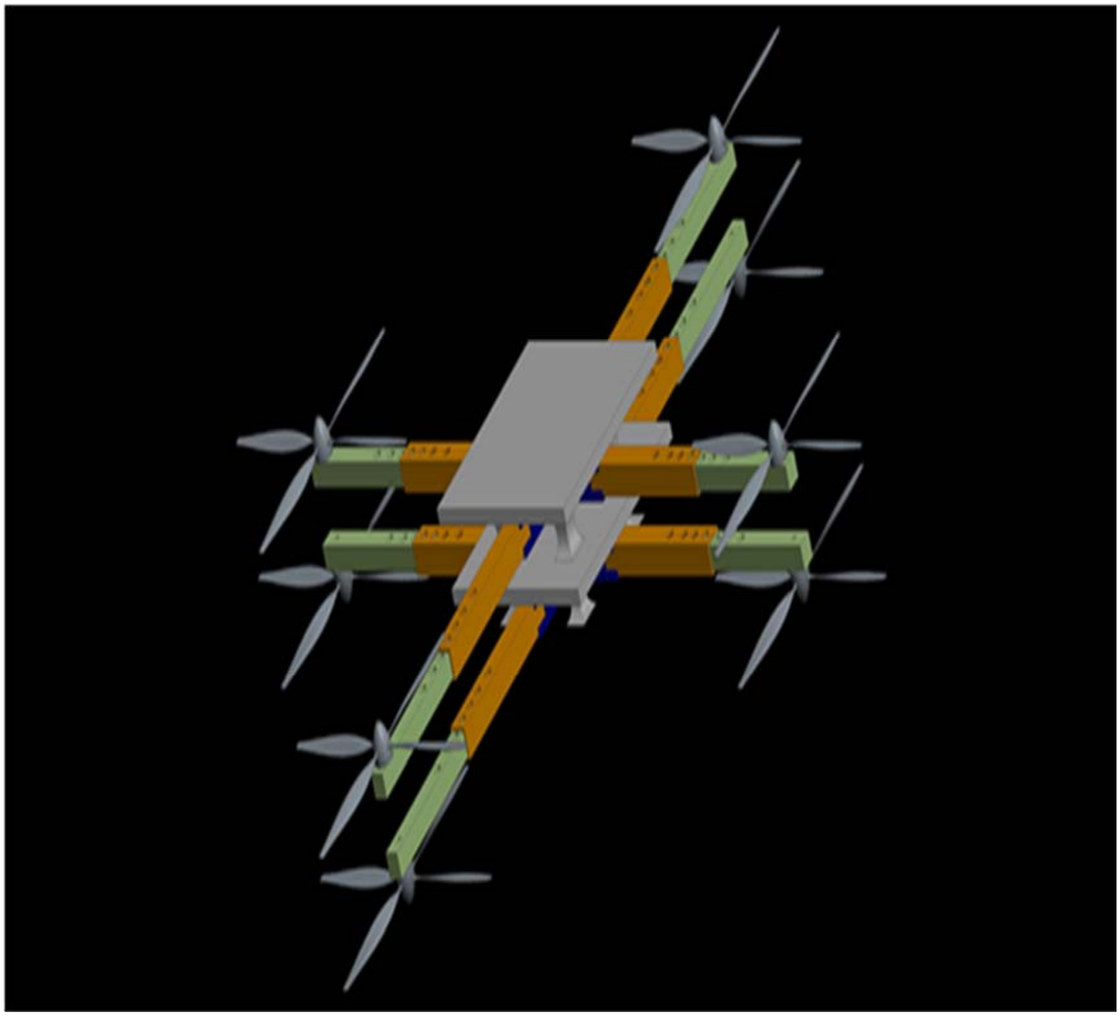
Design and Manufacture of a Rotorcraft

Define Phase Report



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Abstract

This paper presents the investigation of the design and manufacturing of a rotorcraft helicopter. Furthermore, this helps provide research involving the development of an unmanned aerial vehicle (UAV) to be used in search, and rescue applications for the military. Rotorcrafts fall into two categories: highly portable with a low payload capacity, or high payload capacity with low portability. Due to this characteristic of rotorcrafts, a design for both high portable and high payload capacity is investigated. Multiple key components including the frame, propeller, battery, motor, microcontroller, RC transmitter, and the sensor will all be examined in order to ensure a high payload high capacity design. From the battery, motor, and rotor providing aerodynamic forces, one can determine the expected payload capacity and lift performances of the six degree-of-freedom rotorcraft. The results of the selection process and the key equations needed to demonstrate high payload and high portable capacity is examined.

1 Introduction

Rotary unmanned aerial vehicles often fall into one of two classifications: those with a high payload capacity but low portability or those with high portability but a reduced payload capacity. However, there is an increasing need for rotorcrafts that are capable of transporting heavy payloads while still maintaining high portability. 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 heavy (up to 50 lb.) payloads.

The advantages of using a rotorcraft flying machine include an ability to lift off and land vertically. Some rotorcrafts already exist that can lift 50 lbs., however these rotorcrafts do not have high portability due to the sheer size of the rotorcraft. One of the heaviest loads carried 58.7 kilograms, however it 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.

2 Team Organization

For this senior design project the team consist of three mechanical engineers, three industrial engineers, and one electrical/computer engineer. The team reports to the department of Industrial and Manufacturing Engineering and to Dr. Okenwa Okoli, which is the sponsor of the project.

The objective of this team is to work together to create a positive and professional learning environment. This will be established through trust, respect, integrity and communication. We will work in a timely manner but also carefully to ensure that the project is done properly. Figure 1 illustrates the roles delegated to each team member.

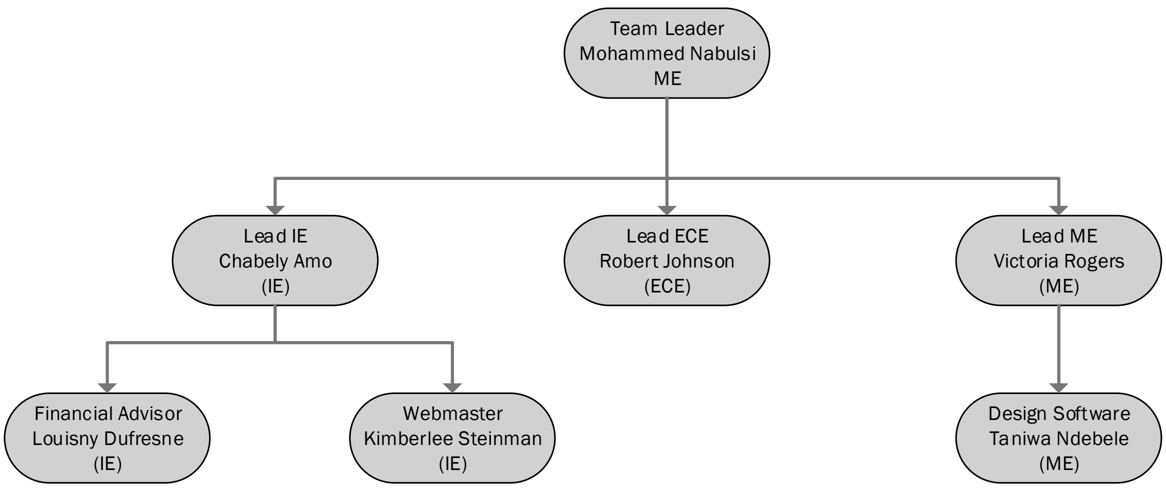


Figure 1. Organizational Chart of Team

- The 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, both between team members, facility member, 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 manages mechanical engineering project requirements with the team leader. The Mechanical Engineering Lead keeps in constant contact with the Electrical/Computer Engineering Lead to ensure project compatibility and is in charge of

the documentation of all drawings, reports, and all other necessary documents regarding the design of the project.

- The Industrial Engineering Lead is responsible for managing industrial engineering members of team and scheduling meetings with the industrial engineering advisor. The Industrial Engineering Lead will manage the overall project requirements and is in charge of the material selection and manufacturing process of the project.
- The Electrical and Computer Engineering Lead is in charge of scheduling meetings with the electrical/computer engineering advisor and the electrical components of the project, as well as the programming of the project.
- 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. The Webmaster will research and share important online information with all project members.
- The Software Designer is in charge of the documentation of all drawings, reports, and all other necessary documents regarding the design of the project.

The primary sources of communication between team members will be through emails, phone calls, and text messages. A GroupMe app is used to coordinate team meetings as well. Each member must check their email once daily for important information regarding the group. If a meeting is canceled, an email must be sent to the group at least 24 hours in advance. Any team member that cannot attend the meeting must inform the group, 24 hours in advance. Repeated absence will not be tolerated.

Meetings have been established once a week. These meetings are on Sunday at 2:00pm. All members are expected to attend meetings and missing these meetings without a valid excuse will not be tolerated. If a team member must miss a scheduled meeting, they must notify the entire team of their absence at least 24 hours in advance. Additional meetings will be scheduled as necessary.

3 Project Definition

3.1 Background Research

The earliest attempt to make a rotorcraft was designed in 1907 by Louis Breguet [2]. The four rotor helicopter was only able to fly at an altitude of a few feet of the ground. Since then the unmanned aerial vehicles (UAV’s) have become commonly used for many applications. There are several programs working on improving these rotorcrafts including [2]:

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

To date, none of these programs have come up with a design that meets the requirements of this senior design project. Every rotorcraft designed by these programs is large and would not meet the constraint of being able to fit the rotorcraft in a standard military backpack$(23" \times 15" \times 14.5")$. 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 without having a limitation on size. Essentially, designing and building a rotorcraft that is capable of lifting at least fifty pounds while still being small enough to fit in a military size backpack has never been accomplished before.

Over this past summer, FAMU-FSU College of Engineering assigned this project to a graduate student in hopes of breaking into the field and creating a revolution product. Dr. Okoli has kept the literature about the design concept and journals of calculations on the previous design confidential until our team comes up several new ideas. This was done to encourage our team to think creatively and in an innovative manner instead of placing us in a box based on the previous design.

Reviewing the various configurations available for rotorcrafts is necessary before an optimal platform can be designed. A rotorcraft is defined as a heavier than air flying machine that uses lift generated by wings called rotor blades that revolve around a mast [3]. An example of a rotorcraft is a quadrotor. A quadrotor generates lift by four set of rotors vertically oriented propellers [4].

Constructing a device with quick deployment and being able to carry heavy payloads would have significant advantages. These advantages would include transporting equipment to remote areas where there are no airports, roads, or even terrain.

As seen in Figure 2, a quad rotor uses two clockwise and two counter-clockwise propellers [3]. These variations of RPM can be used to control lift and torque. There are many variations that

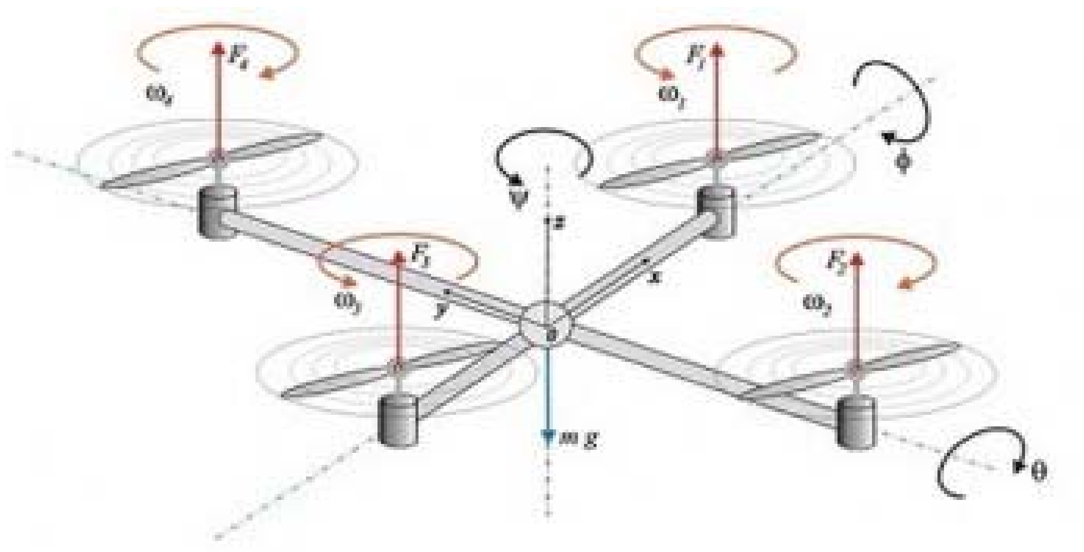


Figure 2. Quadrotor

can be applied to a rotorcraft to change its characteristics such as the raw materials, folding/transport ability, and specifications of the electrical controls that will influence the overall performance of the device. Several configurations of rotorcrafts will be explored, namely the dodecacopter, which uses twelve rotors, and the octocopter, which uses eight rotors. The relationship between the number of rotors and the rotor size determines how much thrust will be needed to effectively lift the vehicle and its payload.

3.2 Need Statement

While there exist rotary unmanned aerial vehicles that carry high pay loads, they lack the portability for practical applications. However, rotorcrafts are beneficial in comparison to more traditional aerial vehicles as they can take off and land vertically. Rotorcrafts have seen an increase of 21.5% in military applications since 1992 [5]. Thus, creating a backpack sized rotorcraft with high payload capacity for field applications is necessary.

3.3 SIPOC Analysis and Business Case

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 in the military. 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 and initiate a market for rotorcraft that carry large loads while being small.

SWOT analysis is a good starting point for analyzing an organization. It is useful in identifying future organizational rules and in further analysis. The SWOT analysis can be seen in Table 1. For our group and project, our greatest strengths lie in our communications, our backgrounds, and our resources, while our weaknesses lie in our group size and management. We have to carefully manage these weaknesses as a group in order to successfully complete the design and manufacture of our rotorcraft.

A similar tool is SIPOC analysis, which allows us to explicitly identify our suppliers, inputs, process, outputs, and customers. The SIPOC analysis for this project can be seen in Table 2. Identifying all these elements helps to define the scope of the project. For our project, one part of the process is the design of the rotorcraft itself and of the processes required to manufacture that design, while the other part of the process is building a prototype of our design. Splitting this process into its two parts lets us identify the input for each part and the supplier for that part. For instance, designing the rotorcraft and manufacturing processes requires our collective knowledge and training in engineering as an input, which has been supplied by the College of Engineering and its various departments.

Table 1: SWOT Analysis Quadrants

<table>
<tr><th>STRENGTHS</th><th>WEAKNESSES</th></tr>
<tr><td>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 sponsor is Dr. Okoli, providing an edge over groups who might have problems maintaining contact with their sponsors.
Several external resources (Emily, Margaret, and Cameron, along with professors and other researchers) provide vital and helpful assistance to the group.</td><td>It is harder to maintain order in a group of 7 students, which is one of the largest groups known to us.
There is only ONE electrical engineer in the group.
Finding literary or other resources for rotorcraft carrying high payloads at a small size is difficult, as normally researchers and hobbyists prioritize one over the other.
There is very limited enforcement of internal deadlines (those set by the team).
Note this does not affect the team’s abilities to meet external deadlines (those set by sponsors and professors).</td></tr>
<tr><th>OPPORTUNITIES</th><th>THREATS</th></tr>
<tr><td>Change in FAA guidelines might make this vehicle more useable in a consumer market, making this research more profitable.
Amazon “delivery drones” could use this research, or their competitors.</td><td>Limited applications outside of the military and hobbyists, which are very differing markets.
As it stands, FAA guidelines highly restrict commercial use of unmanned aerial vehicles.</td></tr>
</table>

Table 2. SIPOC Analysis Chart

Suppliers	Input	Process	Output	Customers
College of Engineering departments (Industrial and Manufacturing, Electrical and Computer, and Mechanical)	Group member's knowledge and training in design and manufacturing	Design a rotorcraft that meets the customer's requirements and the manufacturing processes required to create the rotorcraft	A rotorcraft that can fit in a military backpack (23x14.5x15), can carry a payload of at least 50 pounds, is made with COTS 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.	The Department of Industrial and Manufacturing Engineering at FAMU/FSU
Online retailers	Rotorcraft components: rotors, propellers, battery, IMU sensors, microcontroller, RC transmitter	Build a prototype rotorcraft		Military bodies
HPMI	Frame for rotorcraft			

3.4 Opportunity Statement

Some investment in this project has already been made by the department of Industrial and Manufacturing Engineering. This project was started by graduate student Cameron Alexander over this past summer. As such, failing to successfully complete this project would result in a loss on investment for the department and for Dr. Okoli as the head of the department.

3.5 Goal Statement & Objectives

Using the SIPOC, SWOT, and other analyses described in this report, our goals 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 1.
3. Build a prototype of the rotorcraft described in Goal 1.

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

3.6 Project Scope

We have nearly full authority on this project, within the boundaries of the three departments involved and the budget granted to us. Decisions are made by the team and approved either by the team or by Dr. Okoli, in his role as sponsor. We will work with the goals described above and any and all processes necessary to achieve those end goals.

Our project scope does not include elements outside of the goals described above. This includes but is not limited to graduate level material research, inherent weaponization of the rotorcraft, or operation above those specifications listed in the project requirements.

3.7 Constraints

This rotorcraft must be both compact and have high pay load lifting abilities. The rotorcraft must have a payload capacity of at least 50 pounds. Additionally the rotorcraft cannot exceed the 23” x 15” x 14.5’’ dimensions of a military backpack. The rotorcraft should also be able to travel up to a mile. Further, the rotorcraft’s electrical components should be easily obtained at stores where electrical components are sold to prevent costly repairs. The estimated budget of this project should be kept under $2,400.

4 Analysis of Customer Requirements:

4.1 Critical Customer Requirements (CCR)

Voice of the customer - The voice of customer is a diagram used to capture the customer requirements in depth. Figure 3 illustrates the sponsor's customer requirements and needs and the components required to satisfy the same. Moreover, the voice of the customer will be used to create the House of Quality, which provides a more in depth analysis of the requirements.

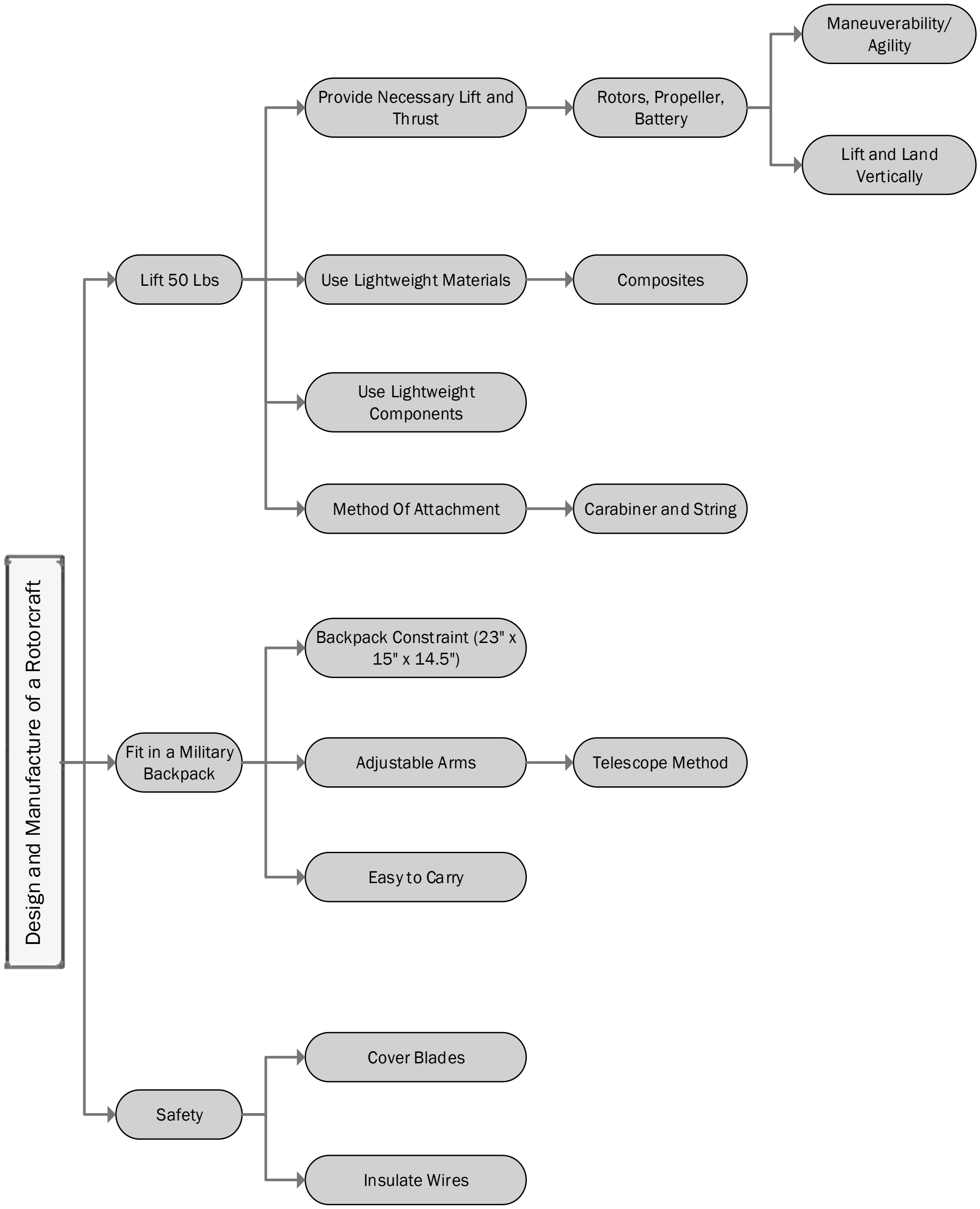


Figure 3a. Voice of the Customer

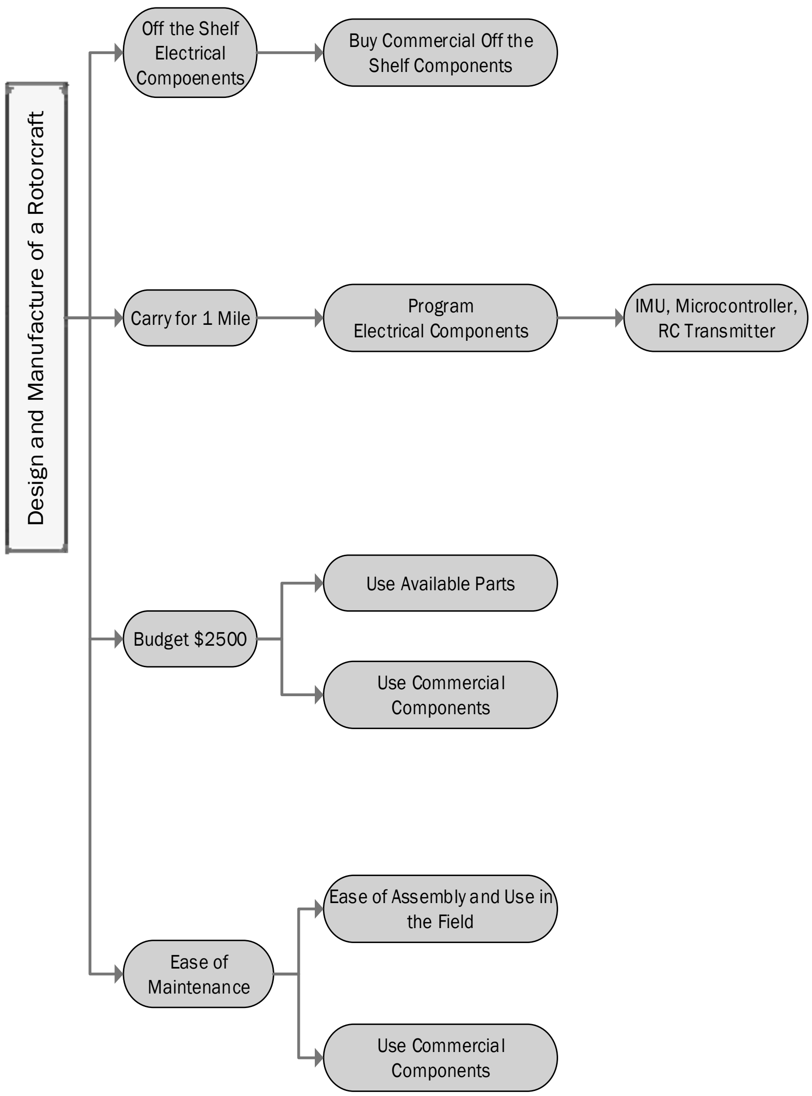


Figure 3b. Voice of the Customer

House of Quality - The House of Quality uses the voice of the customer requirement to define a relationship between customer requirements and the methods the team is going to use to achieve those requirements. The House of Quality uses a planning matrix, an interrelationship matrix, a technical correlation matrix, and technical targets to create planning and communication. Figure 4 illustrates the House of Quality created to analyze the rotorcraft requirements.

The planning matrix shows how well the team meets the customer requirements. It includes the technical weight and the weight percentage as well as the customer requirement ratings, which are assigned depending on their level of importance. It can be observed that requirements “Fit in a Military Backpack” and “Provide the Necessary Lift and Thrust Forces” have the highest importance, based on their percentage rankings. Accordingly, these two aspects should receive more attention when designing the rotorcraft and planning decisions.

The interrelationship matrix provides a connection between the requirements and the method the team is going to implement to fulfill them. Each of the requirements has to have at least one method to fulfill the demand requirements and they will be related using symbols indicating their level of importance. In Figure 3 each requirement is paired with all the possible methods that might influence its fulfillment. If no relationship exists no symbol is placed in this figure. Each customer requirement has a rating, which goes from one to five, depending on the importance of the requirement. The symbols used to specify the relationships have indexes of nine, three, and one. Index nine indicates strong relationship, index three represents moderate relationship, and index one represents weak relationships. All relationships and level of significance are illustrated in Figure 3.

Further, the correlation matrix identify the correlations that exists between the methods that will be used to fulfill the requirements to provide the team with a general idea of the ones that have negative and positive correlations. In Figure 3 it can be observed that “Lift and Thrust Force” has a strong positive correlation with “Lightweight Materials” because the lighter the rotorcraft is, the lower the lift and thrust forces have to be. On the other hand, “Buy Commercial Off the Shelf Electrical Components” and “Use Available Parts” are negatively correlated, because using the parts that are already ordered will reduce the amount of parts that needs to be ordered.

The technical target part illustrates the components, materials, and ways in which the methods are going to be fulfill. As shown in Figure 3, rotors, battery, and propellers are required to provide lift and thrust forces and carbon fiber or glass fiber are lightweight materials that will be used to manufacture the frame.

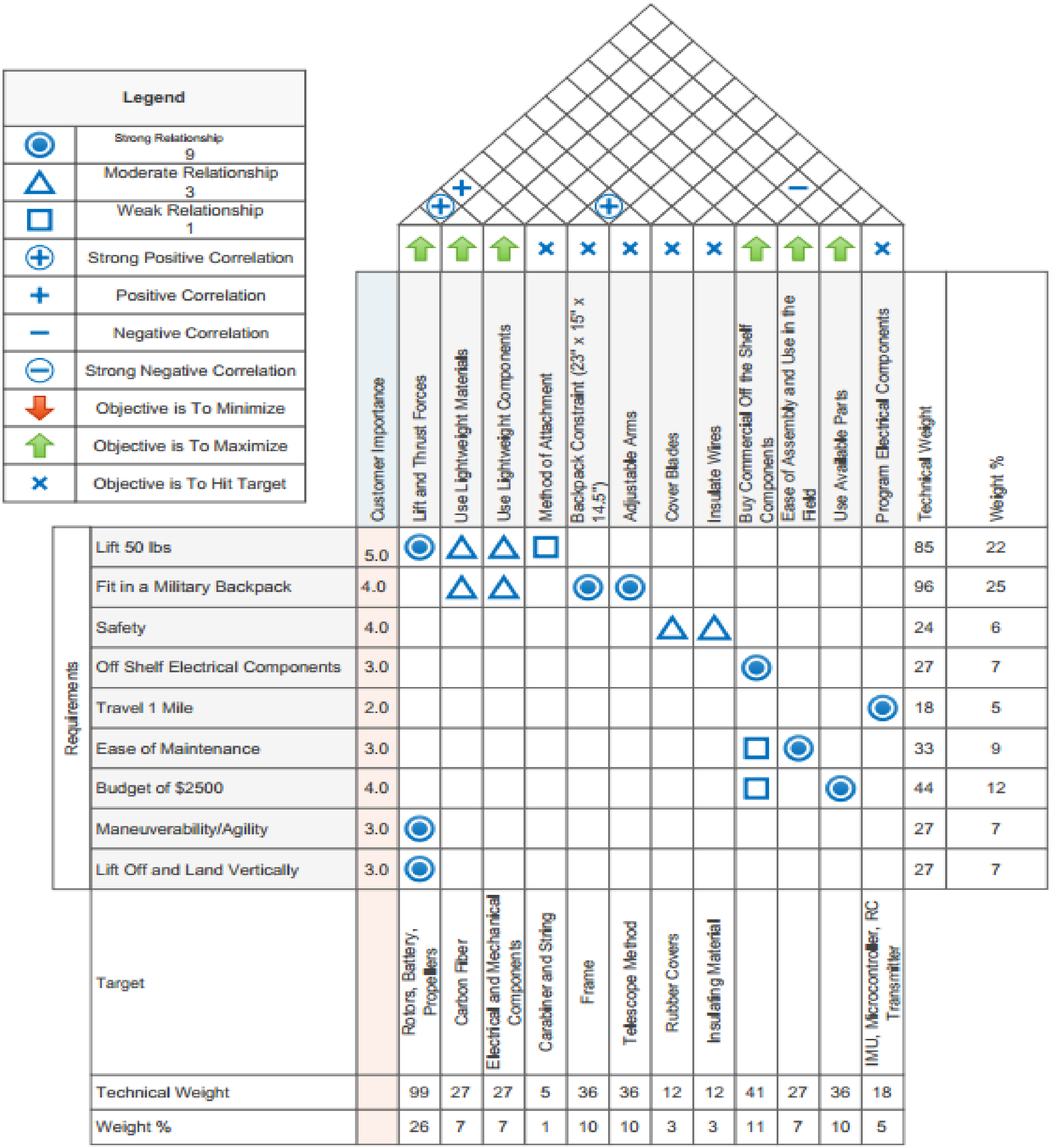


Figure 4. House of Quality

4.2 Meeting CCR

A cause and effect diagram, also called a fishbone diagram, was created for this project. The fishbone provides us with visual display of many potential causes for a specific problem or effect. In our case, meeting the rotorcraft deadline is the problem or effect. There are five potential main causes that can affect us from achieving our goal. These root causes are people, constraints, components, design, and manufacturing method. As a group, we must consider every possible reason why a problem might occur through the main categories. Once completing the fishbone, we are now on our way to understanding the root causes of our problem and if a problem arises,

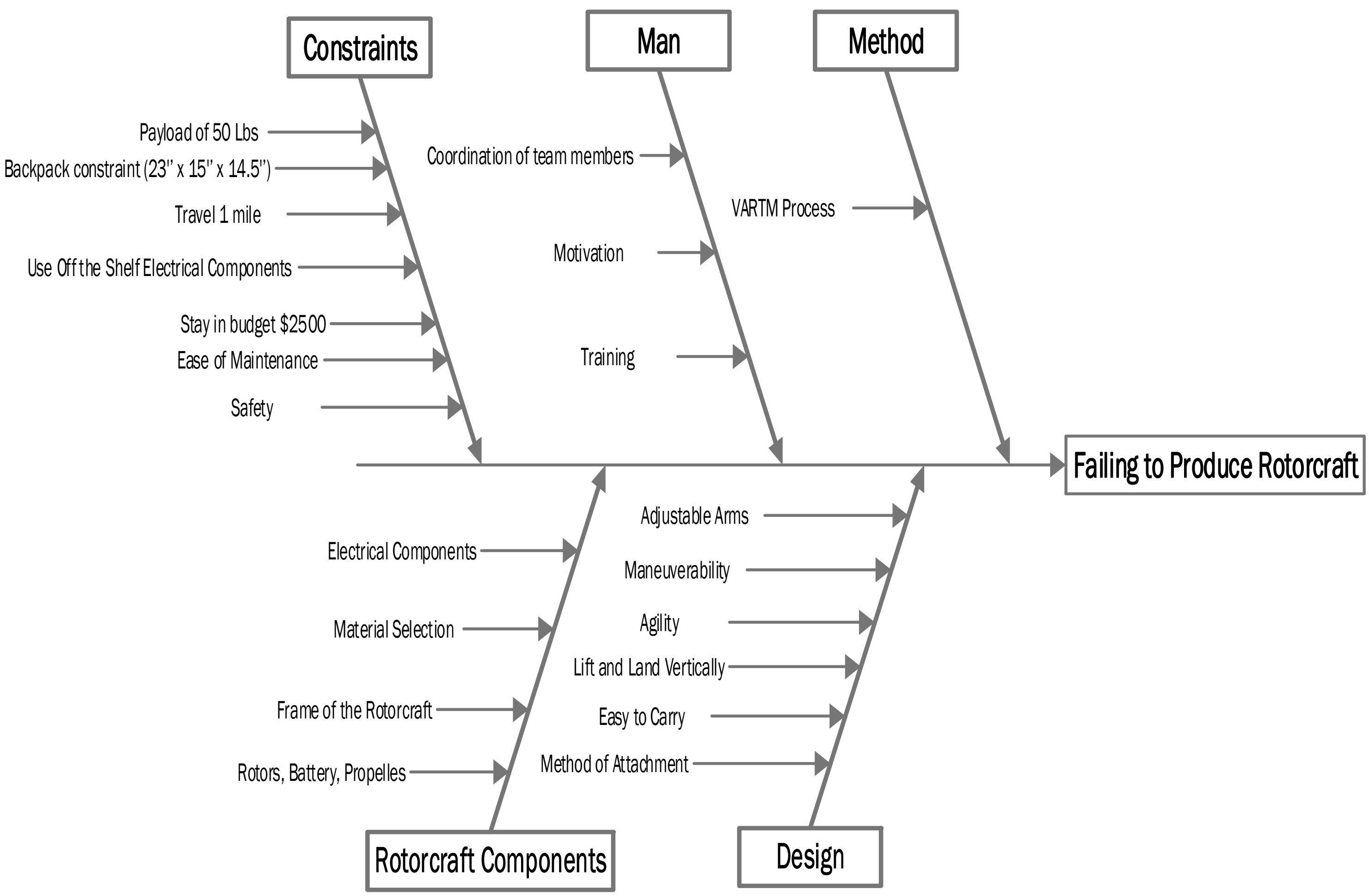


Figure 5. Fishbone Diagram

we can trace the problem back to its root cause. The fishbone diagram created can be seen in Figure 5 above.

5 Design and Analysis:

5.1 Functional Analysis

In the preliminary design phase, critical design parameters associated to the frame, rotors, propellers, battery, sensors, microcontroller, and RC transmitter were investigated. Trade studies related to these critical design parameters evaluated the trade-offs between each aspect's design alternatives. Through extensive research and trial and error, the analysis and optimization of this design can determine the rotorcraft's flight performance.

5.2 Material Selection

Customer requirements for the rotorcraft's frame include strength, weight, and price. Composite materials are defined as two or more insoluble materials combined by an interface, which combination results in a material with better properties that cannot be achieved by either of the constituents on its own [5]. Composite materials are lighter than other materials used in rotorcrafts without sacrificing strength.

There exist different types of composite materials that can be distinguished depending on the type of matrix and reinforcement used. The type of composite material that will be used for the frame is a polymer matrix. Carbon Fiber or Glass Fiber will be used as the reinforcement material and Epoxy resin as the matrix. Moreover, comparisons between carbon fiber and glass fiber are shown, epoxy resin properties are mentioned, and the process that will be used to manufacture the frame of the rotorcraft is explained.

5.2.1Carbon Fiber versus Glass Fiber

When determining the type of material to use for the frame of the rotorcraft, some aspects have to be taken into account. The rotorcraft has to tolerate all kind of stresses, such as those from low to high frequency vibrations, heat, centrifugal forces, and hard landings. Therefore, the material has to be strong and stiff to endure all those factors. Tables 3 and 4 compare properties and characteristics of both materials [6, 7, 8, 9].

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

Material	Tensile Strength (Mpa)	Young Modulus (Gpa)	Density (g/cm^3)	Strength-to-weight ratio	Elongation (%)	CTE	Price/Yard ($)
Carbon Fiber	4127	125 – 181	1.58	1013	1.05	< 2	30 - 40
Glass Fiber	3450	30 – 40	2.66	564	2.5	7 - 8	3 - 6

It should be noted that the numbers shown in Table 3 are estimations and ranges and can vary from sample to sample. This happens because there are many types of carbon and glass fibers, such as E-glass and S-glass, and the manufacturing process and after treatments can affect the figures of the same. However, they are suitable to make comparison between the two materials.

Table 4: General Characteristics of Carbon Fiber and Glass Fiber.

	Carbon Fiber	Glass Fiber
Heat Resistance	Excellent	Excellent
Electrical conductivity	Excellent	Poor
Fatigue Resistance	Good	Good
Abrasion Resistance	Fair	Fair
Chemical Resistance	Excellent	Excellent
Adhesion to Matrix	Excellent	Excellent

Table 4 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 not that high, but the stronger the material the greater the resistance of the rotorcraft. Additionally, carbon fiber presents a Young’s Modulus of 125-181 Gpa and glass fiber presents a Young’s Modulus of 30-40 Gpa. As such, carbon fiber is much stiffer than glass fiber, which is another important factor enabling the resistance of stresses and other factors in the rotorcraft.

Another aspect to be taken into consideration is density. The rotorcraft needs to be lightweight in order to minimize the thrust and lift forces needed to maintain flight. Carbon fiber has a density of 1.58 g/cm^3, while glass fiber of 2.66 g/cm^3, which means carbon fiber will provide a more lightweight frame than glass fiber at the same volume. Finally, budget is an important constraint in this project. Carbon fiber price per yard ranges from $30 to $40 while glass fiber price is between $3 and $6 for the same amount. Carbon fiber is significantly more expensive than glass fiber.

Table 3 shows that both materials present good general characteristics except for electrical conductivity, which is not crucial in the rotorcraft. A carbon fiber frame will be rigid, strong, lightweight, and expensive. On the other hand, a glass fiber frame will not be as rigid as one made of carbon fiber and will weigh more, but will cost less. Taking into account all these considerations carbon fiber appears to be the better alternative due to the mechanical properties it offers. Although its price is much higher than glass fiber, its price still fits within the constraint of our budget. A picture of both carbon fiber and glass fiber can be seen in Figure 6 and Figure 7 [9].

Figure 6: Carbon Fiber

Figure 7: Glass Fiber

5.2.2 Epoxy Resin

Epoxy resin is a thermosetting network polymer that forms when epoxide resin reacts with a polyamine hardener. It presents a highly cross-linked network, which makes it strong, hard, and rigid. Its main purpose is to work as an adhesive with strong resistance coatings and finishes, and it is used as the matrix in fiber reinforced plastics [8]. Table 5 illustrates more characteristics [3,8].

Table 5: Mechanical Properties and Price of Epoxy Resin.

Material	Young Modulus (GPa)	Density (g/cm^3)	Strength-to-weight ratio	Elongation (%)	T_g (°C)	Price/half gallon ($)
Epoxy Resin	3	1 – 1.15	28	4	75	30 - 40

5.2.3Vacuum-Assisted Resin Transfer Molding (VARTM)

VARTM is one of many processes used to manufacture composites and the one that will be used to create the frame of the rotorcraft. This process consists of using atmospheric pressure and a flexible bag to enclose 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 process, and post processing.

The manufacturing process of the vacuum bag can be seen in Figure 8 and it is the most complex because it requires several materials and equipment that are [9]:

- Mold Release → prevents sticking between the matrix and the mold.
- Release Fabric → separate the flow medium from the composite and leave a good surface finish.
- Flow Medium → allows the resin to flow with ease.
- Vacuum Bag → seal and increase 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 → used to apply the vacuum.

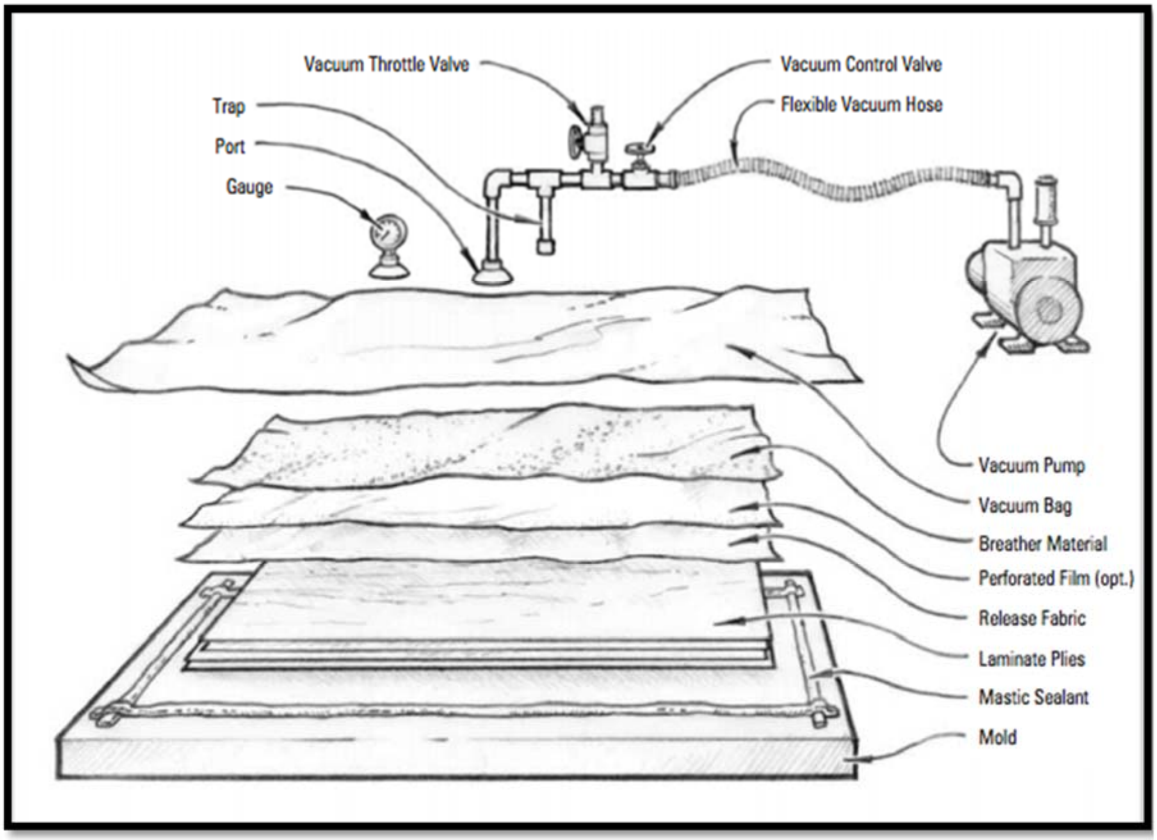


Figure 8: Materials and equipment for the Vacuum Bagging Process.

The vacuum bagging process of a composite consist of six steps:

1. Prepare the area where the composite will be manufacture.
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 7.
4. Prepare the resin. Add curing agent and stir for several minutes until the resin is cured, if required.
5. Start the vacuum bagging process. Connect the pump to the determine tube, infiltrate the resin, and let it cure.
6. Apply post processing to the composite.

5.3 Design Concepts

Frame- is the structure that holds all the components together. It needs to be designed to be strong but also lightweight. The frame should be rigid and able to minimize the vibrations coming from the motors. The frame can consist of two or three parts which don't necessarily have to be the same material. Essentially, the center plate is where the electronics are mounted.

In order to start looking into frames, thrust calculations must be looked at first in order to see how many rotors are adequate. Thrust was examined for a rotorcraft with four, six, eight, and twelve rotors by simply dividing two times the required thrust (accounting for a factor of safety) by the number of rotors in each design.

$$\frac{150\ lbs.}{4\ rotors} \approx 37.5\ lbs.thust\ per\ motor \qquad \textbf{Eq. (1)}$$

$$\frac{150\ lbs.}{6\ rotors} \approx\ 25\ lbs.thust\ per\ motor \qquad \textbf{Eq. (2)}$$

$$\frac{150\ lbs.}{8\ rotors} \approx\ 18\ lbs.thust\ per\ motor \qquad \textbf{Eq. (3)}$$

$$\frac{150\ lbs.}{12\ rotors} \approx 12\ lbs.thust\ per\ motor \qquad \textbf{Eq. (4)}$$

Examining these values, using four rotors is out of the question because generating 37.5 pounds of thrust per rotor is a substantially difficult task. Therefore, the team started with designing a rotorcraft with six rotors. A picture of this design can be seen in Figure 9 below.

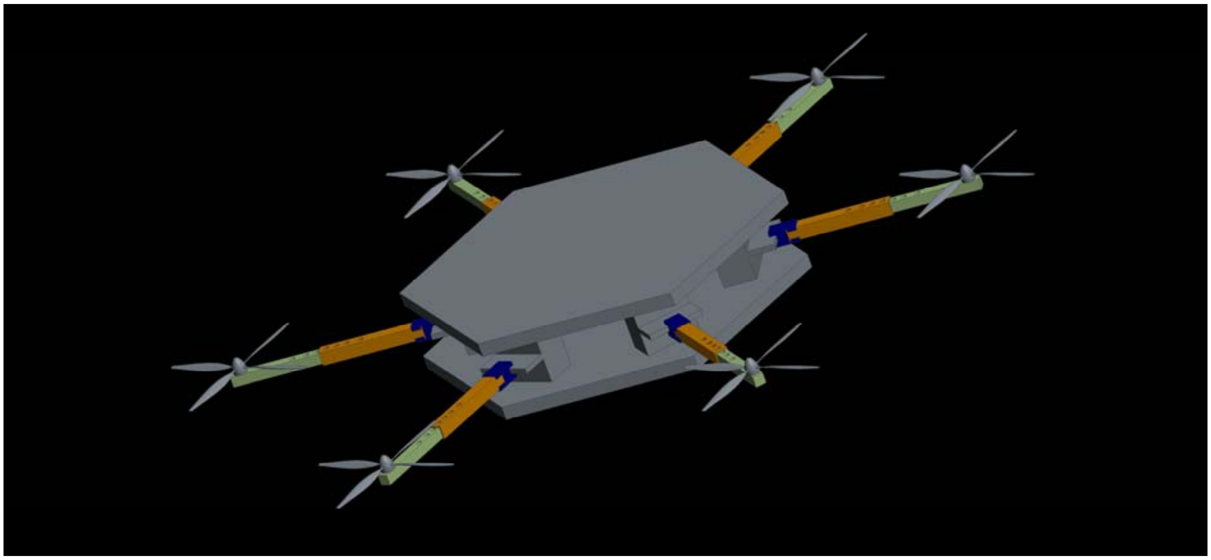


Figure 9. Hexacopter Design in Creo-Parametric 2.0

While using six rotors would make it simpler to fit in a backpack, it would be very difficult to generate 25lbs of thrust per rotor. Therefore, the team began examining the octocopter. Using eight rotors would allow for having a reasonable 18 pounds of thrust while still being cost effective. A huge advantage to having eight rotors is that if one of the rotors were to fail, than the pilot would still have control over the rotorcraft. A picture of the octocopter designed in Creo-Parametric 2.0 can be seen in Figure 10.

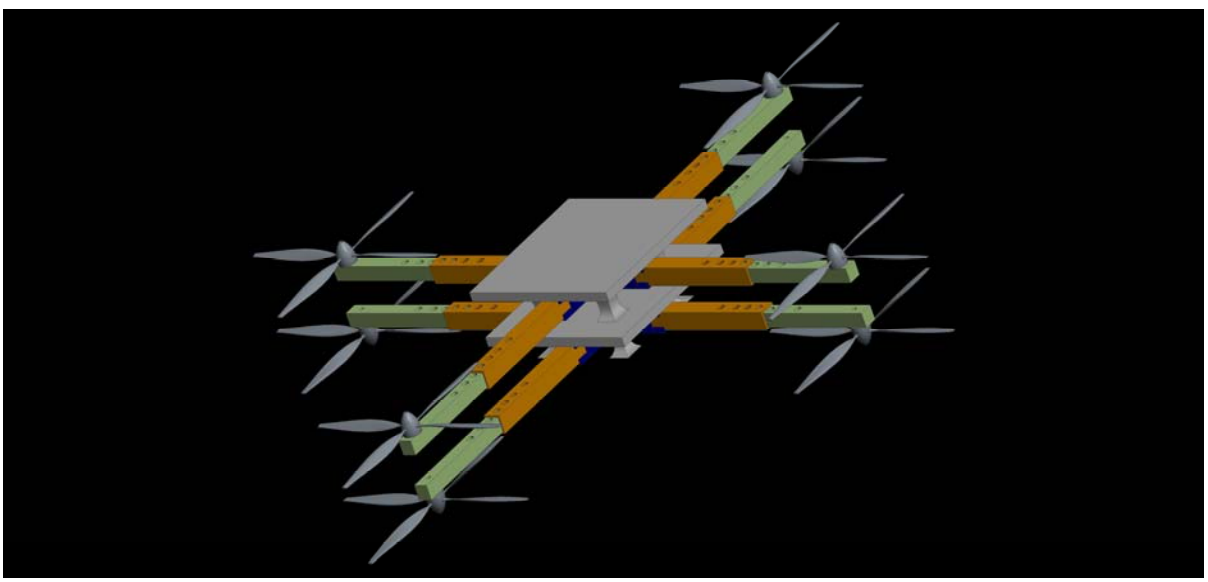


Figure 10. Octocopter Design in Creo-Parametric 2.0

With the use of twelve rotors, one could easily generate enough thrust to lift the fifty pounds. However, some disadvantages for using twelve rotors is the difficulty of fitting it in a backpack and the budget constraint. Due to these characteristics, the octocopter design was chosen.

A closer examination of the octocopter frame shows there will be eight arms mounted on to the center plate in four pairs. At the end of each arm are motor brackets to connect the motor to the arms. A picture of this can be seen in Figure 10. In order to meet our size constraint, pins will be used to slide the motor in and out to fit the backpack. These arms are also detachable, which ensures that they fit in the military backpack.

Motor - The selected motor must be lightweight and capable of rotating the propeller at the desired rpm. Selecting the correct motor is essential in producing the required thrust to lift the rotorcraft of the ground. The motor selection was based on several desired characteristics: low weight, high efficiency, and high power. In order to obtain these characteristics, a brushless motor is going to be used. Brushless motors spin at a much higher speed and use less power at the same speed than DC motors [10]. In addition, brushless motors don't lose power in the brush-transition like the DC motors does, increasing energy efficiency [10]. An important specification when considering brushless motors is the "Kv-rating". Kv-rating shows how many RPMs the motor will do if provided with v-number of volts. A picture of the Turnigy G60 brushless motor that will be considered and can be seen in Figure 11. Another motor under consideration is the E-Flite power

Figure 11. Turnigy G60 Brushless Motor

Figure 12. E-Flite Power 52 Brushless Motor

52 Brushless Outrunner Motor which can be seen in Figure 12. The E-Flite power 52 brushless

motor, which is designed to deliver clean and quiet power while still capable of up to 65 amps continuous current using 4s-6s Lipo pack batteries.

Battery Pack - The selected battery will be lightweight and provide the necessary power to the motor in order to run the desired propeller at a sustained RPM for a specific period of time. The propulsion battery pack must supply high voltage per unit weight in order to minimize the required current draw by the motor [11]. With this in mind, the battery cells will be oriented in series to maximize the battery pack voltage but must be composed of cells with the appropriate electric charge. The battery pack must be composed of several individual cells that are oriented in a desired configuration that will allow for easy installation and removal. The batteries which possess a higher current capacity and electric charge typically have a higher weight and lower voltage. Battery packs with a lower current capacity are lightweight with high pack voltage but have limited flight time. However the Turnigy Nano-tech 5000mah 6S Lipo Pack battery has a higher capacity during heavy discharge, longer cycle life (almost double that of standard li-poly technology), and fast charge capability which is great for this military application [11]. A picture of Turnigy Nano-Tech battery that will be considered is shown in Figure 13. The second battery under consideration is the E-Flite 3200mah 6S Lipo pack battery which can be seen in Figure 14 [12]. This battery will also have higher capacity during heavy discharge and chargers relatively fast compared to li-poly technology. There will be four batteries used, which each battery pack supplying power to two rotors.

Figure 13. Turnigy Nano-Tech

Figure 14. E-Flite

Propeller - The propeller must be large enough to provide the minimum thrust values and have the required pitch to maintain speed in order to navigate through the air within the desired amount of time while overcoming headwind. Once the battery and motor were selected, 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 types. Larger diameter propellers typically 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 top speed but also puts more load on the motor, resulting in higher power consumption. There are three main factors used to assess propeller effectiveness: thrust coefficient, power coefficient, and propeller efficiency [13]. Each of these factors is evaluated with respect to the advance ratio, which is essentially a comparison of linear aircraft velocity to propeller blade velocity. It is desirable for

Figure 15. Graupner CAM Folding Prop

Figure 16. Plastic Propeller Assembly

the advance ratio to be larger as this indicates that less propeller rotations are needed to move the aircraft at a specified velocity. Due to the constraint of fitting the rotorcraft in the backpack, foldable props will be used. A Graupner CAM 16”x10” prop will be used and an image of this prop can be seen in Figure 15 [13]. This prop allows for it to be taken of which does not affect the integrity of the prop. Figure 16 shows the plastic propeller which is also under consideration. The plastic propeller has great properties and is typically substantially cheaper than metal propellers.

Microcontroller- The microcontroller is the brain of the rotorcraft. A microcontroller is a small, programmable computer on a single integrated circuit; it has memory as well as programmable input and output parameters. The chip will be programmed on a computer and saved on the memory on the chip. The microcontroller that is preferred is an Arduino brand. This brand is low-cost and can be programed in the C++ programming language, which is preferred. Things to be cautious about are how many input and output pins for the amount of motors used. If there are eight wings, then there will need to be 16 pins to cover the inputs and outputs for the motors. For this project, it may be beneficial to have a 32 pin board, because that will allow for all of the motors to be accounted for, as well as open the possibility for other modules that may need to be added in as the project advances. One potential chip is the Arduino mini. This chip will also be compatible with many potential IMU units as well. There are differing power and frequency ranges for the chips depending on how much power is needed by the IMU and how much extra power that can be taken from other sources. The prices of the microprocessor board vary from around $6 for the smallest to around $20 for a more effective version.

IMU (sensors) - Another component that must be considered is the IMU. This component is able to measure and report the velocity, orientation, and gravitational forces actually acting on the rotorcraft. This is important because this system will allow the rotorcraft to align itself on a pre-set zero plane so that the weight is as balanced as possible. The IMU sensors vary on how many degrees of freedom that are available in the sensor [5]. This project requires at least six degrees of freedom, because that allows for movement in all three dimensions. The difference between six degrees and nine degrees of freedom is that 9 degrees will also have a compass. This could be helpful in the project if the rotorcraft is to be tracked while in flight. The possible brands for the IMU sensor are the SparkFun Element brand and the Adafruit brand. These brands use analog outputs on their sensors, which can be plugged into the analog inputs in the Arduino microcontroller. The number of analog inputs on the microcontroller also determines how many degrees of freedom the sensor can have. For instance, if there are only six analog inputs on the arduino board, then the IMU can only have six degrees of freedom.

RC-Transmitter- The third major electronic component is the RC transmitter. This is the system that will allow for the rotorcraft to be controlled wirelessly with a remote control of some sort. This system uses frequencies to send radio waves from the transmitter (the remote control) to the receiver (the rotorcraft). The RC transmitter will be connected to the microcontroller so that when a signal is sent from the transmitter, the receiver will take the signal and that received signal will become the input of the microcontroller. As stated, the transmitter and receivers use frequencies to transmit the signals. There is a limited range of frequencies available for commercial use. The transmitter that is used must not only have a frequency that is approved for usage, but it also must be fairly unique. The frequency needs to be somewhat unique because if the frequencies overlap, then the receiver may start receiving signals not only from the transmitter, but from an outside source as well. This will interfere with flight and control of the craft once it is in the air.

There is also a requirement for the project that the transmitter sends and the receiver receives signals effectively for at least a mile. There are two brands that can be used to accomplish this task. The first is the XTend 900 1W RPSMA transmitter. This is said to have a range for 40 miles, which easily covers the project requirement. Another potential option is the XBee-Pro 900 XSC S3B transmitter. This module is also said to cover 28 miles, which also fits the project requirement. Other differences in these two components, besides their range, include power consumption, mass, and how the antenna is attached. The antenna for the XTend board is attached much more securely, but it also weighs slightly more and uses more power. The XBee board has a much more loosely attached antenna, but it does not require as much power and is a much smaller component. Also, it should be noted the cost of the XTend board is around $200, while the XBee board is around $70.

5.4 Evaluation of Designs

Overall Design - In the evaluation of the designs, both which overall design concept should be pursued and what components to use on that design must be determined. First, the main design for the rotorcraft must be selected. The utilization of six rotors would make the design fit more easily into the backpack, however it would be very difficult to generate the 25 pounds of thrust per motor necessary to lift the rotorcraft. Because collapsing the rotors to make the design fit into the backpack currently appears simpler than finding a way to generate such a high thrust, the six rotor design was decided against. Next, the twelve rotor design was examined. With the use of twelve rotors, one could easily generate enough thrust to lift the fifty pounds. Some disadvantages for using twelve rotors is the difficulty fitting it in a backpack and the budget constraint. With the current budget, it would be unlikely that twelve rotors could be afforded. Finally, an octocopter was analyzed. Using eight rotors would allow for having a reasonable 18 pounds of thrust while still being cost effective. A huge advantage to having eight rotors is that if one of the rotors were to fail, than the pilot would still have control over the rotorcraft. Because a collapsible octocopter could fit into the backpack, have a reasonable amount of necessary thrust, and stay within the budget, it was the selected design for this project.

Motor - In Table 6 a comparison of the two motors can be seen. The most important characteristic of a motor for this project is the Kv value. In order to generate more thrust, lower Kv values and larger propellers are required. The Turnigy G60 Brushless Outrunner motor has a 500Kv value as compared to 590Kv for the E-Flite Power 52 Brushless Outrunner motor. When comparing these two motors, there are many similarities such as weight, max current, resistance, and max voltage. However, the biggest difference is the cost. Again, due to budget constraints it is very practical to choose the Turnigy G60 Brushless Outrunner motor since we will be using eight motors.

Table 6. Turnigy G60 Brushless Motor Specs.

Motor	Kv (rpm/v)	Weight (g)	Max Current (A)	Resistance (ohms)	Max Voltage(V)	Power (W)	Shaft (mm)	Cost ($)
Turnigy G60 Brushless Outrunner	500	360	65	0.01	25	1500	6	54
E-Flite Power 52 Brushless Outrunner	590	346	65	0.02	22	1600	6	109

Battery - Keeping our motor decision in mind, Table 7 shows the specs on the Nano Tech battery as well as the E-Flite Lipo pack battery. 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. Both six cell batteries supplies 22.2 volts. Both batteries have a configuration of six cells in series. Comparing the milli-ampere hour (mAh), the Turnigy motor has a capacity of 5000mAh as compared to 3000mAh 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 our application, in order to travel a mile a higher mAh rating is needed. When comparing the discharge of the two batteries, the Turnigy battery has a discharge rating of 65 while the E-flight battery has a discharge of 30 amps. 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 a significant factor. The E-flight battery weighs 1.49 pounds while the Turnigy battery weighs 1.86 pounds. Looking at all these variables and comparing them to the cost of each battery, it would be a simple choice to choose the Turnigy nano-tech battery because of its higher capacity, which translates to a longer run time for only an extra $16.

Table 7 Nano-Tech Lipo Battery Specs.

Battery	Capacity (mAh)	Voltage (V)	Config (s)	Discharge (©)	Weight (Pounds)	Cost ($)
Turnigy Nano-Tech 5000mah 6S Lipo Pack	5000	22.2	6	65	1.86	116
E-Flite 3200mah 6S Lipo Pack	3200	22.2	6	30	1.49	100

Propeller - Due to the constraint of fitting the rotorcraft in the backpack, foldable props will be used. A Graupner CAM 16”x10” and a Plastic 16.5x10 propeller assembly props will be considered and an image of these props can be seen in Figure 16 and Figure 17. These props can be taken off of the motor shaft when the user is finished with their mission. This removal does not affect the integrity of the prop. However, there are some minor differences when comparing the two propellers. The plastic propeller is slightly larger, therefore being able to generate 25 pounds of thrust as compared to the CAM folding prop which can only generate 22 pounds. The plastic propeller only costs $6.75 as compared to the Graupner which cost $17. Again, due to how expensive the Graupner prop is and due to the fact that carbon fiber props have slightly shorter flight time than plastic props of the same size and pitch as well as providing less thrust than plastic, it is a simple decision to choose the plastic propeller assembly.

Figure 16. Graupner CAM Folding Prop

Figure 17. Plastic Propeller Assembly

Microcontroller - Next, the microcontroller was selected. In selecting a microcontroller, the two most important factors are the current and the programming facilities of the controller. A comparison of the two selected options for a microcontroller, a HobbyKing SS Series 90-100A and an 80A Pro Switch Mode BEC Brushless, can be seen in Table 8. It can be seen that both microcontrollers have very similar continuous current, both of which are higher than the minimum current for the motor. The programming abilities of both microcontrollers are very similar, but the 80A Pro Switch has the additional abilities of low voltage cutoff and soft startup of the propellers. However, the HobbyKing microcontroller is a quarter of the price of the 80A Pro Switch, while being almost identical in specifications. It is on the basis of cost that the HobbyKing microcontroller was selected.

Table 8. Microcontroller Specs

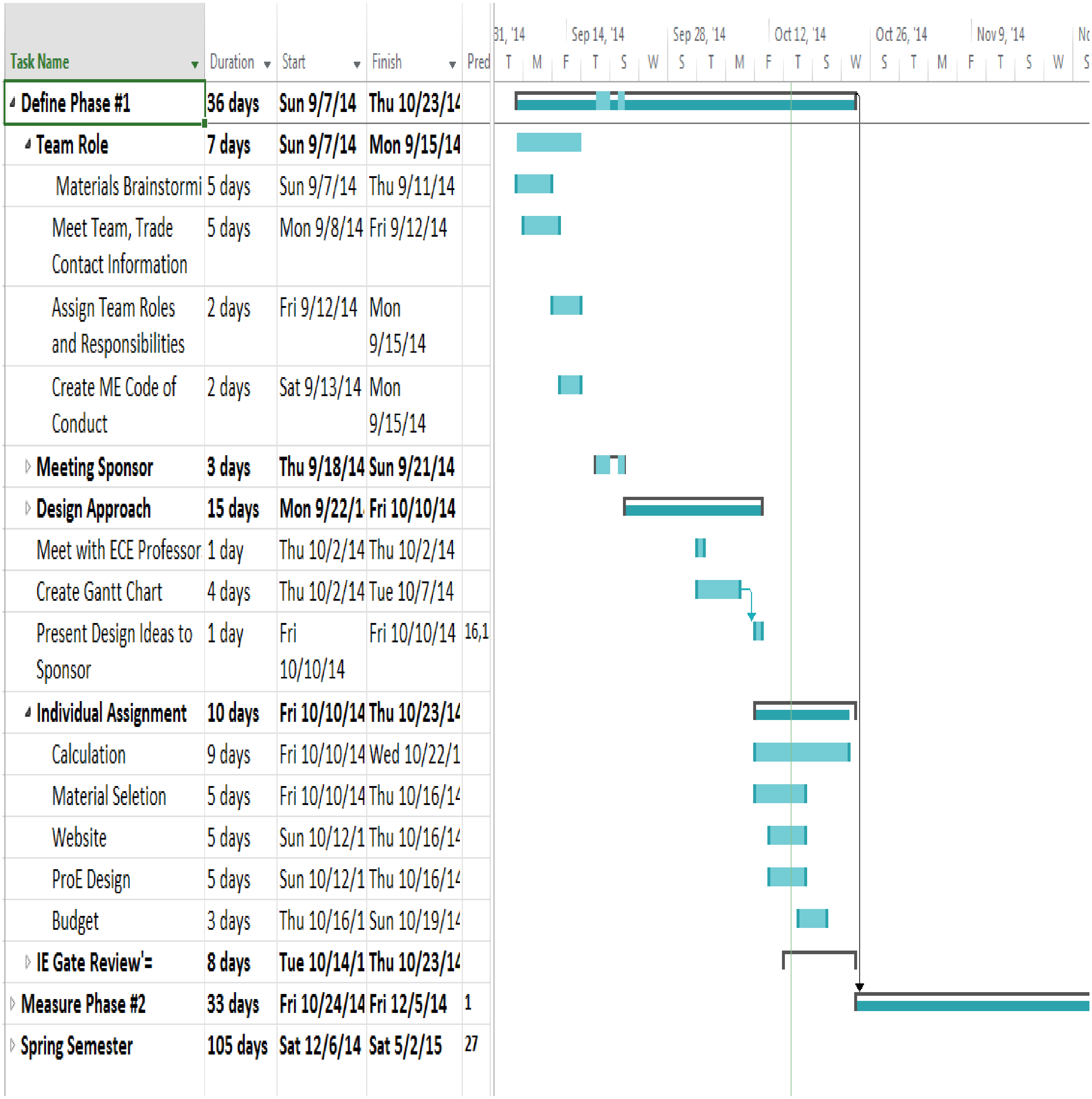
Microcontroller	Continuous Current (A)	Max Current (A)	User Programming Abilities	Cost ($)
HobbyKing SS Series 90-100A	90	100	-Battery Setting -Throttle range -Brake Setting -Timing Mode Setting	25
80A Pro Switch Mode BEC Brushless	80	80	-Battery Setting -Throttle range -Brake Setting -Timing Mode Setting -Low Voltage Cutoff -Soft Start Up	100

5.5 Schedule

Gantt chart – This senior design project is constructed as a DMADV (Define, Measure, Analyze, Design, and Validation) project. The Define and Measure phases are completed in the fall semester and the Analyze, Design, and Validation phases are completed in the spring semester. Our major milestones for fall semester are choosing a final design, selecting materials and components, and ordering those components. This allows for us to build our prototype as soon as possible after winter break.

A detailed outline of our schedule may be seen below in the organized Gantt chart. By setting short term goals our team will be able to assure our client of a product that meets their needs and is finished by the appropriate deadline. Several steps are to be taken along the way including the research required, development of the equations needed to evaluate lift properties, creating drawings for later machining, and communicating with our advisors and sponsors along the way.

We perform thorough research on the subject, then we come up with design concepts, get them approved, build drawings, simulate, and then present our findings at the end of the semester. The Gantt chart will help us complete these short term goals throughout the semester. It also helps us manage unforeseeable obstacles since our overall timeline for the project will be laid out. Any new tasks that need to be added will be completed immediately in order to give our team as much time as possible to adjust to the changes. It is critical to the project to manage our time wisely and the Gantt chart will be our guide. The Gantt chart can be seen in Figure 18.



Task Name	Duration	Start	Finish	Pred
Define Phase #1	36 days	Sun 9/7/14	Thu 10/23/14	
Team Role	7 days	Sun 9/7/14	Mon 9/15/14	
Materials Brainstormi	5 days	Sun 9/7/14	Thu 9/11/14	
Meet Team, Trade Contact Information	5 days	Mon 9/8/14	Fri 9/12/14	
Assign Team Roles and Responsibilities	2 days	Fri 9/12/14	Mon 9/15/14	
Create ME Code of Conduct	2 days	Sat 9/13/14	Mon 9/15/14	
Meeting Sponsor	3 days	Thu 9/18/14	Sun 9/21/14	
Design Approach	15 days	Mon 9/22/1	Fri 10/10/14	
Meet with ECE Professor	1 day	Thu 10/2/14	Thu 10/2/14	
Create Gantt Chart	4 days	Thu 10/2/14	Tue 10/7/14	
Present Design Ideas to Sponsor	1 day	Fri 10/10/14	Fri 10/10/14	16,1
Individual Assignment	10 days	Fri 10/10/14	Thu 10/23/14	
Calculation	9 days	Fri 10/10/14	Wed 10/22/1	
Material Seletion	5 days	Fri 10/10/14	Thu 10/16/14	
Website	5 days	Sun 10/12/1	Thu 10/16/14	
ProE Design	5 days	Sun 10/12/1	Thu 10/16/14	
Budget	3 days	Thu 10/16/1	Sun 10/19/14	
IE Gate Review'=	8 days	Tue 10/14/1	Thu 10/23/14	
Measure Phase #2	33 days	Fri 10/24/14	Fri 12/5/14	1
Spring Semester	105 days	Sat 12/6/14	Sat 5/2/15	27

Figure 18. Gantt chart for Rotorcraft Project

5.6 Bill of Materials

The budget for building this rotorcraft, as provided by our sponsor, is $2,500. After doing research on the components necessary for this project, a bill of materials was compiled and can be seen in Table 9. The amount of carbon fiber and epoxy resin that is needed is still unknown. Once the fabrication of the carbon fiber is tested and the correct dimension of the rotorcraft is finalized, the correct amount of carbon fiber will be obtained. Table 9 shows the list of the materials required, as well of the total cost spent so far. Looking at the Table, the most expensive component is the power source, as four batteries cost $466. The least expensive component is the Microcontroller, which only cost $24. Overall, the project is well within budget at this point.

Table 9 Bill of Materials

Part Name	Quantity	Unit	Unit Cost	Cost
Turnigy G60 Brushless Motor	4	1	$ 54.43	$ 217.72
Turnigy Nano-Tech 5000mah 6S Lipo Pack	4	1	$ 116.70	$ 466.80
Plastic Propeller Assembly	8	1	$ 6.75	$ 54.00
Arduino Leonardo with Headers	1	1	$ 24.95	$ 24.95
Adafruit 9-DOF IMU Breakout - L3GD20 + LSM303	1	1	$ 19.95	$ 19.95
HobbyKing SS Series 90-100A	1	1	$ 24.85	$ 24.85
Carbon Fiber			$ 35.00	$ -
Epoxy Resin			$ 41.95	$ -
Total Amount				**$ 808.27**

6 Conclusion

Based on applicable calculations, a Turnigy G60 motor, Turnigy 5000mAh battery, and a 16x10 propeller were selected to be used in building a high portable and high payload capacity design. Since using eight rotors means only 18 pounds of thrust per rotor must be generated, the octocopter was chosen as the ultimate design. 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. Most of the electrical components are still being analyzed.

The next steps for this project is to speak with our sponsor in order to determine if our team should continue with our design or with the one FAMU-FSU started working on this past summer. The following steps would be to finish Creo-Parametric drawings and order all the parts required to build our rotorcraft. This lightweight, high portability, high payload rotorcraft is going to change the rotorcraft industry for the better.

7 References

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