawn, but rather how long a current can be drawn. For this application, in order to travel a mile, a higher mAh rating is needed.

When comparing the discharge of the three batteries, the Pulse battery has a discharge rating (C) of 65, the Thunder battery has a discharge rating of 70 (C), while the E-flight battery has a discharge of 30 (C). The discharge simply lets one know how many amps can be safely drawn from the battery constantly. Since the rotorcraft needs to be as lightweight as possible for the user carrying the backpack as well as to generate more thrust, weight is an important factor. The E-flight battery weighs 0.67kg (1.49 lbs.), the Thunder battery weighs 1.16kg (2.56 lbs.), and the Pulse battery weighs 0.95kg (2.09 lbs.). Using four batteries for the Octo-copter design, the Thunder batteries would weigh 4.65kg (10.24lbs.) as opposed to 3.8kg (8.36lbs.) for the Pulse battery. Looking at all the available fdactors and comparing them to the cost of each battery, a decision to go with either the Thunder battery or the Pulse battery over the E-Flite battery is made because of the batteries' higher capacity, which translates to a longer run time. The Pulse battery and the Thunder battery also supply more power, which allows the system to generate more thrust necessary to lift the rotorcraft. Again, the selection of the battery is very critical when determining the necessary power supplied to lift the rotorcraft. The selection of the final battery and its justification will be discussed in the next section of this report.

Table 5. Battery Comparison for Each Design

Design	Battery	Capacity (mAh)	Voltage (V)	Discharge (C)	Weight per battery (Pounds)	Cost ($)
Design # 1	**E-Flight Lipo Pack [17]**	3,200	22.2	30	1.49	100
Design # 2	**Thunder Power Lipo Pack [18]**	5,000	33.3	70	2.56	419
Design # 3	**Pulse Lipo Pack [19]**	5,000	25.9	65	2.09	196

Propeller - The propeller must be large enough to provide the minimum thrust values. The propeller must also have the required pitch to maintain speed so that navigation within a desired amount of time is possible, even with headwind. With the battery and motor already selected for each design, the propeller size could be evaluated. Propeller dimensions are characterized by diameter and pitch (displayed as diameter x pitch), which are the primary variations in propeller specifications. Larger diameter propellers generate higher thrust but also consume more power. Pitch refers to the angle or twist of the blade. A larger pitch value generally results in a higher maximum velocity but also puts more load on the motor. This results in higher power consumption when velocities are close to the maximum velocity.

There are three main factors used to assess propeller effectiveness: thrust coefficient, power coefficient, and propeller efficiency [20]. Each of these factors is evaluated with respect to the advance ratio, which is a comparison of linear aircraft velocity to propeller blade velocity. It is desirable for the advance ratio to be larger as this indicates that fewer propeller rotations are needed to move a specified shape aircraft at a specified velocity. The propeller diameter-to-pitch ratio for this application should be approximately 2:1. This is because if the pitch is too high related to the diameter, the prop becomes inefficient at low forward speed. This has the greatest effect during take-off and climbing. At the other end of the scale, a propeller designed for greatest efficiency at take-off and climbing (low pitch & large diameter), will accelerate the model very quickly from standstill but will give lower top speed.

The recommended propeller size is already determined based on the motor chosen earlier for each design. Foldable propellers were chosen so the propellers can be disassembled from the rotorcraft in order to fit in the backpack. An APC electric 18”x10” propeller and an APC electric 24”x12” propeller are proposed by the team. These propellers can be taken off which does not affect the integrity of the prop. A Plastic 16.5”x10” propeller was proposed by intern Cameron Alexander. The weight of these propellers is almost negligible. There are some minor differences when comparing these three propellers. The plastic propeller costs $7 as compared to the APC propeller in design # 1 which cost $8. The most expensive propeller is the one in design # 2 which cost $19. Again, the selection of the propeller is very critical when determining the necessary thrust generated to lift the rotorcraft. The selection of the propeller and its justification will be discussed in the next section of this report. Table 6 shows the propeller selections for the three designs.

Table 6. Propeller Comparison for Each Design

Design	Propeller	Prop Size	Weight (Pounds)	Cost ($)
Design # 1	**Plastic [21]**	16.5”x10”	0.17	7
Design # 2	**APC Electric [22]**	24”x12”	0.19	19
Design # 3	**APC Electric [23]**	18”x10”	0.18	8

8.4 Evaluation of Designs

Design # 1 - As mentioned previously, eCalc was used to evaluate the selection of the propeller, motor, and battery. Figure 9 shows the multicopter calculator for design # 1, for which the parts were chosen by intern Cameron Alexander. Beginning the evaluation of Cameron’s components, the number of rotors chosen to enter in eCalc was 2 even though Cameron’s design has six rotors. The reason for this is because eCalc does its calculations based on the number of rotors per battery. Because there will be three batteries used in Cameron’s design, there will be one battery for every two rotors. Next, the configuration of Cameron's design is "flat", meaning one rotor on each arm. This is similar to the V8 configuration in Figure 9.The model weight entered in eCalc for this design is entered at 12,100 grams (26.6 lbs.). The model weight is the sum of the weight for the entire system, including the battery, motor, propellers, and other components for which the **two rotors are expected to lift**. The components and design chosen for the entire system weights roughly 13.6kg (30 lbs.). Adding the payload of 22.7 kg (50 lbs.), the total weight of the system for this design is estimated to be at 36.3kg (80 lbs.)

$$13.6\ kg + 22.7kg = 36.3\ kg \qquad \text{Eq. (8)}$$

Dividing this total weight of the system by 6 rotors in order to determine how much weight each rotor is expected to lift, the model weight is 6.05kg (13.31 lbs.).

$$\frac{36.3\ kg\ (total\ weight)}{6\ rotors} = 6.05\ \frac{kg}{rotor} \qquad \text{Eq. (9)}$$

This means that **each** rotor is expected to be able to lift at least 6.05kg (13.31 lbs.). Finally, since there are two rotors being analyzed for each battery as stated earlier, the model weight is multiplied by 2 and becomes 12,100 grams (26.6 lbs.).

$$6.05\ \frac{kg}{rotor} \times 2\ rotors = 12.1\ kg \qquad \text{Eq. (10)}$$

It should be noted that the "incl. Drive" means that the weight of the battery, motor, frame, and controller is included in the model weight. It does not matter what is entered as the weight of any of the components in the following section because it has already been taken into account in the model weight.

The field elevation for which this rotorcraft is expected to fly at is set at 100 feet. The standard temperature of 77 °F and standard pressure of 101.3 kPa (kilopascals) is also entered in the multicopter calculator. Entering the information for Cameron's E-flite 3,200 mAh 6S Lipo battery, ESC controller, E-flite Power 52 motor, and propeller chosen, eCalc provides the following alerts:

- The maximum current is over the limit of the speed controller.
- The maximum current is over the limit of the motor.
- The prediction of the motor case temperature is over 175 °F which risks overheating.
- The throttle needs to be at least under 80% for minimal maneuverability, and with this design throttle is at 100 %.

For these reasons, Cameron Alexander's design would have failed.

Another factor to note is the "add. Payload" in Figure 9. "add. Payload" states the maximum additional payload possible to hover with 80% throttle to guarantee maneuverability. As can be seen from Figure 9, these components cannot withstand any additional payload. Furthermore, even if the maximum current by the speed controller was changed to 70 amps, the motor would still not be able to draw the proper amount of current. Also significant is that with the components chosen by the intern Cameron Alexander, there is no maximum speed shown in Figure 9. The reason for this is there are no specifications or submitted data about maximum velocity in the eCalc web base that was tested for the components chosen. The maximum speed is the theoretical maximum attainable forward speed in level flight at maximum tilt. The maximum tilt is the theoretical maximum possible tilt of the copter to maintain level flight. The maximum tilt would be less than

General	Motor Cooling: medium	# of Rotors: 2, flat	Model Weight: 12100 g, 426.8 oz	incl. Drive		Field Elevation: 30 m ASL, 100 ft ASL	Air Temperature: 25 °C, 77 °F	Pressure (QNH): 1013 hPa, 29.91 inHg
Battery Cell	Type (Cont. / max. C) - charge state: custom - normal	Configuration: 6 S 1 P	Cell Capacity: 3200 mAh	Total Capacity: 3200 mAh	Resistance: 0.002 Ohm	Voltage: 3.7 V	C-Rate: 65 C cont., 100 C max	Weight: 139 g, 4.9 oz
Controller	Type: max 100A	cont. Curent: 100 A	max. Curent: 100 A		Resistance: 0.0025 Ohm			Weight: 130 g, 4.6 oz
Motor	Manufacturer - Type (Kv): E-flite, Power 52 (590), search...	KV (w/o torque): 590 rpm/V	no-load Current: 2.3 A @ 18.5 V	Limit (up to 15s): 75 A	Resistance: 0.016 Ohm	Case Length: 58 mm, 2.28 inch	# mag. Poles: 14	Weight: 346 g, 12.2 oz
Propeller	Type - yoke twist: APC Electric E - 0°	Diameter: 16 inch	Pitch: 5.5 inch	# Blades: 2	PConst: 1.08	Gear Ratio: 1 : 1		calculate

Remarks:

- max. current over the limit of the speed controller. Choose a bigger esc.
- max. current over the limit of the motor. Please verify the limits (current, power, rpm) defined by the manufacturer!
- the prediction of the motor case temperature is critical (>80°C/175°F). Risk of overheat, please check!
- For minimal maneuverability you need Throttle of less than 80%

Battery		**Motor @ Optimum Efficiency**		**Motor @ Maximum**		**Motor @ Hover**		**Total Drive**		**Multicopter**	
Load:	62.59 C	Current:	56.18 A	Current:	100.14 A	Current:	95.33 A	Drive Weight:	1965 g	All-up Weight:	12100 g
Voltage:	19.80 V	Voltage:	20.71 V	Voltage:	19.55 V	Voltage:	19.67 V		69.3 oz		426.8 oz
Rated Voltage:	22.20 V	Revolutions*:	11339 rpm	Revolutions*:	10269 rpm	Throttle (linear):	100 %	Current @ Hover:	190.67 A	add. Payload:	- g
Flight Time:	1.0 min	electric Power:	1163.5 W	electric Power:	1957.4 W	electric Power:	1875.6 W	P(in) @ Hover:	4232.8 W		- oz
Mixed Flight Time:	0.8 min	mech. Power:	1064.7 W	mech. Power:	1747.3 W	mech. Power:	1696.1 W	P(out) @ Hover:	3392.3 W	max Tilt:	< 5 °
Hover Flight Time:	0.9 min	Efficiency:	91.5 %	Efficiency:	89.3 %	Efficiency:	90.4 %	Efficiency @ Hover:	80.1 %	max. Speed:	- km/h
Weight:	834 g			est. Temperature:	92 °C	est. Temperature:	82 °C	Current @ max:	200.28 A		- mph
	29.4 oz				198 °F		180 °F	P(in) @ max:	4446.2 W		
						specific Thrust:	3.23 g/W	P(out) @ max:	3494.6 W		
							0.11 oz/W	Efficiency @ max:	78.6 %		

Figure 9. Design # 1 Multicopter Calculator Results

5° for this design. Another interesting fact about this design is it cannot lift even a 5lbs payload. With these components the rotorcraft can barely lift its own weight at 99% throttle. This design is eliminated moving forward because it cannot meet the criteria of lifting any payload. Due to all the reasons discussed above, design # 1 proposed over summer would have failed.

Design # 2 - Figure 10 shows the multicopter calculations for the components chosen by the team. The number of rotors chosen to enter in eCalc was 2 and not 8, despite what one might think based on the name Octo-copter. The reason for this is because eCalc does its calculations based on the number of rotors per battery. There will be four batteries in the Octo-copter design, meaning that each battery will power two rotors. Next, the configuration of the Octo-copter design is "coaxial" meaning two identical counter-rotating motors using the same propeller on each arm. This is similar to the X8 configuration in Figure 10. The model weight for this design was found to be 10,680 grams (23.4 lbs.). Again, this is the sum of the weight for the entire system, which the **two rotors** are expected to lift. The components and design chosen weighs roughly 20kg (44lbs.). Adding the payload of 22.7 kg (50 lbs.), the total weight of the system is estimated to be 42.7kg (94 lbs.)

$$20\ kg + 22.7kg = 42.7\ kg \qquad \text{Eq. (11)}$$

Dividing this total weight of the system by 8 rotors results in 5.3kg (11.8 lbs.) to be lifted by each rotor

$$\frac{42.7\ kg\ (total\ weight)}{8\ rotors} = 5.3\,\frac{kg}{rotor} \qquad \text{Eq. (12)}$$

Finally, since there are two rotors being analyzed for each battery as stated earlier, the model weight found in Equation 12 is multiplied by 2 and simply becomes 10,600 grams (23.5 lbs.).

$$5.3\ \frac{kg}{rotor} \times 2\ rotors = 10.6\ kg \qquad \text{Eq. (13)}$$

The weight expected to be lifted by each rotor in design # 2 is 1.4kg (3.1 lbs.) less than that of design #1. The field elevation for which this rotorcraft is expected to fly at is set at 100 feet as it was in design # 1. The standard temperature of 77 °F and standard pressure of 101.3 kPa is also entered in the multicopter calculator as it was in design # 1 to minimize the number of different variables. Entering the components chosen for design # 2 (The Thunder 5,000 mAh 9S Lipo battery, ESC controller, E-flite Power 360 motor, and propellers) resulted in no errors being reported by eCalc. This design is expected to fly.

The flight time for this design is 1 minute and 48 seconds. The flight time is the expected flight time based on all-up weight when flying at maximum throttle (100 % discharge of battery). The mixed flight time is the expected flight time based on all up weight when moving (85% discharge of battery). The mixed flight time expected for this rotorcraft is 2 minutes and 30 seconds. The reason for the mixed flight time being more than the actual flight time is due to the discharge of the battery. For example, if a cellphone is fully charged at 100% and someone is on the phone till it dies, it will drain your battery very fast and it will die. However if the phone is being used 85% of the time and the other 15% is used by screensaver mode, the battery will last longer. The hover flight time is the expected flight time based on all-up weight when hovering only (85% discharge of battery). The hover flight time expected for the components chosen is 2 minutes and 47 seconds.

To make the Octo-copter hover, meaning the Octo-copter stays at a constant altitude without rotating in any direction, a balance of forces is needed. The flight controller will need to counteract the force of gravity with the lift produced by the rotors. The force of gravity acting on the Octo-copter is equal to the mass of the Octo-copter multiplied by gravitational acceleration. It is assumed that gravitational acceleration is a constant because this rotorcraft is not expected to operate at a significantly large altitude. The lift produced by the Octo-copter is equal to the sum of the lift produced by each of its rotors. Therefore, if the force of gravity equals the force of the lift produced by the motors, the Octo-copter will maintain a constant altitude.

If the lift produced by the Octo-copter is greater than the force of gravity, the craft will gain altitude. If the opposite is true, that is, if the lift produced by the Octo-copter is less than the force of gravity acting on the Octo-copter, then the Octo-copter will fall. The maximum attainable forward speed in level flight is not presented in Figure 10. The reason for this is there are no specifications or submitted data about maximum velocity in the eCalc web base that was tested for the components chosen in the co-axial frame. However, if the components selected were put in the "flat" configuration, the maximum speed would be 35.4 miles per hour (mph).

As stated earlier in the report, brushless motors operate at nearly 90% efficiency and the Power 360 motor operates at a maximum efficiency of 88.7%. There are a few draw backs to using this design. The rotorcraft can lift the necessary weight, but cannot fit in a standard size military backpack and the cost of this design is well beyond the budget of this project.

General	Motor Cooling: medium	# of Rotors: 2 coax (BETA-Test)	Model Weight: 10680 g 376.7 oz	incl. Drive		Field Elevation: 30 m ASL 100 ft ASL	Air Temperature: 25 °C 77 °F	Pressure (QNH): 1013 hPa 29.91 inHg
Battery Cell	Type (Cont. / max. C) - charge state: custom - normal	Configuration: 9 S 1 P	Cell Capacity: 5000 mAh	Total Capacity: 5000 mAh	Resistance: 0.002 Ohm	Voltage: 3.7 V	C-Rate: 65 C cont. 100 C max	Weight: 139 g 4.9 oz
Controller	Type: max 100A	cont. Curent: 100 A	max. Curent: 100 A		Resistance: 0.0025 Ohm			Weight: 130 g 4.6 oz
Motor	Manufacturer - Type (Kv): E-flite Power 360 (180) search...	KV (w/o torque): 180 rpm/V	no-load Current: 6.1 A @ 40 V	Limit (up to 15s): 6000 W	Resistance: 0.019 Ohm	Case Length: 98 mm 3.86 inch	# mag. Poles: 14	Weight: 1240 g 43.7 oz
Propeller	Type - yoke twist: APC Electric E - 0°	Diameter: 24 inch	Pitch: 12 inch	# Blades: 2	PConst: 1.08	Gear Ratio: 1 : 1		calculate

Remarks:

Battery		**Motor @ Optimum Efficiency**		**Motor @ Maximum**		**Motor @ Hover**		**Total Drive**		**Multicopter**	
Load:	33.22 C	Current:	90.32 A	Current:	83.05 A	Current:	47.28 A	Drive Weight:	4390 g	All-up Weight:	10680 g
Voltage:	30.31 V	Voltage:	29.82 V	Voltage:	30.10 V	Voltage:	31.48 V		154.9 oz		376.7 oz
Rated Voltage:	33.30 V	Revolutions*:	4907 rpm	Revolutions*:	4980 rpm	Throttle (linear):	77 %	Current @ Hover:	94.55 A	add. Payload:	636 g
Flight Time:	1.8 min	electric Power:	2693.6 W	electric Power:	2500.1 W	electric Power:	1488.3 W	P(in) @ Hover:	3148.7 W		22.4 oz
Mixed Flight Time:	2.5 min	mech. Power:	2388.9 W	mech. Power:	2216.6 W	mech. Power:	1274.4 W	P(out) @ Hover:	2548.8 W	max Tilt:	< 5 °
Hover Flight Time:	2.7 min	Efficiency:	88.7 %	Efficiency:	88.7 %	Efficiency:	85.6 %	Efficiency @ Hover:	80.9 %	max. Speed:	- km/h
Weight:	1251 g			est. Temperature:	79 °C	est. Temperature:	65 °C	Current @ max:	166.11 A		- mph
	44.1 oz				174 °F		149 °F	P(in) @ max:	5531.3 W		
						specific Thrust:	3.59 g/W	P(out) @ max:	4433.1 W		
							0.13 oz/W	Efficiency @ max:	80.1 %		

Figure 10. Design # 2 Multicopter Calculator Results

Design # 3- Figure 11 shows the multicopter calculator for design #3. As in designs 1 and 2, the number of rotors entered in eCalc is 2. The reason for this is because eCalc does its calculations based on the number of rotors per battery as stated earlier. The configuration of this design is "co-axial" meaning one rotor on each arm. The model weight entered in eCalc for this design is 9,090 grams (19.9 lbs.). As stated earlier, the model weight is the sum of the weight for the entire system for which the **two rotors are expected to lift**. The components and design chosen for the entire system weights roughly 13.6kg (30 lbs.). Adding the payload of 22.7 kg (50 lbs.), the total weight of the system for this design is 36.3kg (80 lbs.)

$$13.6\ kg + 22.7kg = 36.3\ kg \qquad \text{Eq. (14)}$$

Dividing this total weight of the system by 8 rotors results in 4.54kg (10 lbs.) to be lifted by each rotor

$$\frac{36.3\ kg\ (total\ weight)}{8\ rotors} = 4.54\,\frac{kg}{rotor} \qquad \text{Eq. (15)}$$

This means that **each** rotor is expected to be able to lift at least 4.54kg (10 lbs.). Finally, since there are two rotors being analyzed for each battery as stated earlier, the model weight found in Equation 15 is multiplied by 2 and simply becomes 9,090 grams (19.9 lbs.).

$$4.54\ \frac{kg}{rotor} \times 2\ rotors = 9.08\ kg \qquad \text{Eq. (16)}$$

The field elevation for which this rotorcraft is expected to fly at is set at 100 feet. The standard temperature of 77 °F and standard pressure of 101.3 kPa (kilopascals) are also entered in the multicopter calculator. Entering the information for design number three's components (Pulse 5,000 mAh 7S Lipo battery, ESC controller, E-flite Power 52 motor, and propellers) results in the following remark from eCalc:

- The throttle needs to be at least under 80 % for minimal maneuverability, and with this design efficiency is at 98 %.

For this reason, design # 3 would not necessarily fail but would be inefficient. There is no good reason to build a rotorcraft that could lift the necessary payload but cannot move to the desired location. Also, these components cannot withstand any additional payload, as can be seen in Figure 11. This implies that if any more weight was to be added to the payload, there will not be enough power to lift the rotorcraft at all.

General	Motor Cooling: medium	# of Rotors: 2 coax (BETA-Test)	Model Weight: 9090 g 320.6 oz	incl. Drive		Field Elevation: 30 m ASL 100 ft ASL	Air Temperature: 25 °C 77 °F	Pressure (QNH): 1013 hPa 29.91 inHg
Battery Cell	Type (Cont. / max. C) - charge state: custom - full	Configuration: 7 S 1 P	Cell Capacity: 5000 mAh	Total Capacity: 5000 mAh	Resistance: 0.002 Ohm	Voltage: 3.7 V	C-Rate: 130 C cont. 150 C max	Weight: 139 g 4.9 oz
Controller	Type: max 100A	cont. Current: 100 A	max. Current: 100 A		Resistance: 0.0025 Ohm			Weight: 130 g 4.6 oz
Motor	Manufacturer - Type (Kv): E-flite - Power 110 (295) search...	KV (w/o torque): 295 rpm/V	no-load Current: 1.2 A @ 10 V	Limit (up to 15s): 65 A	Resistance: 0.03 Ohm	Case Length: 54 mm 2.13 inch	# mag. Poles: 14	Weight: 490 g 17.3 oz
Propeller	Type - yoke twist: APC Electric E - 0°	Diameter: 18 inch	Pitch: 10 inch	# Blades: 2	PConst: 1.08	Gear Ratio: 1 : 1		calculate

Remarks:

- For minimal maneuverability you need Throttle of less than 80%

Battery		**Motor @ Optimum Efficiency**		**Motor @ Maximum**		**Motor @ Hover**		**Total Drive**		**Multicopter**	
Load:	25.42 C	Current:	37.80 A	Current:	63.54 A	Current:	57.03 A	Drive Weight:	2434 g	All-up Weight:	9090 g
Voltage:	25.67 V	Voltage:	26.30 V	Voltage:	25.52 V	Voltage:	25.71 V		85.9 oz		320.6 oz
Rated Voltage:	25.90 V	Revolutions*:	7202 rpm	Revolutions*:	6756 rpm	Throttle (linear):	98 %	Current @ Hover:	114.06 A	add. Payload:	- g
Flight Time:	2.4 min	electric Power:	994.2 W	electric Power:	1621.2 W	electric Power:	1466.5 W	P(in) @ Hover:	3131.5 W		- oz
Mixed Flight Time:	2.2 min	mech. Power:	910.9 W	mech. Power:	1463.6 W	mech. Power:	1334.2 W	P(out) @ Hover:	2668.5 W	max Tilt:	< 5 °
Hover Flight Time:	2.2 min	Efficiency:	91.6 %	Efficiency:	90.3 %	Efficiency:	91.0 %	Efficiency @ Hover:	85.2 %	max. Speed:	- km/h
Weight:	973 g			est. Temperature:	79 °C	est. Temperature:	70 °C	Current @ max:	127.08 A		- mph
	34.3 oz				174 °F		158 °F	P(in) @ max:	3488.7 W		
						specific Thrust:	3.10 g/W	P(out) @ max:	2927.3 W		
							0.11 oz/W	Efficiency @ max:	83.9 %		

Figure 11. Design # 3 Multicopter Calculator Results For 50 Payload

However, using these components and attempting to lift a payload of 11.3 kg (30 lbs.), produced very favorable results. The design would be able to carry this payload as can be seen in Figure 12. It should be noted that with the components chosen, the expected flight time for this design at maximum throttle (100 % discharge of battery) is 2 minutes and 24 seconds The mixed flight time is the expected flight time based on the all-up weight when moving (85% discharge of battery) and is expected to be 3 minutes and 12 seconds. The hover flight time is the expected flight time based on the all-up weight when hovering only (85% discharge of battery). The hover flight time expected for the components chosen with a 13.6kg (30 lbs.) payload is 3 minutes and 36 seconds. This is the best alternative of all three designs. Design # 1 does not have enough power to lift a 22.4 kg (50lbs.) payload, and therefore was eliminated from further analysis. Design # 2 does have enough power to lift the 22.4 kg (50 lbs.) payload, but was eliminated from further analysis due to cost and inability to fit within the backpack. Design # 3 provides the highest amount of lift while still being cost effective. This design can fit in the backpack via partial disassembly as can be seen in the next section of this report, which also made this design even more appealing. A 13.6kg (30lbs.) payload is still substantial considering how few previous rotorcrafts with a similar budget have actually lifted 13.6kg (30lbs.).

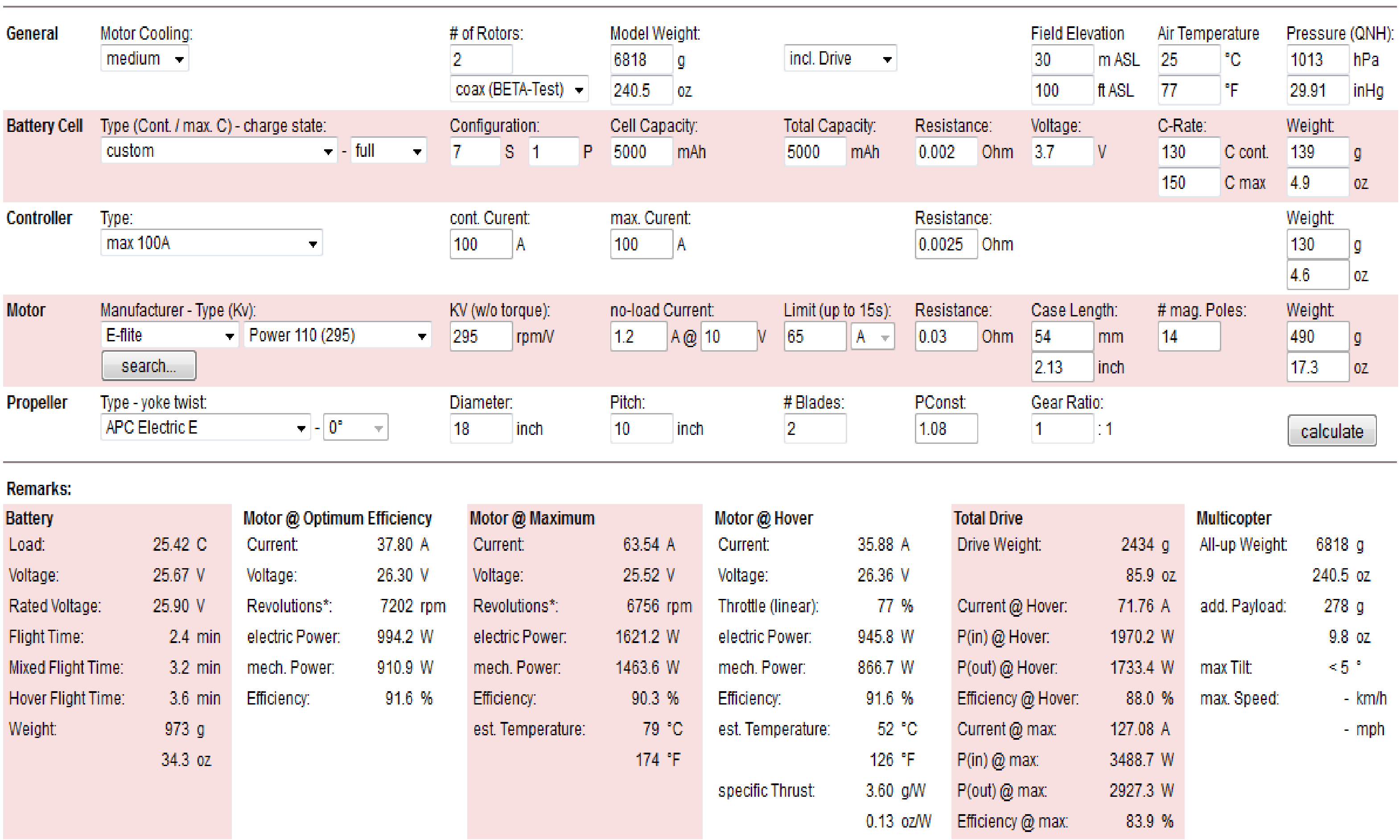

Figure 12. Design # 3 Multicopter Calculator Results for 30 Payload

A summary of the designs chosen can be seen in Table 7. Looking at Table 7, it's clear that design #1 cannot lift the 22.4kg (50lbs.) payload. This is because the maximum current is over the limit of the speed controller and the motor, the motor has the possibility to overheat, and the throttle is at 100% so maneuverability is going to be difficult. Design # 2 is able to lift the 22.4kg (50lbs.) payload and has full maneuverability of the rotorcraft, but was not chosen due to budget constraints and propeller size. The propeller size and how it plays into the elimination of design #2 which will be discussed in further detail in section 8.5. Design # 3 was able to lift the payload at 98% throttle. meaning maneuverability is minimal. However, because the design is able to lift a 13.6kg (30 lbs.) payload while still being cost effective as will be shown in the coming sections, design #3 was chosen to move forward with this project.

Table 7. Multicopter Calculator Summary for the Three Designs

Design	Lift Payload of 50 Lbs.	Comments
Design #1	No	-Max current over limit for speed controller and motor -Motor overheat potential -Throttle at 100% (minimal maneuverability)
Design #2	Yes	-Throttle at 77% (full maneuverability)
Design #3	Conditionally	-Throttle at 98% (minimal maneuverability)

8.5 General Design and Assembly

Due to the size constraint of the backpack, as previously stated the rotorcraft will have to be collapsible. When the rotorcraft is not in use it will be folded up and will look similar to a table that has been placed upside-down on its tabletop. However, the tabletop will be the bottom plate where the hook will be connected. When placed in the backpack, the rotorcraft will not have any of the propellers in place. This is because when connected, one end of the propeller sticks out of the top of a backpack that is 23 inches in height. It hangs out by 4 inches for design #1 as can be seen below in Figure 13. Design # 2 uses the largest size propeller and its props hang out by 12 inches. Design # 3 uses props a little bit bigger than that of Design # 1 and its propellers hang out by 6 inches. Some possible alternatives in order to fix this issue is by potentially adding a flap or extra section to the top of the backpack so that the propellers fit. Another solution would be to dissemble the propellers from the Octo-copter and have them stored away in another compartment of the backpack. This is still under consideration and will be further examined in the implement phase next semester.

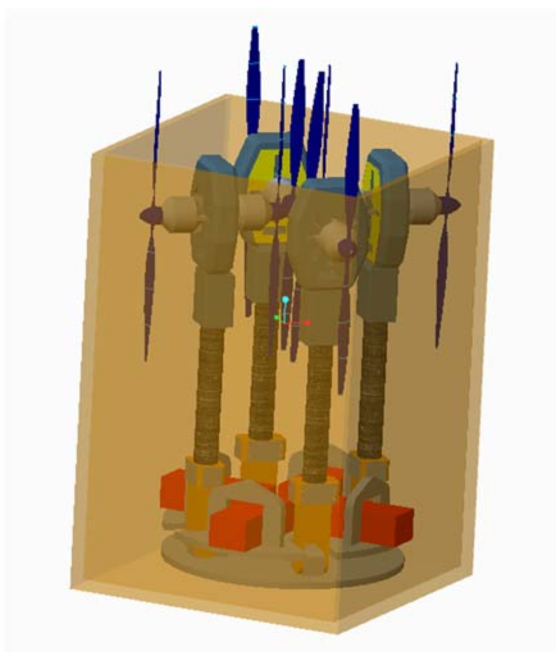

Figure 13. Design #1 Displayed in the Backpack

The rotorcraft will have a height of approximately 20 inches. This number was calculated based on the thickness of two base plates, the distance between them (a total of 3.5 inches for both plates and space between), and the height of the arms with motor mountings. In order to further compact the design, the mounting motor piece will be rotated 90^{o} in relation to its functioning position, if this were not done the shafts from the motor will be pressing/poking the side casing of the backpack. This may damage the backpack and the shafts as well.

Though initially the battery was to be placed between the two plates, this is not possible because the batteries are larger than the gap between the plates. If the gap were to be enlarged to fit the batteries, the rotorcraft would be too tall to fit into the backpack, even with smaller propellers. The battery will be placed on the top plate, with the other electrical components residing in between the two plates. The batteries can be held in place above the craft simply by strapping or clamping them down. The thicknesses of all the electrical components are very thin and will easily fit in the gap between the plates. An added bonus of placing the electrical components within is that they are much better protected from the weather than if they were on top.

When the rotorcraft is being prepared for flight, the arms will fold out and down from a hinge joint as can be seen in Figure 14. The top plate will twist and lock in place to ensure that the arms will not pop out of position when in flight due to rough weather conditions or obstacles. The hinge will also have its own lock mechanism. The mounting motor arms will be rotated 90^{o} so that the motor shafts are vertically aligned. There will be groove markings to ensure that they are positioned properly because if placed incorrectly this will affect the flight of the rotorcraft. Last to be assembled will be the propellers which will be screwed into place.

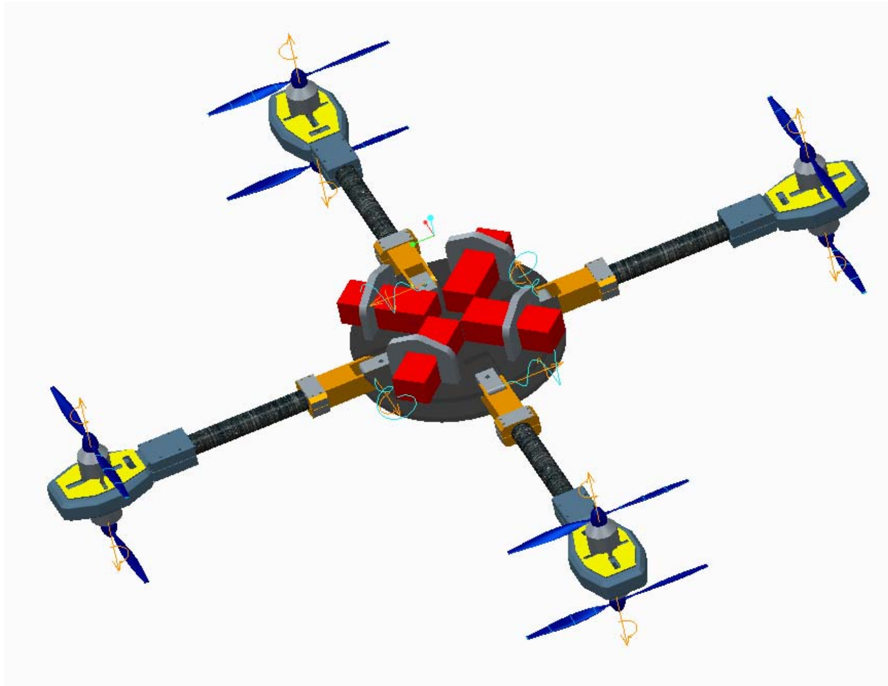

Figure 14. Octo-copter Before Take Off

8.6 Stress Analysis

To further compare the rotorcraft design done by Cameron Alexander and the designs produced by the senior design team, a stress analysis was performed on the design created by team and then compared to the stress analysis previously done by Cameron. Though the team created two designs, the arms and base plate of the rotorcraft is the same in both designs. Because of this, only one stress analysis for the team's work is necessary. The main purpose of this analysis was to ensure that the rotorcraft could handle carrying a 50 pound load without any permanent deformation to the arms or baseplate. This stress analysis was performed in the Creo-Parametric software. In order to perform the stress analysis, all of the components of the rotorcraft were first built and assembled in Creo-Parametric and then the 50 pound load was put on two portions of the craft separately.

First, for the teams design, the entire load was put onto the hook at the bottom of the portion of the base plate called the base circle. Figure 15 shows a bottom-side view of the displacement the load caused on the base circle. The pink outline above the base circle signifies the location of the base circle before the load caused any displacement. The shading on the plate represents the amount of displacement the load caused on different portions in millimeters. A key to the amount of displacement each color represents can be seen on the upper right hand corner of Figure 15. The maximum displacement that the load caused was 0.00142 mm. This maximum displacement occurred on the outer edge of the base circle and on the bottom of the hook where the load was placed. Figure 16 shows a top-side view of the same base circle under the same 50 pound load.

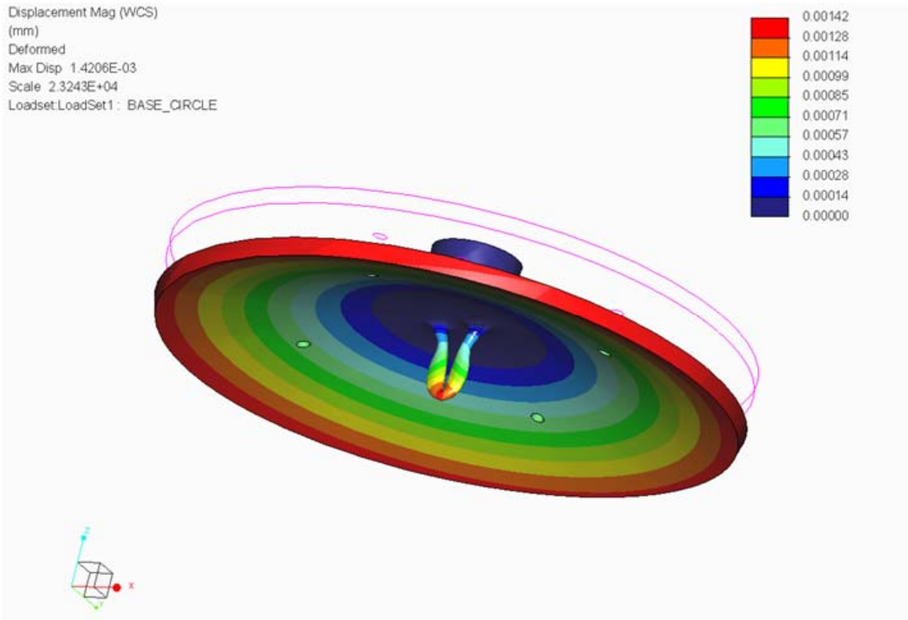

Figure 16. Bottom-Side View of Creo-Parametric Base Circle Stress Analysis

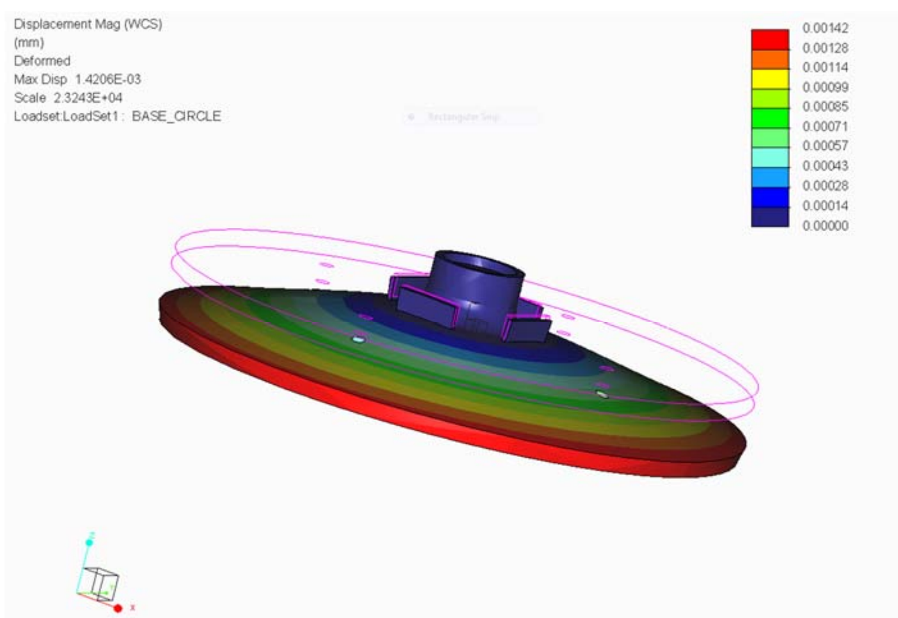

Figure 15. Top-Side View of Creo-Parametric Base Circle Stress Analysis

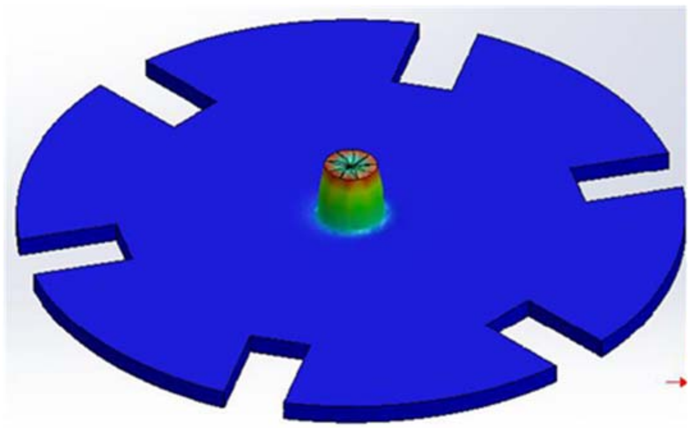

Figure 18. Bottom-Side View of Cameron’s Design with Load on Center of Base Plate

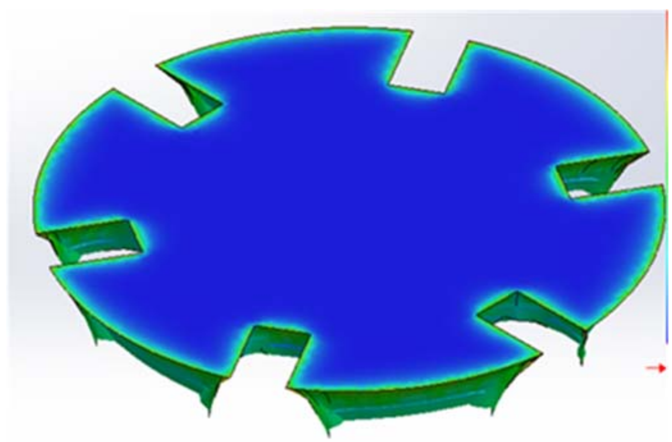

Figure 17. Bottom-Side View of Cameron’s Design with Load on Base Plate

The amount of deformation that occurred was at a maximum on the outer edge of the base circle and decreased inwardly towards the center of the plate. The stress analysis showed that only elastic deformation occurred on the base circle meaning that once the load was removed from the craft the base circle would return to its original, not deformed location. Based on the stress analysis done on the base circle it is anticipated that the carbon fiber used should not have any plastic, or permanent, deformation from the load and the maximum temporary deformation on the plate would be 0.00142 mm. Because of this, carbon fiber is an appropriate material for the base circle. This analysis was then compared to the analysis done by Cameron. Figure 17 and Figure 18 show the yield stress of the plate if the load were to be placed on the hook or on the entire plate respectively. Unfortunately a full comparison of the design's stress analysis is not possible due to limited information provided by Cameron. Neither the amount of deformation that the plate in his design underwent from the load nor what the colors in his stress analysis meant were available. However from his report, it is clear that the parts did not fail meaning that no plastic deformation occurred from the load.

Next, a stress analysis was performed on the arms of the team's rotorcraft design. This was done by putting the entire 50 pound load on the end of an individual arm of the craft. This is the worst case scenario for any arm because as a force is moved from the center of a body to the farthest and least constrained point, in this case the end of an arm, the deformation will increase to a maximum. Figure 19 shows the displacement map from the stress analysis of an arm. Again, the pink outline above the arm represents the original location of the arm before the 50 pound load and the colors on the arm represent the amount of displacement that occurred. As expected, the maximum deformation occurs at the end of the arm where the displacement is 0.71894 mm while no displacement of the arms occurs where the arms are attached to the base of the rotorcraft. Again, only elastic deformation occurs on the arms. Based on the stress analysis performed on the arms, the carbon fiber is anticipated to not have any plastic deformation and so the carbon fiber is an appropriate material for this application. This was next compared to the stress analysis done by Cameron. Cameron's design stress analysis for the arms can be seen in Figure 20. Unlike the team's stress analysis where amount of deformation was determined; Cameron again tested for yield stress and placed the load at the center of the arm instead of the end. This means that more deformation could occur if the load was put onto the end of the arm not attached to the rotorcraft. Again, due to limited information available on his design it was not possible to perform a stress analysis with the load at the end of the arms. The stress analysis showed that small elastic deformation occurred at the center of the arm where the colors range from red to green. No deformation occurred at either end of the arm where the shading is all blue. Again, no permanent plastic deformation occurred on the arms. Because of this in terms of stress analysis both Cameron's design and the team's design can support a 50 pound load without any permanent deformation to the craft.

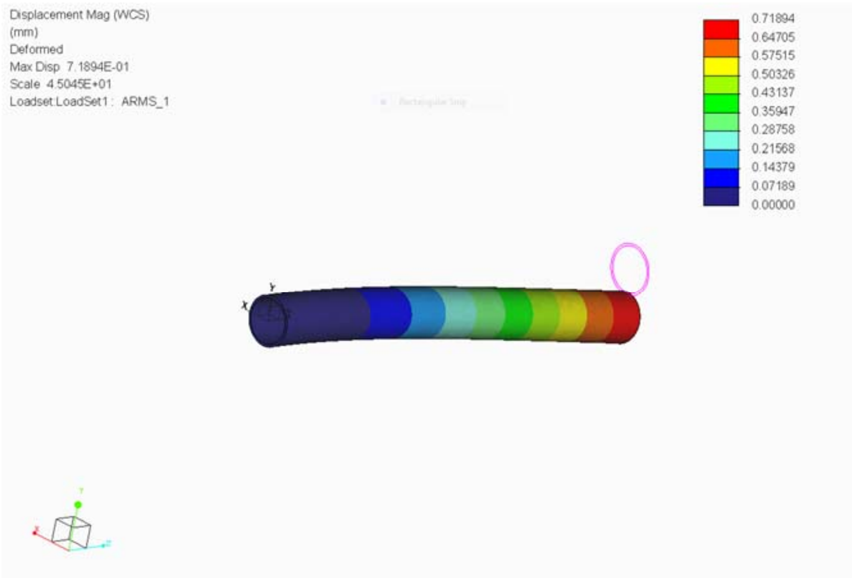

Figure 19. Side View of Creo-Parametric Arm Stress Analysis

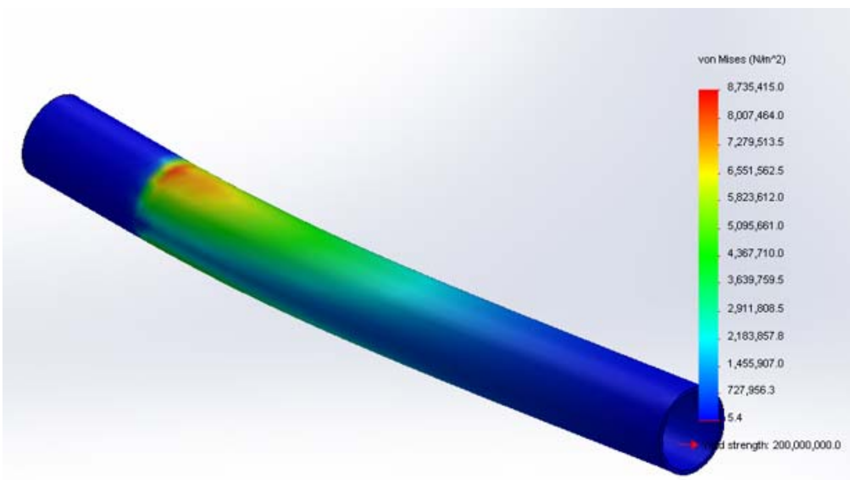

Figure 20. Cameron's Stress Analysis on Arms

9 Electrical Components

Microcontroller - For this design, the group selected the Arduino Leonardo board to serve as the microcontroller. One of the main reasons this particular controller was chosen over other available microcontrollers was the amount of pins offered by the board. The Arduino Leonardo offers 20 digital input/output pins and 12 analog input pins [24]. The design for this project has eight propellers, so at least eight digital inputs are required to control the propellers. The RC transmitter will also be considered a digital input, so there must be enough digital I/O ports for the RC transmitter in addition to the eight required for the propellers. The analog inputs correspond to the degrees of freedom available for the IMU sensor. The IMU sensor that has been chosen offers nine degrees of freedom, so the microcontroller must have at least this many analog inputs [24].

Another reason this board was chosen over others was the ease of use in terms of programming. This board can be programmed in the C++ programming language, which is a programming language in which both of the electrical and computer engineering team members are comfortable programming. As such, initial work as well as proof reading and error checking between the two team members will be smoother and easier than if one or both programmers were unfamiliar with the language.

As an extra precaution, the Arduino brand has many tutorials and trials available for users who are new to their controllers. This means if the members encounter a problem with the microcontroller, there are outside methods available for problem solving instead of relying on team member knowledge.

Most importantly, the cost of this microcontroller along with the others is very comparable. Many boards are priced in between $20-$40, whether they are Arduino brand or not. The Arduino Leonardo board is roughly $23. The decision to use an Arduino Leonardo is a sound choice based on hardware, software, and component cost.

The location of the microcontroller is very important for the design of the craft. This component of the project will be placed inside of the frame of the craft. This location serves to protect the microcontroller from environmental elements. If the controller is placed inside the craft, weather such as rain or snow will not have as much of an effect on the performance of the controller as it would if the controller were unprotected. Electronically speaking, this rotorcraft will be able to function in all weather conditions because the brain of the rotorcraft will be protected at all times. The microcontroller is also extremely light compared to the rest of the rotorcraft components. Thus, placing the controller inside of the frame will not add any significant weight to the craft and the forces required to lift the craft as well as the weight of the rotorcraft are not heavily affected by this component.

IMU Sensor - For this project's chosen design, the Adafruit 9 DOF (degrees of freedom) IMU sensor was selected. This IMU sensor was chosen over the other sensors available in particular for its compatibility with the Arduino microcontrollers. In addition, the IMU sensor must have at least 6 degrees of freedom in order could travel in all directions as well as measure the speed and acceleration in these directions [25]. The 9 DOF board provides all these capabilities, along with the potential capability to track where the craft has flown. This capability could be useful to further improvements on this rotorcraft design, even though it is beyond the scope of this project.

Another reason why this sensor was selected was because it comes with a voltage regulator. This voltage regulator prevents the sensor from burning out during operation. The IMU sensor can be connected directly to the power source for the microcontroller and will regulate itself. Further protection methods for the IMU sensor include placement inside the frame of the rotorcraft. This will protect the IMU sensor for the same reasons that placement inside the frame of the rotorcraft protects the microcontroller.

10 Schedule

The full Gantt chart for the Measure phase of this project can be found in **Appendix C**. Some of the tasks, their planned start and duration, actual start and duration, and percent completion can be found below in Table 8.

Table 8. Partial Task List for Measure Phase Scheduling

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Track Down Rotorcraft Parts	4	8	4	13	**100%**
Order Parts	25	1			**0%**
UAV Seminar	14	1	14	1	**100%**
VARTM Demonstration with Jerry Horne	21	1	21	1	**100%**

At the beginning of the Measure phase, the team expected to be able to easily track down the rotorcraft parts previously ordered during the summer. The process of finding the rotorcraft parts was longer than expected and culminated in the discovery that no parts had been ordered other than the propellers. Because of this, the actual duration is much longer than the planned duration and the task of ordering parts was partially delayed.

As of the writing of this report, the parts for the rotorcraft have not been ordered. This is partially due to the delay in tracking down the previous parts and partially due to a delay in finalizing component selection. The team worked to verify that the selected parts would be able to accomplish the goals of this project, which is explored in more detail later in this report.

Two separate events with field experts were held during the Measure phase. The first was a seminar on unmanned aerial vehicles with Lawrence M. Harvey from Gulf Unmanned Systems Center held at the AME (Aero-Propulsion, Mechatronics and Energy) building. The second was a demonstration of the VARTM (Vacuum Assisted Resin Transfer Method) in creating composite materials with Jerry Horne at HPMI (High Performance Materials Institute). Both of these expert events were vital in improving team member understanding of research applicable to this project.

As of the writing of this report, a Gantt chart for the spring semester has not be compiled. This planning will take place over the winter break, which begins on December 13, 2014.

11 Bill of Materials

The budget for this project is $2,500 as provided by Dr. Okoli and Dr. Dickens. After doing research on the components necessary for this project, a bill of materials was compiled and can be seen in Table 12. This report provides several bills of materials for three different design. Design 3 has two associated bills of materials - Table 11 is a list of what our team will be actually ordering, and Table 12 is a list of everything that is needed to make the rotorcraft. The other items that are not included in Table 11 are being provided to the team by outside sources. Even with the exclusion of donated items, our team exceeds the budget by about $130.62. As such, the budget must be expanded in order for the team to build the prototype rotorcraft. The total cost of the rotorcraft is $3,700, assuming that all components must be purchased and none are donated.

After further analysis of the designs, our team discovered that the Define phase component list was incomplete. Our team also discovered that the Define phase preliminary calculations were incorrect and the components originally selected would not lift the rotorcraft. Due to these errors, this project will go over budget despite previous claims. Another factor affecting the budget is the requirement that all components be made by companies based in the United States. For example, the Power 110 Brushless Outrunner Motor, 295kv that was selected has a cost of $139.99 per motor, while the equivalent Turnigy G110 Brushless Outrunner 295kv has a cost of $69.62 per motor. The Turnigy motor is manufactured in China, so the more expensive option must be selected. This is true for several components previously selected in the Define phase.

Table 10 lists a bill of materials for of Design 2, which would only fit in the backpack but not carry the 50lb payload. Design 2 has a different motor, battery, and propeller when compared to Design 3. The motor used for Design 2 costs about 61% more than Design 3, and the battery costs about 53% more. The bill of materials for Cameron’s design has different batteries, motors, propellers, and material in creating the arms, as can be seen in Table 9. Compared to Design 3, Cameron’s design has a slightly cheaper battery, motor, and propeller. The overall total between the three design shows that Design 1 is the most financially feasible.

Table 9. Design # 1: Cameron's Bill of Materials

Part Name	Qty	Unit Cost	Cost
E-Flite Power 52 Brushless Outrunner	6	$ 109.99	$ 659.94
3200mAh 6S 22.2V 30C LiPo, 12AWG EC3	6	$ 99.99	$ 599.94
Plastic 16.5"x10" propeller	6	$ 7.00	$ 42.00
XP-100A-HV ESC High Voltage Brushless Electronic Speed Controller	6	$ 99.99	$ 599.94
Arduino Leonardo ATmega32u4 with headers	1	$ 24.95	$ 24.95
Adafruit 10-DOF IMU Breakout - L3GD20H + LSM303 + BMP180	1	$ 29.95	$ 29.95
With 2:1 Ratio Slow Epoxy Hardener (32 oz.)	1	$ 41.95	$ 41.95
PVA Release Film (1 Gal)	1	$ 24.75	$ 24.75
High-Strength Carbon Fiber Tube, 1.313" OD, 1.188" ID, .063" Wall Thick(6ft)	5	$ 230.59	$ 1,152.95
Hard High-Strength 7075 Aluminum, .375" Thick, 24"x24	2	$ 308.04	$ 616.08
Yellow Sealant Tape ½" wide; 1⁄8" thick; 25 feet per roll	1	$ 7.95	$ 7.95
3/8 in. x .170 in. x 25 ft. Polyethylene Tubing	1	$ 4.99	$ 4.99
Stretchlon 200 Bagging Film (1 yd roll)	2	$ 4.95	$ 9.90
Nylon Release Peel Ply (1 yd roll)	2	$ 12.95	$ 25.90
		Total Cost	$ 3,841.19

Table 10. Design #2 Bill of Material

Part Name	Qty	Unit Cost	Cost
E-Flite Power 360 Brushless Outrunner	8	$ 359.99	$ 2,879.92
Thunder Power Lipo Pack(5000mAh 9-Cell/9S 33.3V G8 Pro Force 70C LiP)	8	$ 419.99	$ 3,359.92
APC Electric Propeller 24"x12"	8	$ 19.00	$ 152.00
XP-100A-HV ESC High Voltage Brushless Electronic Speed Controller	8	$ 99.99	$ 799.92
Arduino Leonardo ATmega32u4 with headers	1	$ 24.95	$ 24.95
Adafruit 10-DOF IMU Breakout - L3GD20H + LSM303 + BMP180	1	$ 29.95	$ 29.95
With 2:1 Ratio Slow Epoxy Hardener (32 oz.)	1	$ 41.95	$ 41.95
PVA Release Film (1 Gal)	1	$ 24.75	$ 24.75
High-Strength Carbon Fiber Tube, 1.313" OD, 1.188" ID, .063" Wall Thick(6ft)	5	$ 230.59	$ 1,152.95
Hard High-Strength 7075 Aluminum, .375" Thick, 24"x24	2	$ 308.04	$ 616.08
Yellow Sealant Tape ½" wide; 1⁄8" thick; 25 feet per roll	1	$ 7.95	$ 7.95
3/8 in. x .170 in. x 25 ft. Polyethylene Tubing	1	$ 4.99	$ 4.99
Stretchlon 200 Bagging Film (1 yd roll)	2	$ 4.95	$ 9.90
Nylon Release Peel Ply (1 yd roll)	2	$ 12.95	$ 25.90
		Total Cost	$ 9,131.13

Table 11. Design #3 Bill of Material Ordering

Part Name	Qty	Unit Cost	Cost
Power 110 Brushless Outrunner Motor, 295Kv	8	$ 139.99	$ 1,119.92
XP-100A-HV ESC High Voltage Brushless Electronic Speed Controller	8	$ 99.99	$ 799.92
APC 18x10 E-Prop	8	$ 9.96	$ 128.00
Arduino Leonardo ATmega32u4 with headers	1	$ 24.95	$ 24.95
Adafruit 10-DOF IMU Breakout - L3GD20H + LSM303 + BMP180	1	$ 29.95	$ 29.95
With 2:1 Ratio Slow Epoxy Hardener (32 oz.)	1	$ 41.95	$ 41.95
PVA Release Film (1 Gal)	1	$ 24.75	$ 24.75
High-Strength Carbon Fiber Tube, 1.313" OD, 1.188" ID, .063" Wall Thick(6ft)	2	$ 230.59	$ 461.18
		Total Cost	$ 2,630.62

Table 12. Design #3 Bill of Material Overall

Part Name	Qty	Unit Cost	Cost
Power 110 Brushless Outrunner Motor, 295Kv	8	$ 139.99	$ 1,119.92
XP-100A-HV ESC High Voltage Brushless Electronic Speed Controller	8	$ 99.99	$ 799.92
PULSE LIPO 5000mAh 25.9V 65C- ULTRA POWER SERIES	4	$ 196.99	$ 787.96
APC 18x10 E-Prop	8	$ 9.96	$ 128.00
Arduino Leonardo ATmega32u4 with headers	1	$ 24.95	$ 24.95
Adafruit 10-DOF IMU Breakout - L3GD20H + LSM303 + BMP180	1	$ 29.95	$ 29.95
5.7oz Twill Carbon Fiber Fabric 3k (6ft)	5	$ 35.50	$ 177.50
With 2:1 Ratio Slow Epoxy Hardener (32 oz.)	1	$ 41.95	$ 41.95
PVA Release Film (1 Gal)	1	$ 24.75	$ 24.75
High-Strength Carbon Fiber Tube, 1.313" OD, 1.188" ID, .063" Wall Thick(6ft)	2	$ 230.59	$ 461.18
Yellow Sealant Tape ½" wide; 1⁄8" thick; 25 feet per roll	1	$ 7.95	$ 7.95
3/8 in. x .170 in. x 25 ft. Polyethylene Tubing	1	$ 4.99	$ 4.99
Stretchlon 200 Bagging Film (1 yd roll)	2	$ 4.95	$ 9.90
Nylon Release Peel Ply (1 yd roll)	2	$ 12.95	$ 25.90
		Total Price	$ 3,644.82

12 Conclusion

The objectives for this project are as follows:

1. Design a rotorcraft that can:

   a. Fit in a military backpack (23x14.5x15)

   b. Can carry a payload of at least 50 pounds

   c. Made with COTS components (off the shelf)

   d. Has a range of approximately 1 mile

   e. Easy to maintain and use in the field

2. Design the manufacturing processes to be used in creating the rotorcraft described in Goal

3. Build a prototype of the rotorcraft described in Goal 1.

Based on critical customer requirements, fishbone diagram, and the House of Quality diagram the team focused on being able to generate enough thrust to lift 50 pounds for this measure phase. The three essential components necessary to generate thrust are the battery, motor, and propeller. Design # 1 presented by the intern failed because the maximum current supplied would be over the limit of the motor and the speed controller. Design # 2 was able to lift the 22.4 kg (50 lbs.) payload but cannot fit in a standard military backpack and the components necessary to build the rotorcraft are beyond the budget of this project. After extensive research in to find the cheapest components that falls within the specifications necessary, design # 3 was chosen. Design # 3 includes the E-flite Power 110 motor, 5000mAh Pulse battery, and an 18x10 propeller because they provide the best opportunity to build high portable and high payload capacity design. These components generated the most amount of lift, while yet still being cost effective. Although when carrying a 22.4kg (50 lbs.) payload the design is running at 98% throttle, it can still lift it with minimum maneuverability. However, when carrying a 13.6kg (30lbs.) payload, the rotorcraft is able to operate at very high efficiency.

The coaxial setup was chosen for the Octo-copter because it has more room to fit larger props and motors, which allows more thrust and lifting capacity. The coaxial frame also is easier to transport because there is less arms involved. Several materials were analyzed, including glass fiber and carbon fiber. Ultimately carbon fiber was chosen because it provides the best combination of strength and weight. Although, glass fiber is significantly cheaper than carbon fiber, the weight would be too much to overcome with any of the components chosen. Also Creo-Parametric 2.0 drawings was constructed in order to show how the rotorcraft actually would fit in the backpack, and in order to show the simulation of the rotorcraft for the sponsor. From these drawings it was concluded that no propeller or design would be able to fit in the backpack without it being disassembled from the rotorcraft. Some electrical components such as the RC transmitter and IMU sensor are still being analyzed.

The next step for this project is to speak with Dr. Okoli and Dr. Dickens in order to verify the design chosen is acceptable. The following steps would be to order the parts so that the team can move forward with building the high portable high payload rotorcraft in the next phase of this project. This lightweight, high portability, high payload rotorcraft is going to change the rotorcraft industry for the better.

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Appendix A – Equations used in glass fiber versus carbon fiber comparison

Mass $m = AL\rho$ (Eqn. A)

Stiffness $S = \frac{C_1 EI}{L^3}$ (Eqn. B)

2nd moment of inertia $I = \frac{\pi}{4}({r_o}^4 - {r_i}^4) \cong \pi r^3 t$ for $t \ll r_o \; or \; r_i$ (Eqn. C)

Area $A = \pi({r_o}^2 - {r_i}^2) \cong 2\pi rt$ (Eqn. D)

Resultant mass of the arm in terms of stiffness

$$\boxed{m = \left(\frac{8SL^6\pi^2t^2}{C_1}\right)^{1/3}\left(\frac{\rho}{E^{\frac{1}{3}}}\right)} \quad \text{(Eqn. E)}$$

$$F = \frac{CZ\sigma}{L} \quad \text{(Eqn. F)}$$

Section Modulus $Z = \frac{\pi}{4r_o}({r_o}^4 - {r_i}^4) \cong \pi r^2 t$ (Eqn. G)

Resultant mass of the arm in terms of strength

$$\boxed{m = \left(\frac{4F\pi L^3 t}{C_2}\right)^{1/2}\left(\frac{\rho}{\sigma^{\frac{1}{2}}}\right)} \quad \text{(Eqn. H)}$$

Frequency $f = \frac{C_3}{2\pi}\sqrt{\frac{EI}{m_o L^4}}$ (Eqn. I)

Mass per unit length $m_o = \rho A$ (Eqn. J)

Resultant mass required to overcome vibrational frequencies from rotors

$$m = \left(\frac{4\pi f L^3 t}{C_3}\right)\left(\frac{2\rho}{E}\right)^{1/2} \quad \text{(Eqn. K)}$$

Resultant mass of the plate in terms of Stiffness

$$\boxed{m = \left(\frac{12SL^6b^2}{C_1}\right)^{1/3}\left(\frac{\rho}{E^{\frac{1}{3}}}\right)} \quad \text{(Eqn. L)}$$

Resultant mass of the plate in terms of Strength

$$\boxed{m = \left(\frac{6FL^3}{C_2}\right)^{1/2}\left(\frac{\rho}{\sigma^{\frac{1}{2}}}\right)} \quad \text{(Eqn. M)}$$

Appendix B – Force equilibrium calculations

Force Equilibrium for Design # 1:

$$\sum F_y = Lift\ Forces + System\ Weight = 0$$

$$\sum F_y = 6L + (-30\ lbs) + (-50\ lbs) = 0$$

Where L is lift generated, W_s is the weight of system, and W_p is the weight of the payload

$$\sum F_y = 6L + (-80\ lbs) = 0$$

$$\sum F_y = 6L = 80\ lbs$$

$$\sum F_y = L = \frac{80\ lbs}{6\ rotor}$$

$$\sum F_y = L = 13.33\ \frac{lbs}{rotor}$$

Force Equilibrium for Design # 2:

$$\sum F_y = Lift\ Forces + System\ Weight = 0$$

$$\sum F_y = 8L + (-47\ lbs) + (-50\ lbs) = 0$$

Where L is lift generated, W_s is the weight of system, and W_p is the weight of the payload

$$\sum F_y = 8L + (-97\ lbs) = 0$$

$$\sum F_y = 8L = 97\ lbs$$

$$\sum F_y = L = \frac{97\ lbs}{8\ rotor}$$

$$\sum F_y = L = 12.13 \frac{lbs}{rotor}$$

Force Equilibrium for Design # 3:

$$\sum F_y = Lift\ Forces + System\ Weight = 0$$

$$\sum F_y = 8L + (-35\ lbs) + (-50\ lbs) = 0$$

Where L is lift generated, W_s is the weight of system, and W_p is the weight of the payload

$$\sum F_y = 8L + (-85\ lbs) = 0$$

$$\sum F_y = 8L = 85\ lbs$$

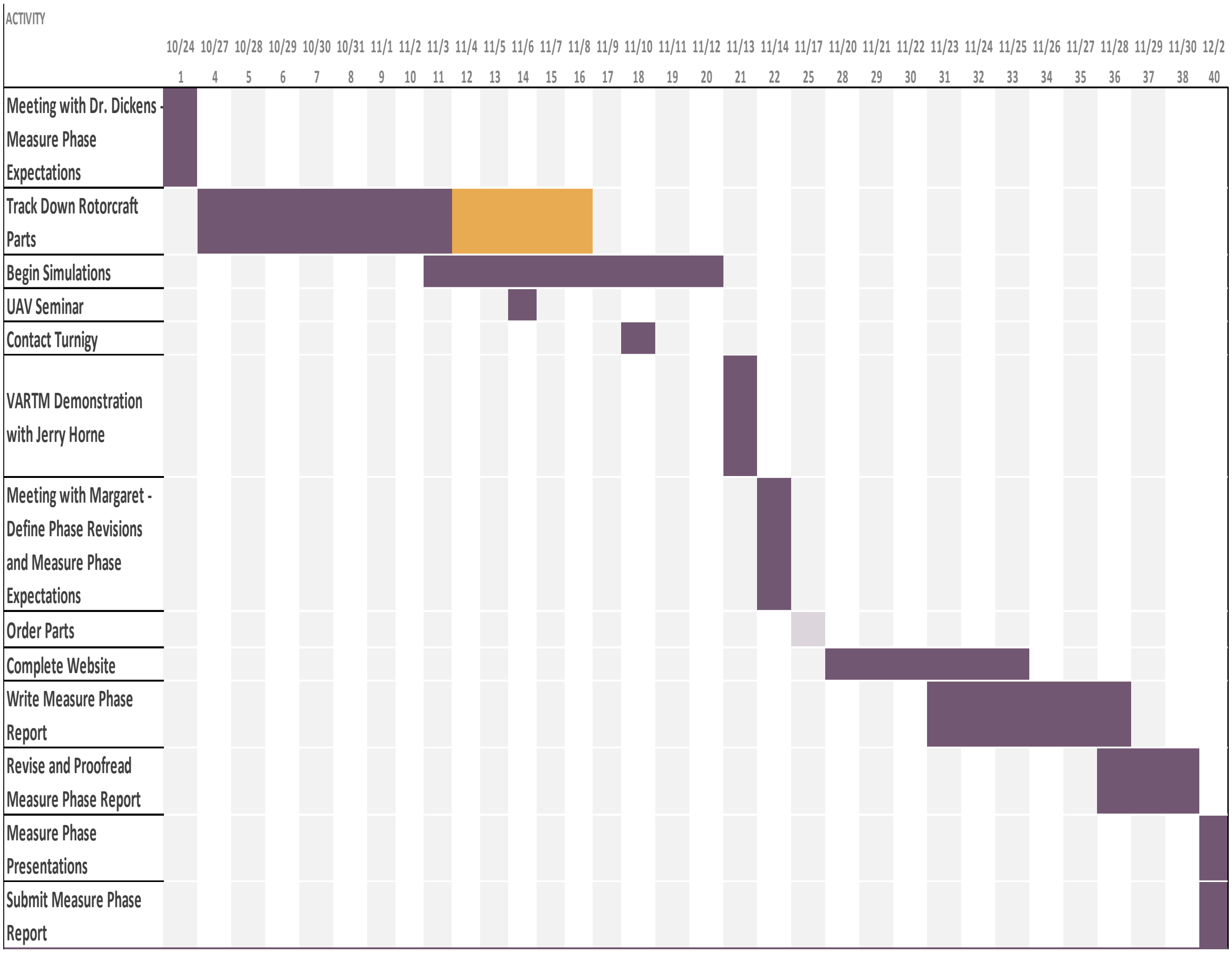
$$\sum F_y = L = \frac{85\ lbs}{8\ rotor}$$

$$\sum F_y = L = 10.64 \frac{lbs}{rotor}$$

Appendix C – Gantt chart

Measure Phase Gantt Chart

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Meeting with Dr. Dickens - Measure Phase Expectations	1	1	1	1	**100%**
Track Down Rotorcraft Parts	4	8	4	13	**100%**
Begin Simulations	11	10	11	10	**100%**
UAV Seminar	14	1	14	1	**100%**
Contact Turnigy	18	1	18	1	**100%**
VARTM Demonstration with Jerry Horne	21	1	21	1	**100%**
Meeting with Margaret - Define Phase Revisions and Measure Phase Expectations	22	1	22	1	**100%**
Order Parts	25	1			**0%**
Complete Website	28	6	28	6	**100%**
Write Measure Phase Report	31	6	31	6	**100%**
Revise and Proofread Measure Phase Report	36	3	36	3	**100%**
Measure Phase Presentations	40	1	40	1	**100%**
Submit Measure Phase Report	40	1	40	1	**100%**


ACTIVITY
10/24 10/27 10/28 10/29 10/30 10/31 11/1 11/2 11/3 11/4 11/5 11/6 11/7 11/8 11/9 11/10 11/11 11/12 11/13 11/14 11/17 11/20 11/21 11/22 11/23 11/24 11/25 11/26 11/27 11/28 11/29 11/30 12/2
1 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 25 28 29 30 31 32 33 34 35 36 37 38 40
Meeting with Dr. Dickens - Measure Phase Expectations
Track Down Rotorcraft Parts
Begin Simulations
UAV Seminar
Contact Turnigy
VARTM Demonstration with Jerry Horne
Meeting with Margaret - Define Phase Revisions and Measure Phase Expectations
Order Parts
Complete Website
Write Measure Phase Report
Revise and Proofread Measure Phase Report
Measure Phase Presentations
Submit Measure Phase Report