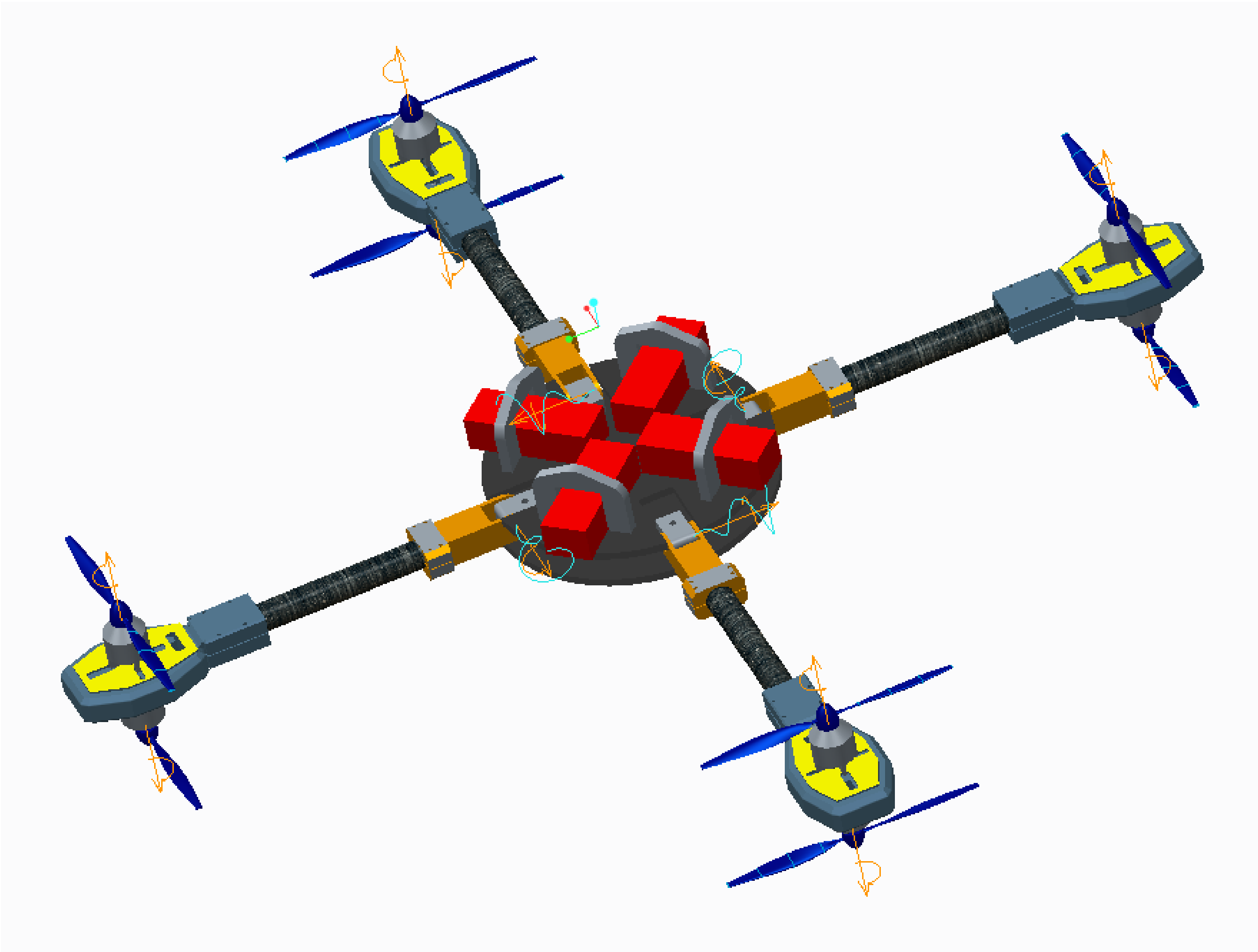
Design and Manufacture of a Rotorcraft

Design Phase Report



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Abstract

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.

This paper represents an overview of the fourth of five phases in this project. This phase is known as the Design phase, in which the detailed design and plan for manufacturing the rotorcraft is presented. This report will also review the previous progress made by the team in the Define, Measure, and Analyze phases.

With the final design of the rotorcraft selected in the Measure phase, and mechanical, electrical, and ergonomic assessments done in the Analyze phase, this report focuses on a full explanation of all components for the craft. Specifically this includes a guide to the assembly of the rotorcraft and a full explanation of how the carbon fiber baseplate was manufactured.

1. Introduction

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 pounds; however, the rotorcraft could only hover a few feet off the ground [1].

Major design considerations for this project 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 seen in Section 3. The most common application for these needs would likely be delivering explosive devices to enemy territory.

In the Design phase, the team finalized arrival dates for rotorcraft parts, along with creating the base plate at the High Performance Materials Institute and creating an assembly guide for the mechanical and electrical assembly of the rotorcraft.

2. Project Charter

2.1 Overview

2.1.1 Background and History

A rotorcraft is a heavier than air flying machine that uses lift generated by wings called rotor blades that revolves around a mast. 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

The rotorcrafts produced by these programs have a variety of uses such as in world-class engineering research laboratories, military and law enforcement applications, and commercial use for aerial imagery [2], but none of these programs have designed a rotorcraft that meets the requirements of this senior design project. The primary difference between this senior design project and the rest of these programs is the rotorcraft's portability. For most programs, rotorcrafts are designed with no limitation on size. As such, a rotorcraft capable of lifting a payload of thirty pounds or more while still being small enough to fit in a military size backpack has never been successfully designed before.

Reviewing the various configurations available for rotorcrafts is necessary before an optimal platform can be designed. An example of a rotorcraft is a quadrotor. A quadrotor generates lift via four sets 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 1, a quadrotor uses four rotor blades [3]. A quadrotor is a useful example to show how these rotorcrafts perform because of its relative simplicity. Ω_2 and Ω_4 (angular velocities) rotate in the clockwise direction, while Ω_3 and Ω_4 rotate in the counter-clockwise direction. 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. This enables the user to control the maneuverability, speed, and lifting power of the rotorcraft.

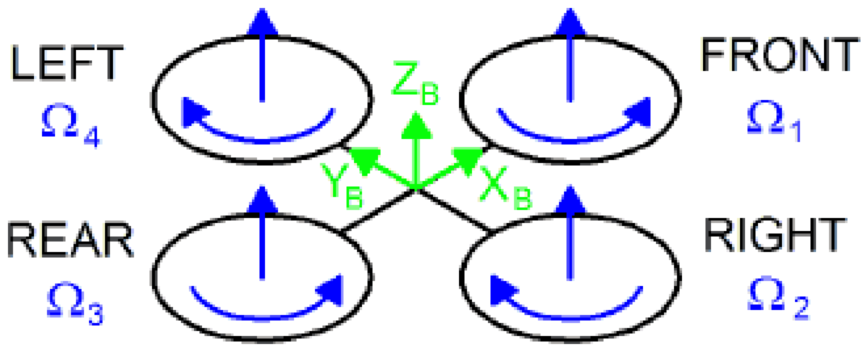

Figure 1. Diagram of Quadrotor

2.1.2 Objectives and Expected Benefits

Following the results from the Define and Measure reports and discussions between the stakeholder and the team, the team goals are the following:

1. Design a rotorcraft that can:
    - Fit in a military backpack (23”x14.5”x15”)
    - Carry a payload of at least 30 pounds
    - Be made with commercial off the shelf (COTS) components
    - Travel up to approximately 1 mile
    - Be easily maintained and used in the field
2. Design the manufacturing processes to be used in creating the rotorcraft described in objective 1
3. Build a prototype of the rotorcraft described in objective 1
4. State the protocols for the operation and assembly of the rotorcraft

These four goals together are the overall goals for this project. Requirements in addition to 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, rotorcraft prototype, and protocols for operation and assembly of the apparatus) 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.

2.1.3 Business Case

Current rotorcrafts on the market prioritize either payload capacity or rotorcraft size. However, there are applications where both payload capacity and minimization of rotorcraft size are desired, such as equipment or explosive material delivery in the military. By designing a rotorcraft with the given specifications (must carry a large payload 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 could lay the groundwork for a market for rotorcrafts with compact size and high payload capacity.

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. 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 the group size and management ability. Managing and organizing eight people and their unique schedules is a challenge, 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. • The team's 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 the team's 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 funded group also developing a rotorcraft similar to the one described in this report might devalue the results of the team's project.

Another tool utilized to analyze 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

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 30 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.	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	Materials for the frame for the rotorcraft			

The SIPOC and SWOT analyses allow 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. This rotorcraft could help improve soldier safety and effectiveness if utilized in battle or in training. As such, the team is undertaking this project because of the value of such a rotorcraft to military bodies.

2.1.4 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, to Dr. Okenwa Okoli, and to Dr. Tarik Dickens who together are 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 2 illustrates the roles delegated to each team member for the Design phase and to whom each team member reports.

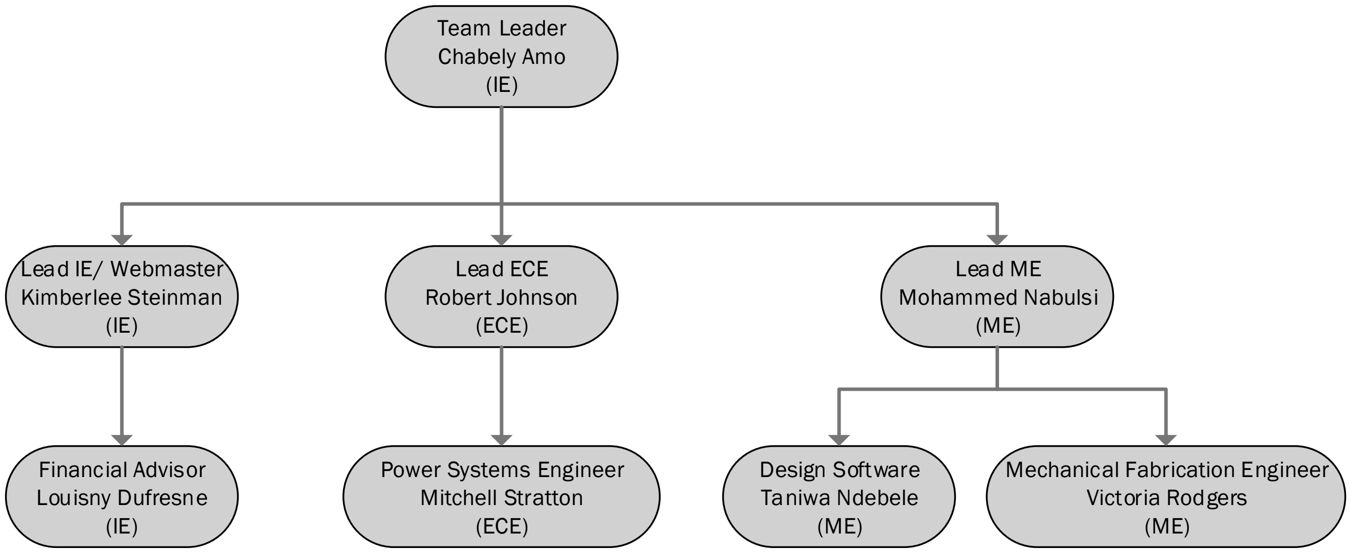

Figure 2. Organizational Chart of Team

- 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 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 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.
- The Mechanical Fabrication Engineer is the lead of the mechanical portion of the rotorcraft build and in charge of the creation of the build plan.

2.2 Approach

2.2.1 Define, Measure, and Analyze Phase Review

Following the DMADV (Define, Measure, Analyze, Design, Verify) methodology, the team has already concluded the Define, Measure, Analyze, and Design phases. For the Define phase, the team met with Dr. Okoli and Dr. Dickens to define the customer and technical requirements, which were used as the boundaries for the rotorcraft design created by the team in Creo PTC. Additionally, the team stated all the necessary mechanical and electrical components required for the operation of the rotorcraft and the manufacturing method necessary to build the rotorcraft's frame out of composites.

During the Measure phase, the team's design was finalized, stress analyses were performed, and a tool called eCalc was implemented to evaluate the optimal combination of motor, battery, and propeller. The team compared three different designs using the eCalc tool, stress analyses, and simulation of the designs as references. Design one was proposed by Cameron Alexander in a previous iteration of this project while designs two and three were proposed by this project team. Designs two and three have the same design but they differ in their payload lifting capacity, ability to fit in a military backpack, budget, and estimated weight of the craft itself due to different components being used in each. As shown in Table 3, design one would not be able to lift 50 lbs. and exceeds the given budget, but the rotorcraft would fit in a military backpack and a soldier would feasibly be able to carry the rotorcraft. Design two can lift the 50 pounds but would not fit in a military backpack and would exceed the given budget, along with being too heavy for a soldier to be reasonably expected to carry. A fully loaded military backpack typically weighs about 40 pounds and so the team’s maximum weight for the rotorcraft was also set to be 40 pounds [2]. Design three can inefficiently lift 50 pounds, can fit in the military backpack, is more likely to be able to be carried by a soldier, and is conditionally within the budget. After discussions between the team and the stakeholders, design three was chosen and the minimum payload requirement was reduced from 50 pounds to 30 pounds.

Table 3. Design Comparisons

DESIGN	LIFT PAYLOAD OF 50 POUNDS?	FIT IN A MILITARY BACKPACK?	ESTIMATED WEIGHT IN POUNDS	TOTAL COST IN DOLLARS
DESIGN #1	No	Yes	32	3,841
DESIGN #2	Yes	No	47	7,451
DESIGN #3	Conditionally	Yes	38	2,630

In the Analyze phase, the team verified mechanical and electrical analyses performed in the Measure phase due to a change in components being used. The team also performed an ergonomic analysis using Siemens Jack software and defined milestones for the Design and Verify phases.

2.2.2 Assumptions

The team has to make assumptions that cannot be proven by the team members but are necessary for the completion of the project. These assumptions are the following:

- Mechanical Assumptions:
    1. The outside wind velocity will not cause the rotorcraft to exceed its maximum tilt.
    2. The eCalc utilized in component selection is accurate within 10% as guaranteed on the website.

3. The stress analysis done is Creo Parametric 2.0 is accurate because the carbon fiber composite created by the team has the same properties as available in the program. This results in no permanent deformation of the craft under a load up to fifty pounds.
4. The net torque of the craft under steady state equilibrium conditions is equal to zero.

- Electrical Assumptions
    1. The microcontroller and sensor will be adequately protected from the weather by being inside the baseplates.
    2. The wires and connections will stay intact while the craft is being moved in the backpack as well as in flight.
    3. The batteries do not have to be removed or recharged after use because the rotorcraft will not return after its mission.
    4. The batteries will discharge at full capacity the entire flight time.
    5. The current will remain constant through the entire flight time.
    6. All soldering will remain in usable condition throughout the entire usage of the rotorcraft.
- Quality Control Assumptions:
    1. The quality control standards that each vendor utilizes are adequate and thus every component ordered for this project meets the requirements for the project.
    2. Each motor is manufactured to be identical.
    3. Purchased parts are not defected and need no assessment beyond rudimentary visual inspection by the team.
    4. Parts manufactured by the project team (that is, the discs of the frame and the cut arms) are created without defects.
- Testing Assumptions:
    1. The weight of the payload used in testing is accurately known and within the project parameters.
- Ergonomic Assumptions:
    1. The ergonomic software Jack generates accurate and reliable results.
    2. The ground on which the user is working is relatively stable and flat.

3. The user does not travel more than a meter when placing the rotorcraft on the ground.
4. The rotorcraft is built to be symmetrical and thus the orientation of the rotorcraft does not matter as long as it is placed upright on the ground (that is, with the folded arms pointed up).
5. The soldier user is in a group or squad of two or more soldiers total and is not responsible for carrying ammunition or weaponry other than the rotorcraft.

2.2.3 Deliverables

At the end of the spring semester, the team is expected to deliver the following items to the sponsor and stakeholders:

- Rotorcraft prototype
- Protocol for the assembly of the rotorcraft
- Protocol for the operation of the rotorcraft on the field
- Full bill of materials.

2.2.4 Milestones and Schedule

Moving into the spring semester, the team is concentrating on completing the Analyze, Design, and Verify phases along with finalizing the project. The milestones per phase are the following:

- Analyze phase:
  - Industrial Engineers:
    - Perform ergonomic simulation using Siemens Jack software to ensure the safe operation of the rotorcraft and identify any region of the soldier's body that might be affected during operation of rotorcraft
  - Mechanical Engineers:
    - Analyze component characteristics using the eCalc tool and ensure their compatibility
    - Perform stress analysis on the whole design
    - Perform simulation to make sure the rotorcraft fits the backpack
  - Electrical and Computer Engineers:

    - Perform power analysis
- Design Phase:
    - Creation of protocol for the operation of the rotorcraft
    - Write detailed mechanical and electrical assembly instruction manual
    - Build the rotorcraft prototype and provide assembly instructions
- Verify Phase:
    - Compare actual apparatus performance with simulations performed in previous phases
- Business Plan:
    - Finalize the project and establish a business case

The milestones for the Design phase (protocol for operation, assembly instructions, and an assembled rotorcraft) were not fully met due to the fact that the team did not have all the ordered parts before the end of the Design phase. Currently all parts have been ordered and should be in by no later than March 15th if everything goes as scheduled. Some of the assembly has begun, and the rest of the assembly of the Rotorcraft will be carried on once the rest of the parts come in.

A Gantt chart is a specialized bar chart used to illustrate a project schedule. In a Gantt chart, a project is broken into several smaller finite elements in order to establish which elements must be performed first in addition to an overall schedule for the project. A Gantt chart typically includes a critical path – that is, a set of elements that would cause a project to not be completed on time if any of the individual elements were not completed by their schedule on time. In this project, the critical path is related to the actual assembly of the rotorcraft. The critical path from the Design phase onwards is thus defined as ordering the parts that need to be ordered, receiving the ordered parts, manufacturing the parts made by the team, and building the rotorcraft.

The full Gantt chart for the spring semester (Analyze phase, Design phase, Verify phase, and Business Case) can be found in Appendix A. The critical path was delayed greatly due to delays in purchase order approval and in placing the correct orders, which are discussed in more detail in section 2.2.6. However, the project is still expected to be completed within the spring semester and the plan is for the rotorcraft to be fully assembled and for flight testing to be completed within the Verify phase.

2.2.5 Scope

The extent of what the team is expected to follow can be seen in section 2.2.3. For this design phase, the group worked tirelessly to make sure all the parts get ordered. There was complications as far as getting certain parts approved from FAMU. All parts have now been ordered as stated in the milestone and schedule section. The group is now awaiting the arrival of all the parts so that assembly can be completed. It should be noted that the team is not responsible for the user not following the law of using the equipment responsibly. This Rotorcraft is not suitable for people under the ages of 18.

2.2.6 Budget

As the project progressed through the Design phase, various changes or additions to component selection were made due to concerns that the selected components would be insufficient or parts that were forgotten in previous material lists. Currently, the team has surpassed the original budget of $2,500; in total the cost to the Department of Industrial and Manufacturing Engineering has been $3,306. This is different from the total cost of the ordered parts listed in Table 4, but this difference is because the cost of the batteries is not included in the cost to the department.

Some of the issues encountered that led to component changes include:

- Components being unavailable or issues with purchasing orders – for example, the originally chosen speed controllers had been discontinued
- Failure to implement motor mounts in the original design
- Size of the originally ordered carbon fiber tubes for the arms being incompatible with the motor mounts required
- Improved eCalc results with 18x10 propellers over the 19x12 propellers previously chosen.

So far, many parts have not arrived due to late orders, changed orders, or orders awaiting approval from P.I., Purchasing, and Sponsored Programs. When parts begin arriving that can be made into subassemblies, assembly can begin. Until that occurs, the project is at a virtual standstill.

The largest delay comes from the RimFire 1.60 motors. The team has maintained nearly daily communication with Coby from HobbyTown, where the order for the motors was placed.

One of the eight motors has arrived, but the remaining seven are on backorder. The motors are manufactured by Great Plains Manufacturing, which will not communicate directly with the team. According to Coby, the motors are to be shipped to HobbyTown on March 15th, and this project has the highest priority when they arrive. There are no motors in stock that would be a suitable replacement for these motors, so the team is forced to wait on the arrival from Great Plains Manufacturing.

Table 4. Rotorcraft's Bill of Materials

Description	Part Name	Qty	Unit Cost	Cost	Expected
Microcontroller	Arduino Leonardo ATmega32u4 with headers	1	$24.95	$24.95	✓
Batteries	5000mAh 9-Cell/9S 33.3V G8 Performance Pro 45C LiPo, Split w/Interconnect	4	$384.99	$1,539.96	✓
IMU Sensor	Adafruit 10-DOF IMU Breakout - L3GD20H + LSM303 + BMP180	1	$29.95	$29.95	✓
Resin	With 2:1 Ratio Slow Epoxy Hardener (32 oz.)	1	$41.95	$41.95	✓
Motor	RimFire 1.60	8	$179.99	$1,439.92	March 15
Speed Controllers	eRC 120A HV Brushless Programmable Opto ESC	8	$139.99	$1,119.92	March 15
Arms	High-Strength Carbon Fiber Tube, 1.000" OD, 0.938" ID, .031" Wall Thick (6ft)	2	$152.73	$305.46	March 7
Propellers	18x10 APC Electric Prop	8	$11.40	$91.20	March 7
Motor Mount	MOTOR MOUNT 25mm BOOM HEAVY LIFT COAX (PAIR)	4	$57.00	$228.00	March 7
Polyvinyl Alcohol	PVA Release Film (1 Gal)	1	$24.75	$24.75	March 5
		Total Cost	$4,846.06		

Since some parts haven't been approved yet, the team has volunteered to ordered parts on their own. One of these orders that was made by the team include the order of the microcontroller, and inertial measurement unit (IMU) sensor, which arrived the week of February 23 and the components are in the ownership of the electrical engineers.

3. Defining Customer & Technical Requirements

3.1 Meeting Critical Customer Requirements

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 in Figure 3 and each cause is explained by category below.

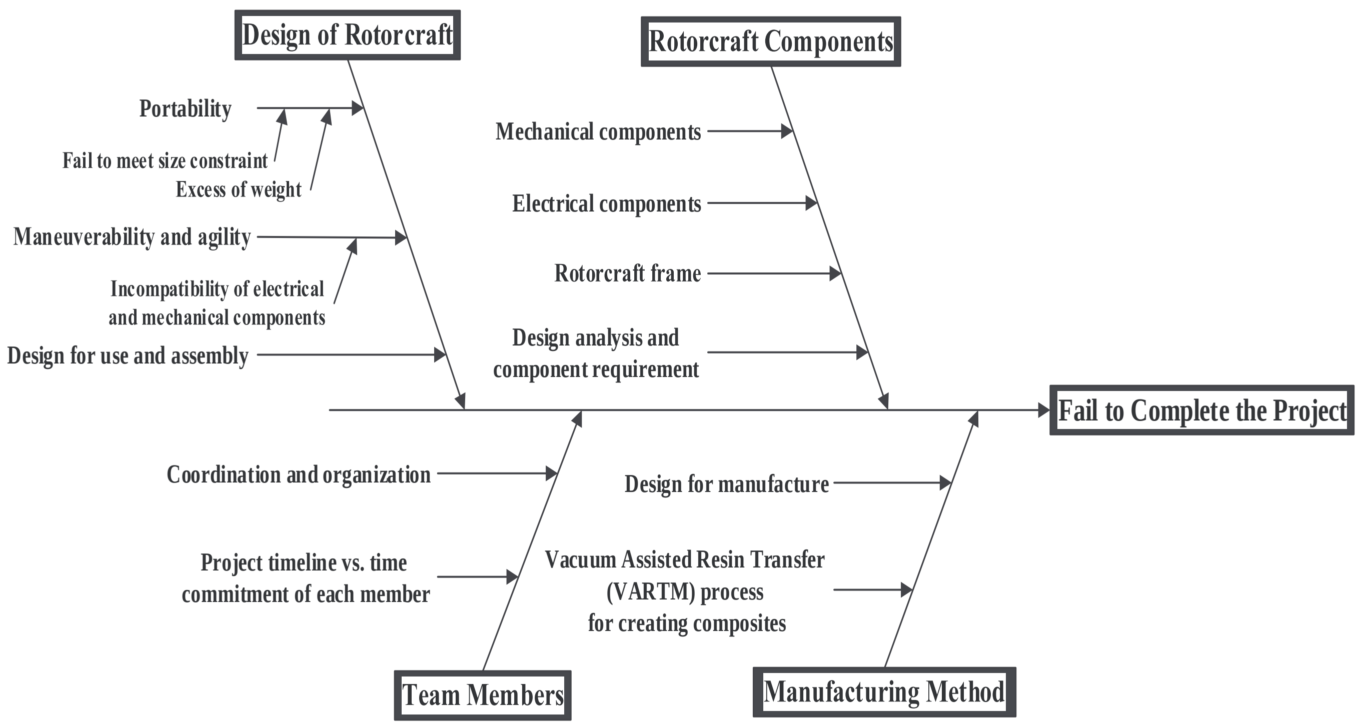

Figure 3. Fishbone Diagram

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, meaning it has to meet the given size constraint of fitting in a military backpack and does not exceed the appropriate weight limit for a soldier to carry. Additionally, the electrical and mechanical components must be compatible with each other to ensure the rotorcraft's maneuverability and agility 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 calculated 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 mechanical components that are: 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.

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. 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 if the carbon fiber were to break while the rotorcraft was in flight.

To avoid project failure or incompletion, the team used 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. Intensive analyses and calculations were performed to make sure all the selected components and materials are capable of meeting customer requirements and are compatible with each other. The team previously 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 implemented the knowledge acquired on the demonstration as well as further assistance by Mr. Jerald Horne, to ensure the quality of the parts meet with specifications. Finally, a Gantt chart is 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.

3.2 Critical Customer Requirements (CCR)

3.2.1 Voice of the Customer Tree

The Voice of the Customer tree is a diagram used to capture the customer requirements in depth. The customer requirements for the rotorcraft were determined after several discussions between the stakeholders and the team, taking into consideration the cause and effect diagram (fishbone diagram) created by the team and discussed in Section 3.1. Figure 4 illustrates the rotorcraft customer requirements and the approaches to achieve an appropriate 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 thirty pounds.
- The rotorcraft must fit in a military backpack.
- The rotorcraft should be easy to carry.
- The rotorcraft must be easy to assemble and use in the field.
- The rotorcraft must be safe to use.
- The rotorcraft design must use off the shelf electrical components.
- The rotorcraft must be manufactured for less than $2,500.
- The rotorcraft must have a flight range of one mile.

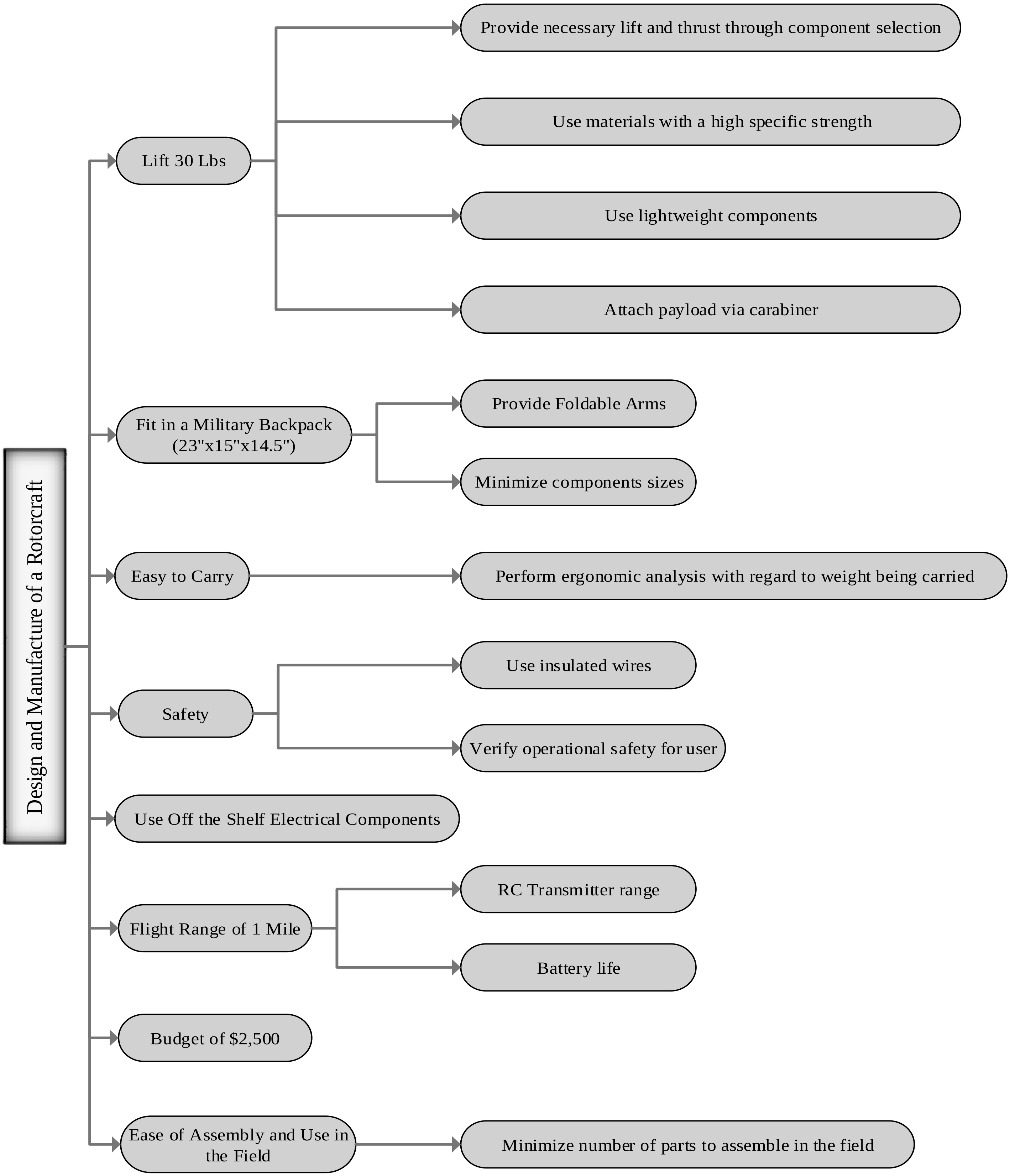

Figure 4. Voice of the Customer Tree

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 lift 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. Mechanical and electrical components sizes will be taken into consideration at the components selection stage, and a simulation of the rotorcraft with all the components on it will be performed to ensure they all fit together and meet the size constraint.

Since this project is for a military application, the rotorcraft must be easy to carry 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. Further, the RC transmitter must be adequate to maintain user control of the rotorcraft over the entire flight range.

3.2.2 House of Quality Matrix

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 of the house contains the technical requirements that represent how the team will meet the customer requirements.

Relationship 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 thirty-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 thirty pounds. Since lifting thirty 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 thirty pounds. Equation 1 shows how the technical weights for the technical requirements were calculated.

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

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

$$R = Requirement\ Rating\ (1-5)$$

$$I = Relationship\ Index\ (9, 3, or\ 1)$$

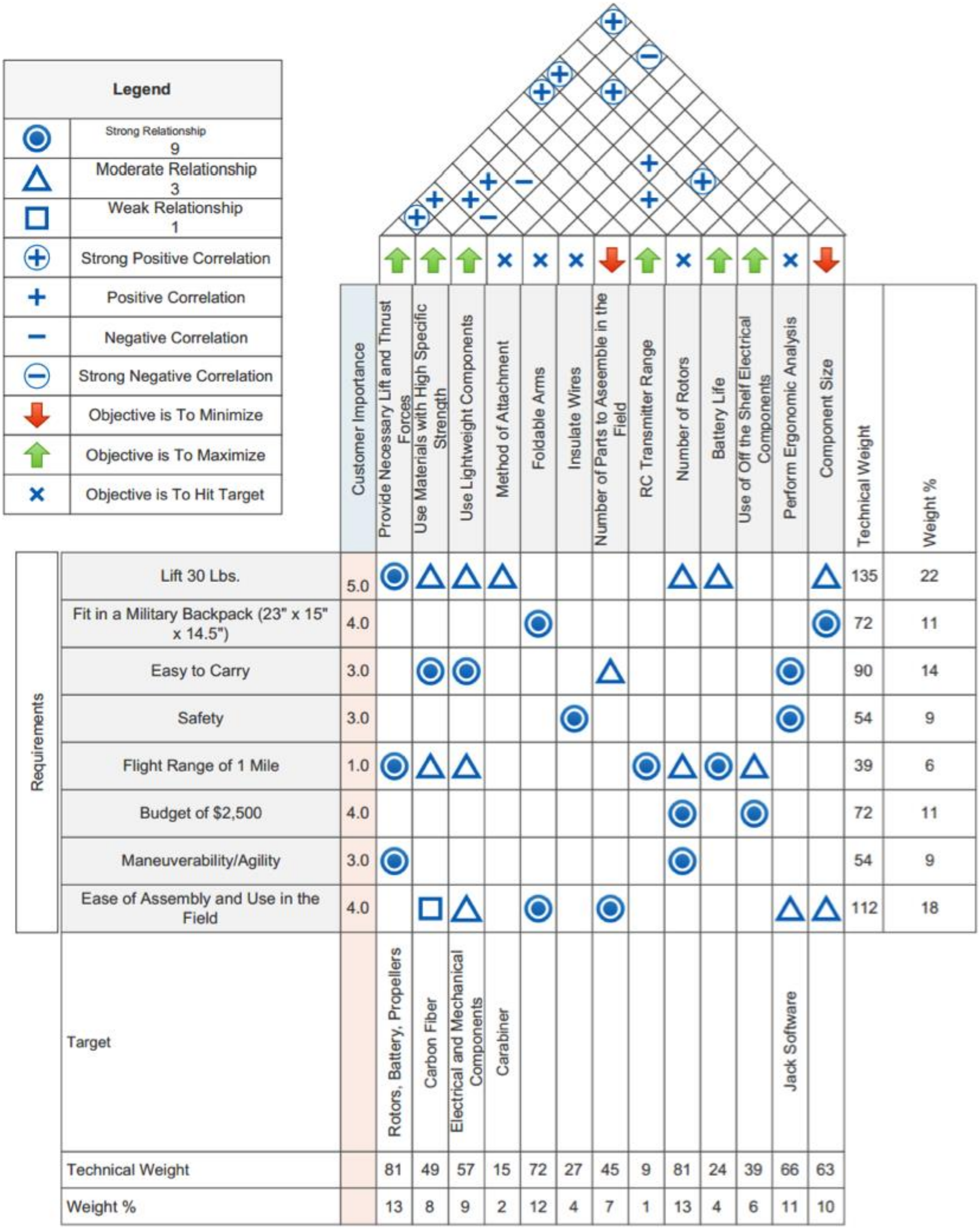

Figure 5. House of Quality

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 to ease of assembly and use in the field. The relationship index between both foldable arms and ease of assembly and use in the field with fitting in the military backpack is nine (strong). Additionally, the rating for both fitting in the military backpack and ease of assembly and use in the field is four. Therefore, multiplying nine and four and adding it to the product of, again, nine 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.

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 lifts and thrust forces.
5. **Provide necessary lift and thrust forces** and **Component size:** The size of individual components is directly correlated with the weight of individual components, which is in turn directly correlated with the total weight of the rotorcraft. As total weight of the rotorcraft increases, the necessary lift and thrust forces increase (that is, a heavier rotorcraft requires greater lift and thrust than a lighter rotorcraft).
6. **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.
7. **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.
8. **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.
9. **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.
10. **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 and thus the components selected are dictated at least partially by their weight.

11. **Use lightweight components** and **Component size:** The total weight of the rotorcraft depends on the overall weight of its components. Components of the same type (that is, comparing batteries to batteries or motors to motors) tend to have similar densities overall and thus larger components weigh more than smaller ones. Larger components lead to a heavier rotorcraft.
12. **Insulate Wires** and **Battery life**: Insulating the wires extends the battery life, as there is less current discharged to the environment as compared to bare wires.
13. **Number of parts to assemble in field** and **Number of rotors**: Generally speaking, more rotors lead to more actions to be performed in the field.
14. **RC (radio controlled) 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.

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 requirements that need to be minimized are “number of parts to assemble in the field” and “component size”. Finally, the technical requirements that needs to be met are “method of attachment”, “foldable arms”, “insulation of wires”, “number of rotors”, and “perform ergonomic analysis”. 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 a payload of thirty pounds, ease of assembly and use in the field, easy to carry, fitting in the military backpack, and staying within budget. The team will concentrate on providing the necessary lift and thrust forces by selecting the most efficient combination of battery, rotors, and propellers using the eCalc tool and on choosing lightweight materials and components in order to maximize payload capacity. An ergonomic analysis in Siemens software will be performed to ensure a proper and efficient way to use and assemble the rotorcraft on the field and ensure the weight of the rotorcraft doesn't exceed the maximum amount of weight a soldier can safely carry. To stay within budget, the team will use commercial off the shelf components. Finally, foldable arms will be implemented to keep the rotorcraft small enough to fit in a military backpack and a simulation of the design will be performed in Creo Parametric 2.0 to ensure all the components fit the backpack. All these analyses and components selection were performed on the Define, Measure, Analyze, and Design phases and they will be addressed later in this report.

4. Analysis

4.1 Analysis Results

The ergonomic analysis performed in the Analyze phase determined that the task of taking the rotorcraft out of the backpack would not cause undue stress to the solder carrying and operating the rotorcraft. This determination was based on the lower back analysis and static strength prediction provided by the Jack software. Jack also provided a timing report for a simulation. Using this report, the team determined that the rotorcraft can be pulled out of the backpack and set on the ground in a time frame of roughly 3 to 8 seconds. The act of carrying the rotorcraft into a mission was not analyzed due to the assumptions that the soldier is not carrying anything other than the rotorcraft and that the rotorcraft weight is the same weight as what the soldier is currently expected or less, making the carrying of the rotorcraft into a mission ergonomically irrelevant. The act of assembling the rotorcraft was also not analyzed, due to the limitations of the Jack software.

The team changed some of the components chosen in the Measure phase and re-analyzed the new components in eCalc. The specific expected results of a rotorcraft built with these components and a 30-pound payload can be seen in Figure 6. Key findings include the maximum tilt was found to be 22 degrees. The maximum speed of the rotorcraft was calculated to be 28.6 miles per hour according to eCalc. The expected flight time was found to be 2 minutes and 10 seconds. A full discussion of these results can be found in the Analyze phase report. The team is eager to verify these eCalc results in the Verify phase. The team also re-analyzed the baseplate and rotorcraft arms as designed in Creo Parametric 2.0. This analysis is fully discussed in the Analyze phase report. The team determined that the components do not undergo any permanent deformation and will return to its original shape once the load is removed. Because of this, carbon fiber is an appropriate material for the baseplate and arms.

Finally, an electrical hardware analysis was used to demonstrate the circuitry planned for the rotorcraft and how the various electrical components and motors would be powered. This analysis can be found in full in the Analyze phase presentation.

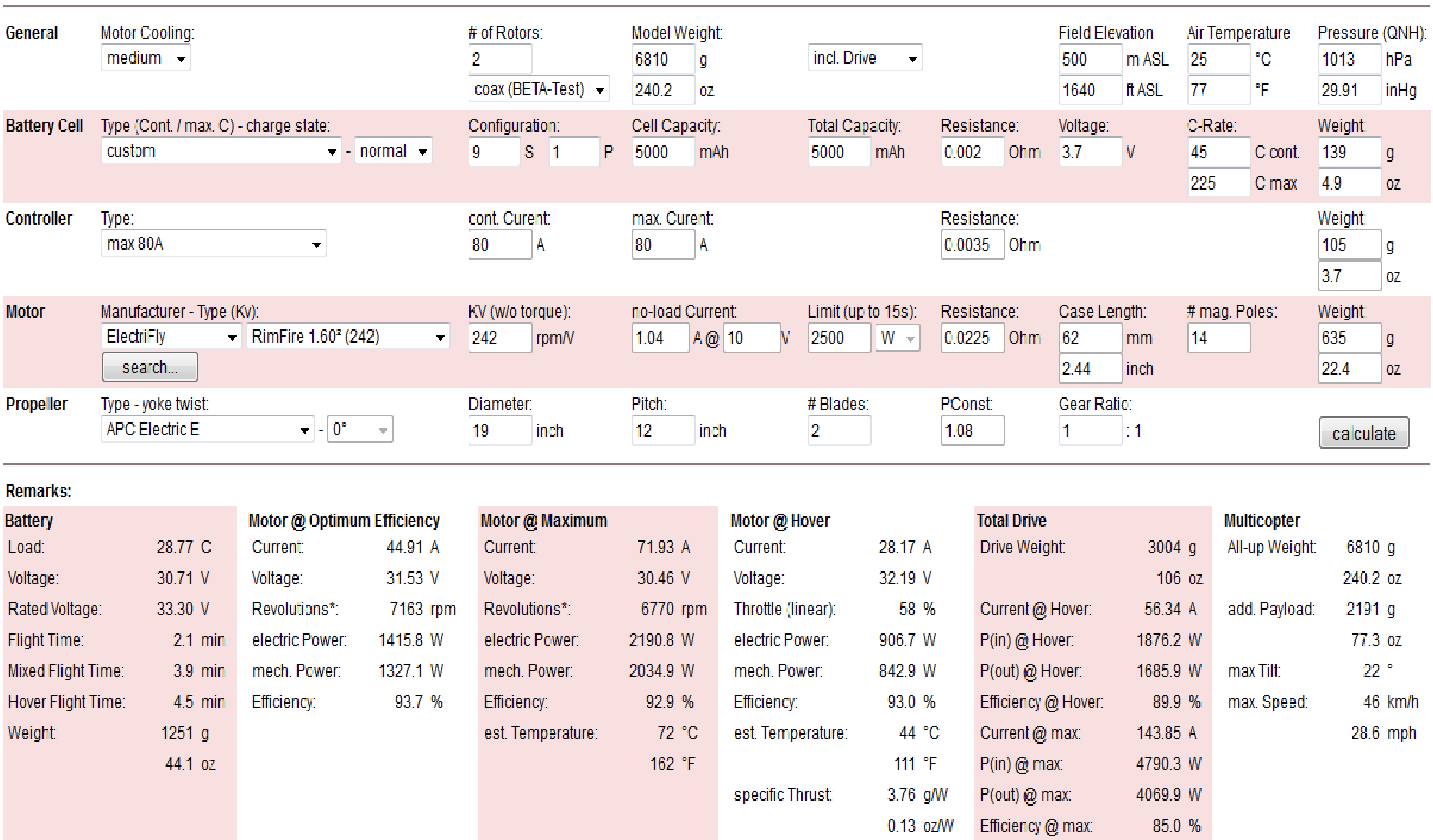

Figure 6. eCalc with payload of 30 pounds

4.2 Manufacture of Rotorcraft's Baseplates

In order to manufacture the rotorcraft's base plates the team decided to follow the vacuum-assisted resin transfer molding (VARTM) process, because the team members are familiar with the process and the resources are available at the High Performance Materials Institute (HPMI). VARTM is one of the processes use to manufacture composites and consists of using pressure to vacuum seal a flexible bag that encloses the reinforcement, in this case carbon fibers, and the matrix together until the resin cures. This process requires three steps: the creation of the mold (based on the design of the rotorcraft), the process itself, and post processing.

Since the base plates of the rotorcraft present a flat and uniform geometry, a specific mold wasn't required to build the plates. Instead, a square flat glass was used as the foundation to lay all the materials and perform the process. The materials required to perform the VARTM process are the following [4]:

- Mold Release: prevents sticking between the matrix and the mold
- Flow Medium: allows the resin to flow with ease
- Release Fabric: separates the flow medium from the composite and leaves a good surface finish
- 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
- Gate Tube: filtrates the resin into the vacuum bag
- Vent tube: controls the vacuum pressure
- Pump: enables vacuum state.

To manufacture the base plates the team used polyvinyl alcohol (PVA) as the mold release, an extruded polymer as the flow medium, peel ply as the release fabric, a thin polymer film as the vacuum bag, tacky tape as the mastic sealant, carbon fibers as the reinforcement, and vinyl ester resin. The team chose to work with vinyl ester resin instead of epoxy resin (as was stated on the define phase report), because vinyl ester resin is suitable for this process since it presents lower viscosity than epoxy resin. Using a low viscosity resin allows the resin to flow better through the layup and fully saturate, which enables good quality on the part. Additionally, the team incorporated balsa wood to the composite because it provides rigidity to the base plates making them less brittle and doesn't add a significant amount of weight to the plates.

The steps performed by the team to execute the VARTM process to build the base plates of the rotorcraft are the following:

1. Clean the working area with acetone and draw a square using a marker to indicate the area where the composite was build.
2. Paste tacky tape on the perimeter of the working area and press down until its well placed to avoid any leaks.

3. Apply PVA across the glass surface using a brush and wait until is completely dry.
4. Cut the carbon fibers, peel ply, and flow medium and lay them down across the working area in their respective order. Figure 7 shows the correct layup of materials in the VARTM process, however, for the manufacture of the base plates a different configuration was used because of the balsa wood [4]. The team used two layers of flow medium and peel ply, six layers of the carbon fiber, and balsa wood. The materials were positioned in the following order: one layer of flow medium, one layer of peel ply, three layers of carbon fiber fabrics, balsa wood, three layers of carbon fiber fabrics, one layer of peel play, and one layer of flow medium as shown in Figure 8. This configuration was implemented because it allows the resin to flow evenly through the carbon fiber fabrics and the wood resulting in a better part.

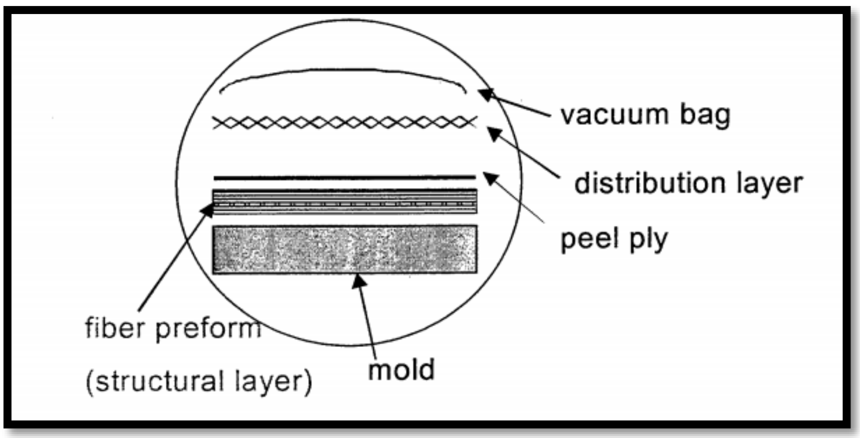

Figure 7. Layup of Materials in VARTM Process

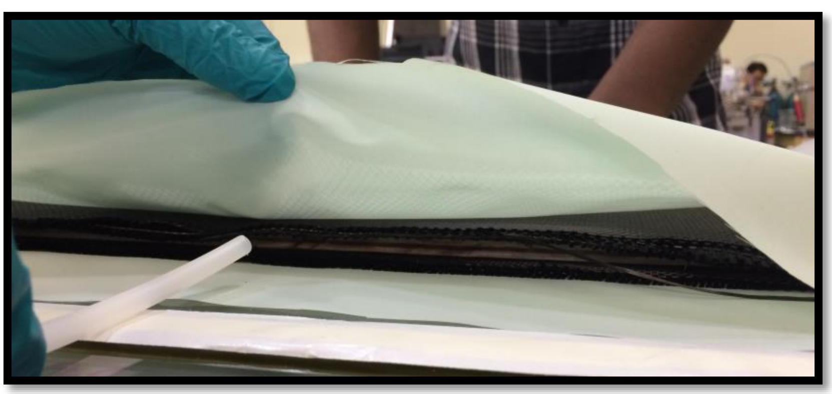

Figure 8. Layup of Materials for the Manufacture of the Base Plates

5. Place the gate tube at one end of the layup and the vent tube at the other end and stick them to the tacky tape.
6. Position the polymer bag on top of the layup and stick it to the tacky tape.
7. Clamp the gate tube, connect the vent tube to the pump, and start the vacuum process. Wait approximately 30 min. before the resin infusion to confirm there are no leaks in the layup. Figure 9 shows the composite layup before resin infusion.

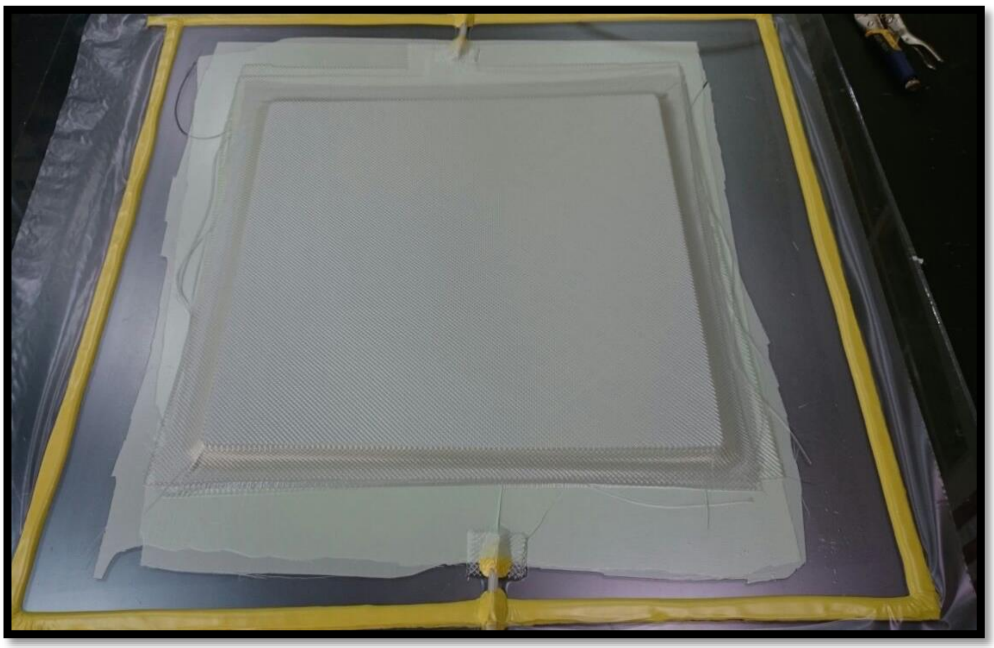

Figure 9. Composite Layup before Resin Infusion

8. Add curing agent to the vinyl ester resin and stir for 5 min.
9. Put gate tube inside the vinyl ester resin container and remove the clamp. Wait until the resin infusion is complete as shown in Figure 10.

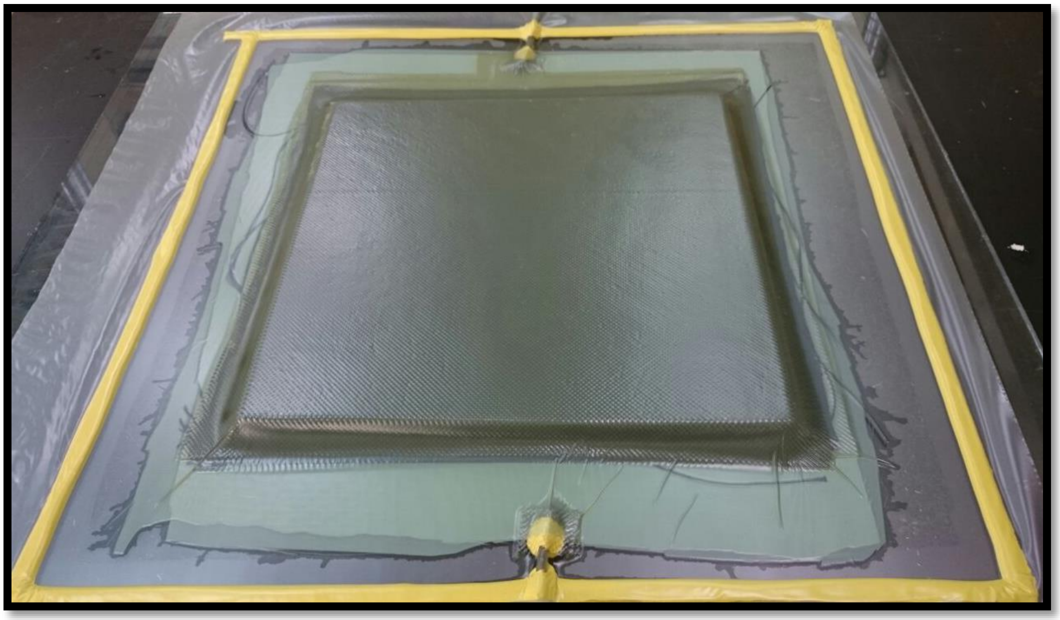

Figure 10. Resin Infusion Process

10. Clamp the vent and gate tubes and let the composite sit for 24 hours.
11. Remove the composite from the bag and place it on the oven at 60°C for one hour to release resin residues from the balsa wood.

Since the base plates of the rotorcraft have to have a circular geometry according to the design created by the team, the water jet machine located at the HPMI was used to cut the composite to a 13" diameter circle. Four replications were made, two for the actual rotorcraft and two extra just in case something goes wrong. Thus, carbon fiber vinyl ester composite was chose for the base plates of the rotorcraft because it offers a high strength and lightweight part, which are important factors the rotorcraft must have in order to meet customer requirements.

4.3 Mechanical and Electrical Assembly

4.3.1 General Design

The configuration of the rotorcraft design is "coaxial" meaning there are two identical counter-rotating propellers using the same motor on each arm. This means that there are two motors per arm and eight motors in total. This is similar to the X8 configuration in Figure 11. With the configuration of the craft determined, the ideal setup of the rotorcraft must be chosen. The setup of a rotorcraft essentially boils down to number of booms and single or coaxial engine mounting. The choice of frame will affect many aspects of the rotorcraft, including efficiency, lifting power, flight times, and stability. The number of physical engines present is also important, as this can affect the ability for the aircraft to cope should one engine be lost. Figure 11 shows the radial and coaxial configuration for a rotorcraft [5].

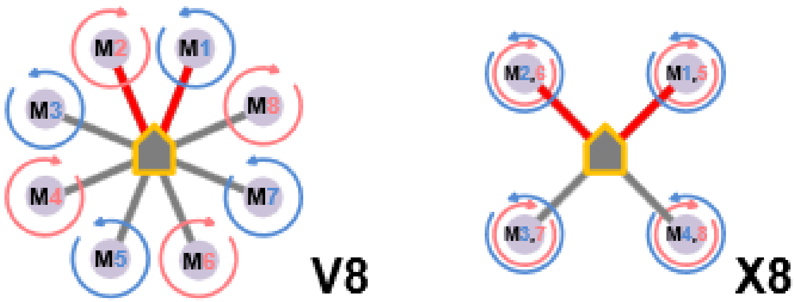

Figure 11. Multi-Copter Configuration

Taking a look at the different configurations, the key component to keep in mind is the number of booms, which in most cases equals the number of motors. Coaxial versions, such as the X8 in Figure 11, have two engines mounted coaxially on the ends of each boom. One motor is on the top of the boom and the other is on the bottom. The vast majority of designs opt for non-coaxial setups, as the coaxial rotorcrafts have a few drawbacks. These drawbacks include poor efficiency and a tendency to overshoot on the yaw (z-direction). However, coaxial rotorcrafts excel in lifting power and stability. The reason for the high lifting power of the coaxial craft is that a lower number of booms result in more room for propellers and components in comparison to a non-coaxial design of the same size. Larger propellers allow for more thrust and lifting capacity. Another positive attribute of the coaxial frame is ease of transport because of the lower number of booms involved.

Due to the size constraint of the backpack, the rotorcraft will be collapsible. When the rotorcraft is not in use, the arms will be folded up and will look similar to a table that has been placed upside-down on its tabletop. The tabletop in this metaphor is the bottom plate. 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. The propeller would hang out by 6.5 inches, as can be seen below in Figure 12. A possible alternative to fix this issue is adding a flap or extra section to the top of the backpack so that the propellers fit. The extra flap would have to be roughly 8 inches tall for the backpack to close comfortably. The additional flap should prevent any damage to the propellers.

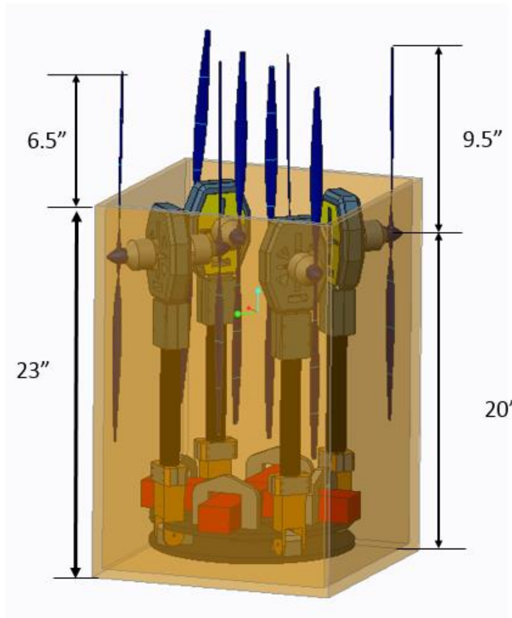

Figure 12. Rotorcraft Displayed in the Backpack

The rotorcraft will have a total height of 29.5 inches. This number was calculated based on the thickness of two base plates, the distance between them, the height of the arms, and the motor mountings and propellers. In order to further compact the design, the mounting motor piece, the blue and green piece surrounding motor in Figure 12, which has the propellers attached to it to will be rotated 90^{o} in relation to its functioning position so that all the components are able to fit into the backpack. If this were not the case, the shafts from the motor will be pressing and poking the side casing of the backpack. This may damage the backpack or the shafts themselves.

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. The batteries can be held in place above the craft simply by strapping or clamping them down. The other electrical components are very thin and will easily fit in the gap between the plates. An added bonus of placing the electrical components within the two plates is that they are better protected from the weather than if they were on the top plate.

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 13. 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 motor mounts 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 the motor shafts are placed incorrectly the flight of the rotorcraft will be greatly affected.

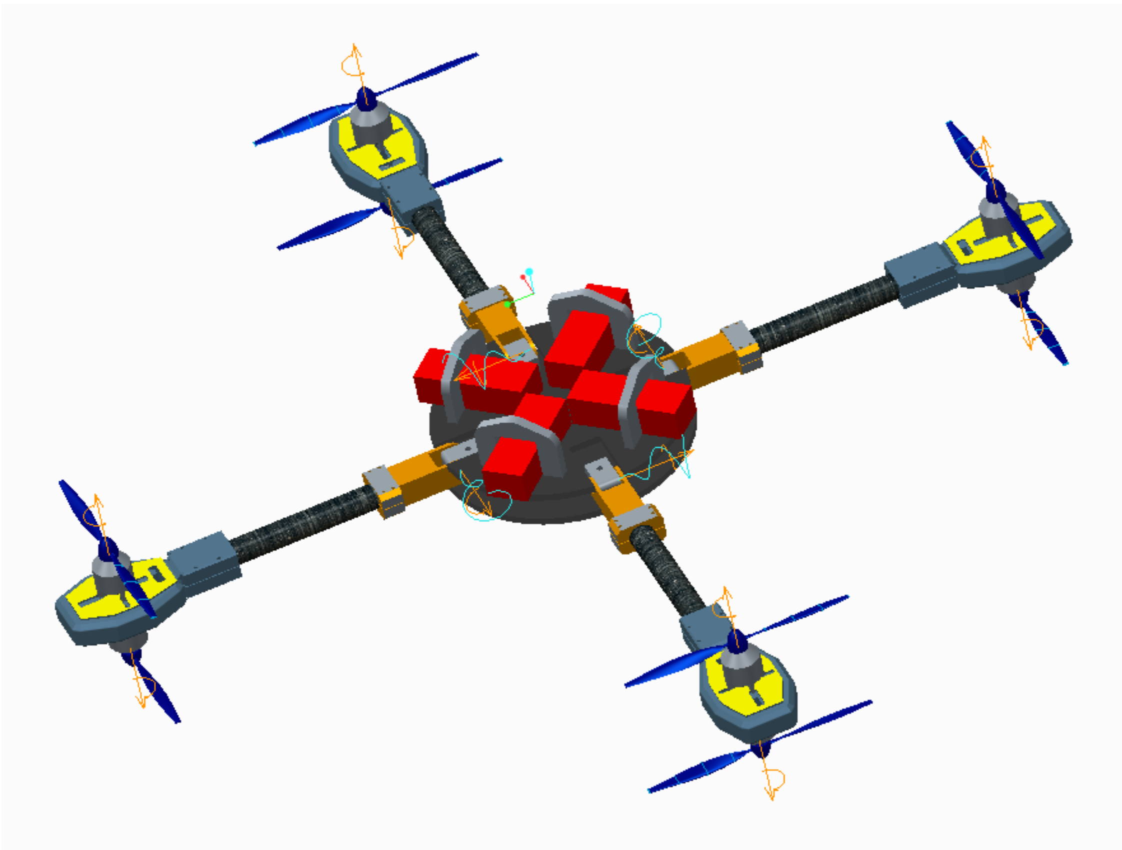

Figure 13. Rotorcraft Before Take-Off

4.3.2 Mechanical and Electrical Assembly

Before discussing the assembly of this Rotorcraft please keep these safety notes in mind. If this Rotorcraft is going to be mass-produced and used by someone other than the Air Force, fly only in safe areas and always away from other people. Do not operate rotorcraft within the vicinity of homes or crowds of people. RC machine are prone to accidents, failures, and crashes due to a variety of reasons including pilot error, radio interference, and lack of maintenance. Pilots are responsible for their actions and damage or injury occurring during the operation of this rotorcraft.

When flying the Rotorcraft, the fast rotating props may cause serious injuries with any accident occurred. Therefore please keep in mind that safety is at first during the flight.

Check List

In this section the essential Rotorcraft components will be reviewed. The propellers will convert the rotary motion from the motor to provide propulsive force. The propellers used for the assembly of this Rotorcraft are APC 18x10 (diameter x pitch) inch and there will be four propellers rotating clockwise and four rotating counter clockwise. Next, there must be eight Electrifly Rimfire 1.60 motors, propellers, and motor mount sets. The Electrifly Rimfire synchronous brushless motor will provide a higher torque per watt (increased efficiency), increased reliability, and is powered by a direct current electric source. Also, the power to weight ratio of this motor provides the necessary power for this application. A detailed drawing of the motor mount and propeller mount can be seen in Appendix B. The APC propellers, Electrifly Rimfire motor, and motor mounts can be seen in Figure 14.

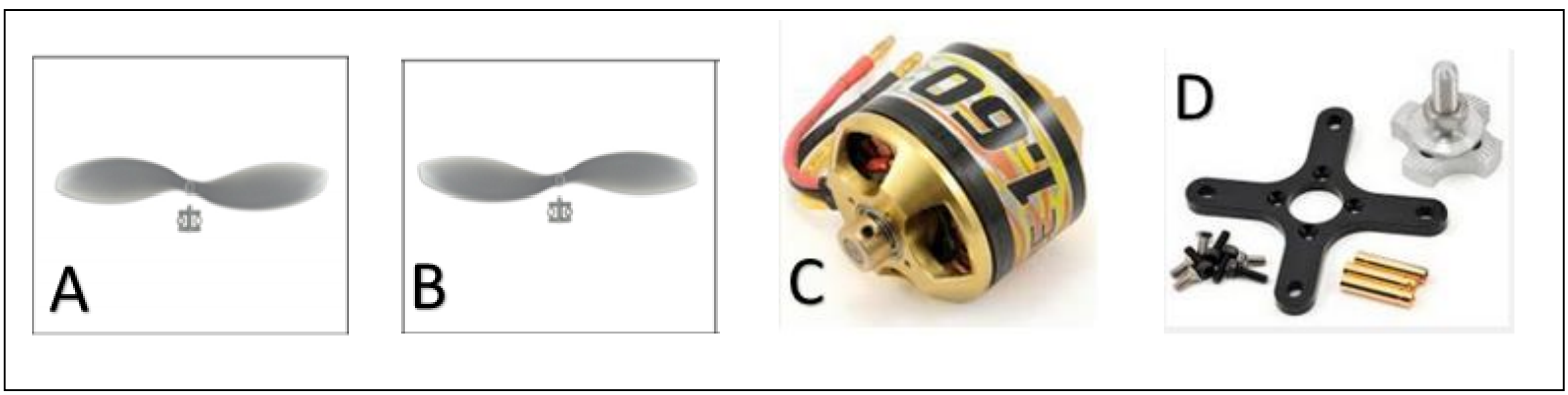

Figure 14. Propellers, Motors, and Motor Mounts Descriptions

A. APC Prop 18x10 (CW) **(Quantity 4)**

B. APC Prop 18x10 (CCW) **(Quantity 4)**

C. Electrifly Rimfire 1.60 Motors **(Quantity 8)**

D. Prop and Motor Mount Set **(Quantity 8)**

Next, the 12-inch servo extension wires will be explained. These twisted cables have a female style connector on both ends that allows the connection between the microcontroller and the electronic speed controller. This is convenient because it connects various three-pin sensors to a controller. Additionally, eight red and eight black American Wire Gauge (AWG) wires will be required, which are just standardized wire gauges that are electrically conducting. These AWG wires and the servo extension wire can be seen in Figure 15.

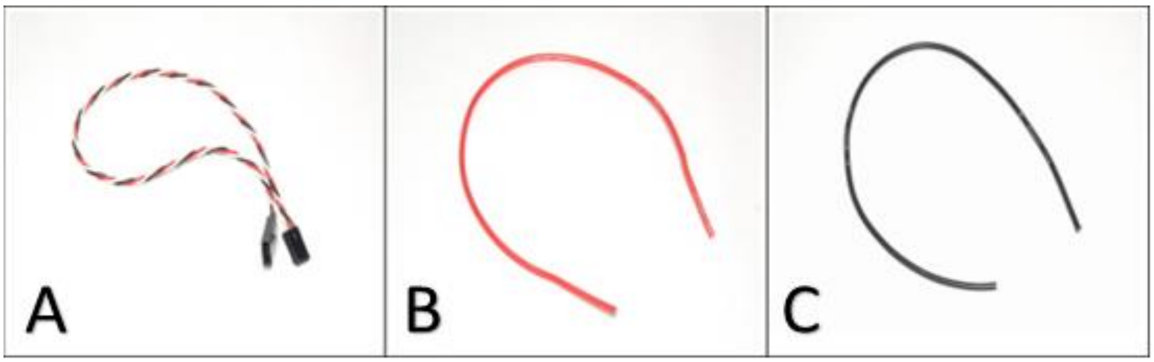

Figure 15. AWG Wires and Servo Extension Descriptions

A) Servo Extension Wire
B) AWG wire red
C) AWG wire Black

The next items on the checklist include the necessary parts to assemble the frame. The frame is the structure that holds all the components together. The rotorcraft's frame will be rigid and able to minimize the vibrations coming from the motors. These vibrations will be minimized because carbon fiber is more vibration absorbent than aluminum, wood, etc… The center plate for this frame will consist of a bottom base plate, and a top base plate. The bottom and top base plates will be connected using four U clamps. Figure 16 shows the bottom base plate and the U clamps necessary in order to clamp both plates together. Figure 17 shows the carbon fiber arms that will be used in this assembly and 12.75 in of the same will be required.

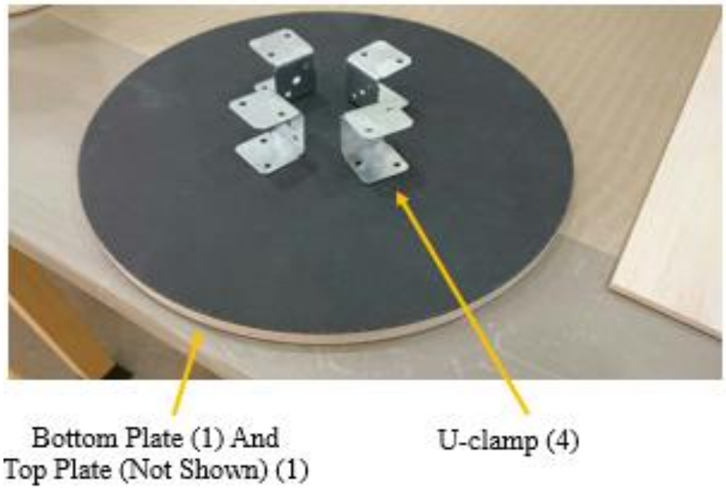

Figure 16. Bottom Base Plates and U-Clamps

Figure 17. Carbon Fiber Arms

Continuing with the item checklist for the frame assembly are the T hinges. There will need to be four T-shaped hinges as seen in Figure 18 [6]. These will be placed on the bottom center plate. Also, two screws will be placed into the base plate, and two screws with washers will be placed into the carbon fiber arms to allow the arms to move.

Figure 18. T-Shape Hinge

Furthermore, Figure 28 shows the rotorcraft's heavy lifter motor mount pair needed to finish building the main frame assembly [7]. The top motor mount is typically the top plate and has a 2.5mm diameter holes for the mounting bolts. The other mount utilizes press nuts and is used as the lower mount. This mount will accommodate motors with a bolt pattern from 22mm to 36mm. The Electrifly motor has a 25mm bolt pattern. There will need to be four pairs for this rotorcraft.

The electronic speed controller (ESC) is the device generating three high frequency signals with different but controllable phases continually to keep the motor turning. The ESC is also able to source a lot of current as the motors can draw a lot of power. There will be eight 120Amp ESC as shown in Figure 19. There will also need to be eight 3mm bullet connector and eight standard connectors for the batteries and microcontrollers. The bullet connectors are a simple, durable wire connector used in many wiring applications.

Figure 19. Electronic Speed Controller, Bullet Connector, and Connector for Batteries and Microcontroller

A) 120 amp ESC (33.3V 9S)
B) 3mm Bullet connector (Female)
C) Connector for Batteries and Microcontroller

Figure 20 shows the Thunder Power 33.3 volt 9S (cells) lithium polymer battery and Figure 21 shows the 9s Lipo charger needed for building this Rotorcraft [8]. The Thunder Power battery has a capacity of 5,000 milli-Ampere per hour (mAh). There will need to be four batteries for this Rotorcraft. The batteries do not come fully charged so there will also need to be 1 nine cell Lithium polymer charger in order to charge all the batteries. There are three more components needed as part of the checklist including the microcontroller, Arduino board, and inertial measurement unit (IMU) that will be discussed in the Software section.

Figure 20. Thunder Power 33.3 V 9S Lithium Polymer Battery

Figure 21. 9S Lipo Charger

Assembly Steps- Motor, ESC, and Battery Connection

It should be noted, that some pictures were taking from online resources in order to help illustrate that steps of building this Rotorcraft. This was done due to the fact that all the parts for the team are not yet received.

Step 1- Begin with soldering all 8 ESCs, so that the 3mm Bullet Connector can be attached as seen in Figure 22 [9].

Figure 22. Solder Connectors

Step 2- Install the prop mount to the motor using 3mm mounting screw as seen in Figure 23 [10].

Figure 23. Mounting Prop Mount to Motor

Step 3- Connect motor cables to electronic speed controller bullet connectors. Each motor must connect to only one ESC as shown in Figure 24 [9].

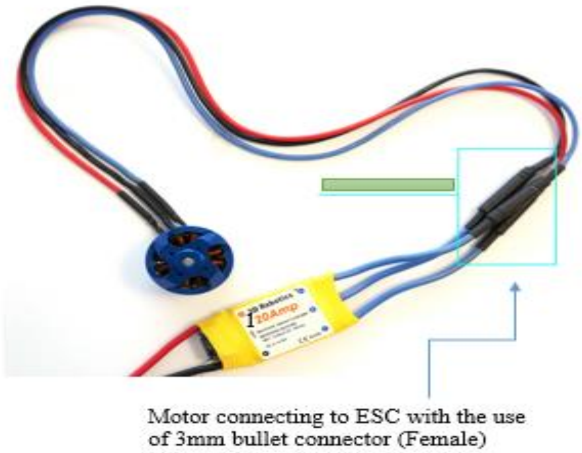

Figure 24. Connecting Electrical Speed Controller to Motor

Step 4- Connect ESC dean connector to Microcontroller board connectors that are attached to the IMU sensor. Connect ESC for motor 1 to PDB pins marked M1, motor 2 to PDB pin marked M2, etc.… as shown in Figure 25 [9].

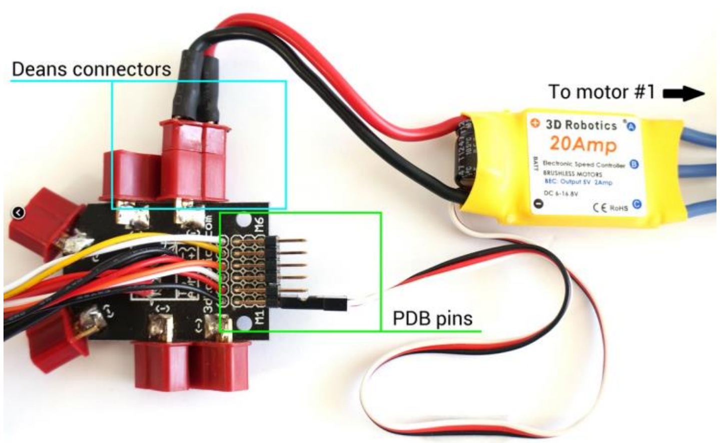

Figure 25. Connecting Electrical Speed Controller to PDB Pins

Step 5- Connect the ESC to the battery by sliding the female connector inside the male connector as shown in Figure 26 [11].

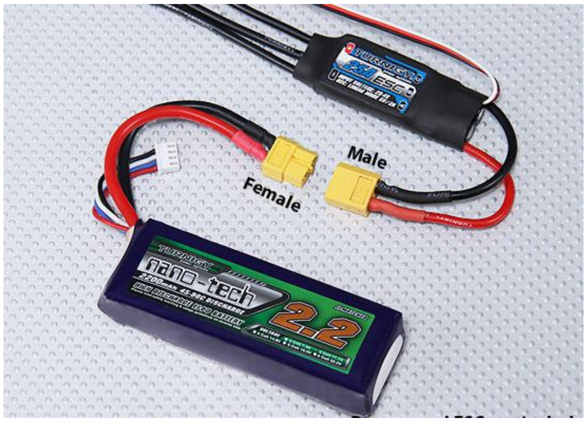

Figure 26. Connecting the Electrical Speed Controller to the Battery

As a review of the first five steps a general layout can be seen in Figure 27 to better help understand how the layout is supposed to be [9]. The general layout for this rotorcraft includes that two motors be powered by one battery. Again as mentioned earlier, first connect the motor to the brushless electronic speed control. Next connect the connect ESC deans connector to Power Distribution Board Deans connectors which are attached to the IMU sensor. Last but not least connect the ESC to the battery in order to supply the motor with power.

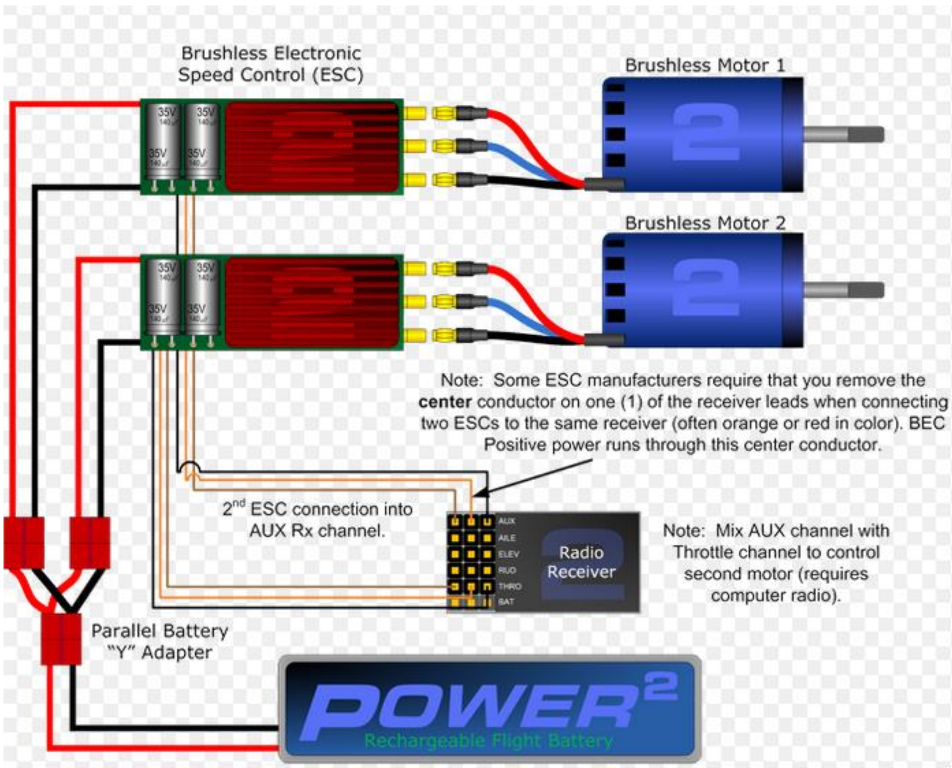

Figure 27. General Layout of ESC, Battery, IMU, and Motor Connections

Assembly Steps- Motors and Props

Step 6- Secure the motor mount to the carbon fiber arms using four M3x6 screws as shown in Figure 28 [7].

Figure 28. Secure Motor Mount to Carbon Fiber Arm

Step 7- Secure the Electrifly motor to the motor mount as seen in Figure 29 [7].

Figure 29. Secure the Motor to the Motor Mount

Step 8- After ensuring the motors are running in the correct direction, prepare the 18x10 APC props and prop mounting screw and washer from the motors.

Step 9- Install the propeller to the motor and secure it with the prop mount screw and washer as seen in Figure 30 [7].

Figure 30. Install Propeller onto the Motor

Assembly Steps- Hinges and Battery Straps

Step 10 – Attach the T shaped hinge to the base plate as shown in Figure 31. This can be done by screwing in the 9mm screw into the plate and two 9mm screws into the carbon fiber arms.

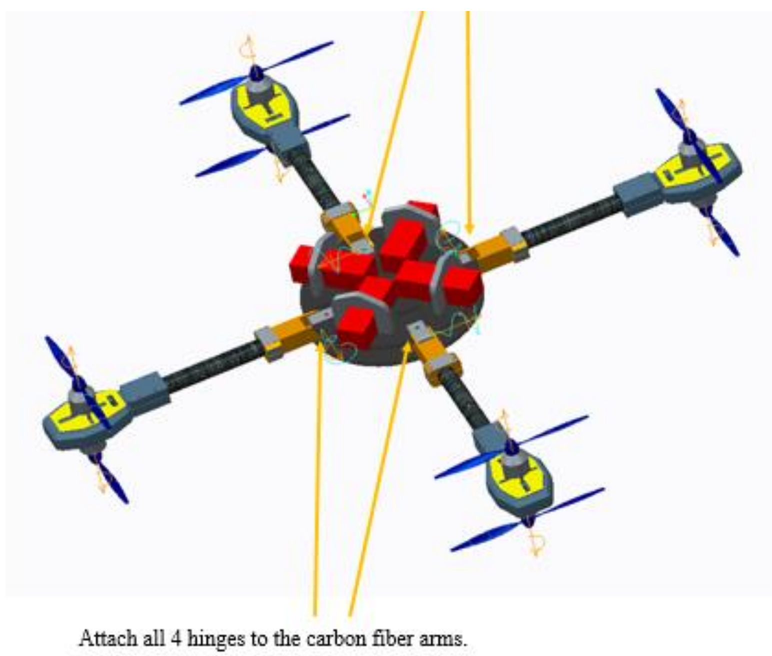

Figure 31. Attach Hinges to the Base Plate

Step 11- Connect the bottom plate to the top plate via four U-clamps. This will be done using sixteen 10 mm screws. There will be two screws on the top plate, and two screws on the bottom plate via each of the four U-clamps.

Step 12- Attach the Velcro straps over the batteries tightly as shown in Figure 32 in order to minimize battery movements.

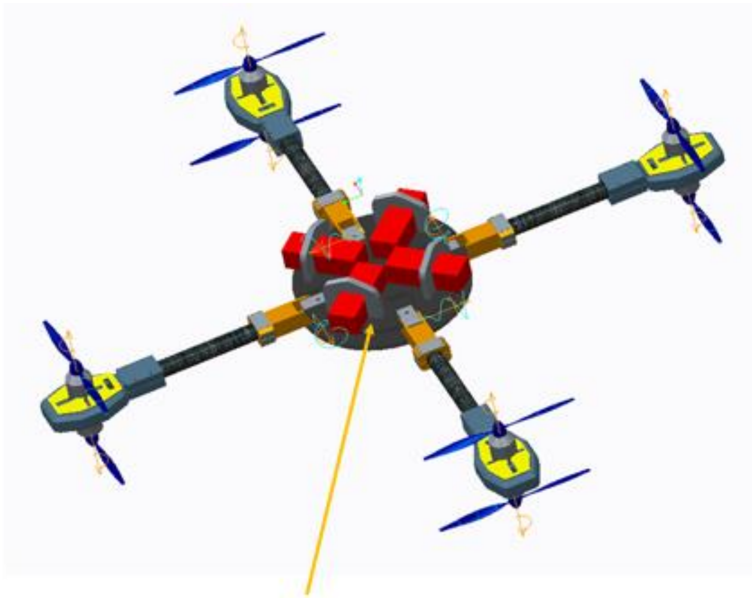

Figure 32. Place the Velcro Straps Over the Batteries

4.3.3 Software Connections:

Microcontroller Unit:

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 [12]. 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 [12].

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.

Inertial Measurement Unit:

For this project's chosen design, the Adafruit 9 DOF (degrees of freedom) IMU sensor was selected and can be seen in Figure 33. 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 [13]. 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.

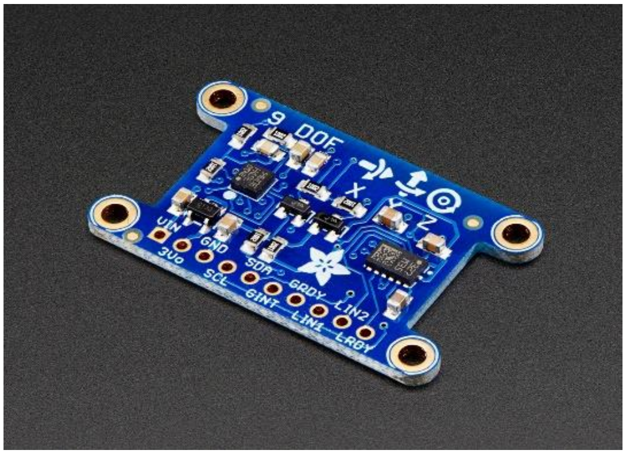

Figure 33. Inertia Measurement Unit (IMU)

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.

The following are the steps that are taken to attach the Arduino Board to the IMU sensor and can be seen in Figure 34:

1. Attach the pull-up resistors to two of the wires.
2. Using another wire split one of the ends on the pull-up resistor wire into two for both pull-up resistor wires.
3. Connect the ground to the ground (GND).
4. Solder a wire to the 3.3V port on the MCU to the VCC port in the IMU.
5. Using a pull-up resistor wire, port A4 on the MCU attaches to both VCC and SDA on the IMU.
6. Using a pull-up resistor wire, A5 attaches to both VCC and SCL.

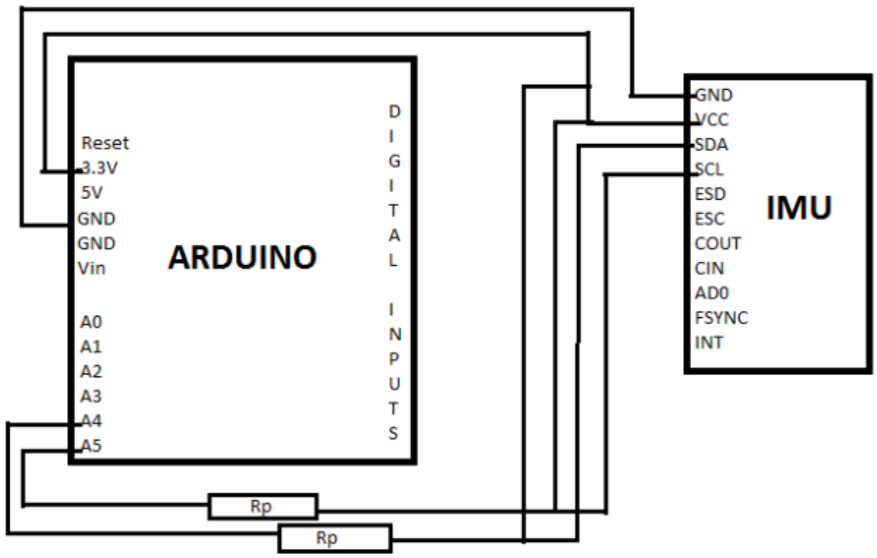

Figure 34. Connecting Arduino Board to IMU

These are some additional comments for the electrical software assembly. Even though all of the connections made are "hard connections" this falls under the scope of software, because the components being connected are where the software for the rotorcraft will be stored. To clarify the short hand on the components, SCL is for the clock line and SDA is for the data line. The clock line controls the speed at which the IMU collects and send data to the MCU. The data line is the actual line through which the information is passed. We will be using the 3.3V power port on the MCU to power our IMU. Lastly, A0 through A5 are the 6 analogue ports, which are needed to attach the IMU, because the IMU sends analogue data.

5. Conclusion

In conclusion the problem that needs to be addressed is building a rotorcraft that has a high portability and high payload capacity. The main objectives of this project include being able to carry a payload of 30 pounds and fit the Rotorcraft inside a standard size military backpack (23x14.5x15)". Within the Design phase, a detailed mechanical and electrical assembly was provided in addition to a checklist of parts in order to prepare for the build of the rotorcraft. First, a full step by step explanation of how to manufacture the carbon fiber baseplates was provided. The team used the vacuum-assisted resin transfer molding (VARTM) process to create both baseplates out of carbon fiber.

Additionally, the general design of the rotorcraft was re-presented in this phase and a checklist of necessary parts was written. The checklist includes every part necessary to build the rotorcraft. Further, the protocol for the mechanical and electrical assembly was provided. The detailed assembly was divided into two portions. Portion one focused on the assembly of the Motor, ESC, and Battery Connection while the second portion outlined the assembly of the motors and propellers. Last, this report also explains the software connections and the electrical configuration of the rotorcraft. Specifically, the chosen microcontroller and IMU are explained and the steps to connect the Arduino Board to the IMU sensor are detailed.

The next step for this project is to continue calling vendors to ensure that all the ordered components are delivered as soon as possible. In the next phase, Verify, the rotorcraft will be assembled and the team will test its flight ability. Additionally the results from the rotorcraft will be compared to the e-Calc results to verify our measurements and analysis.

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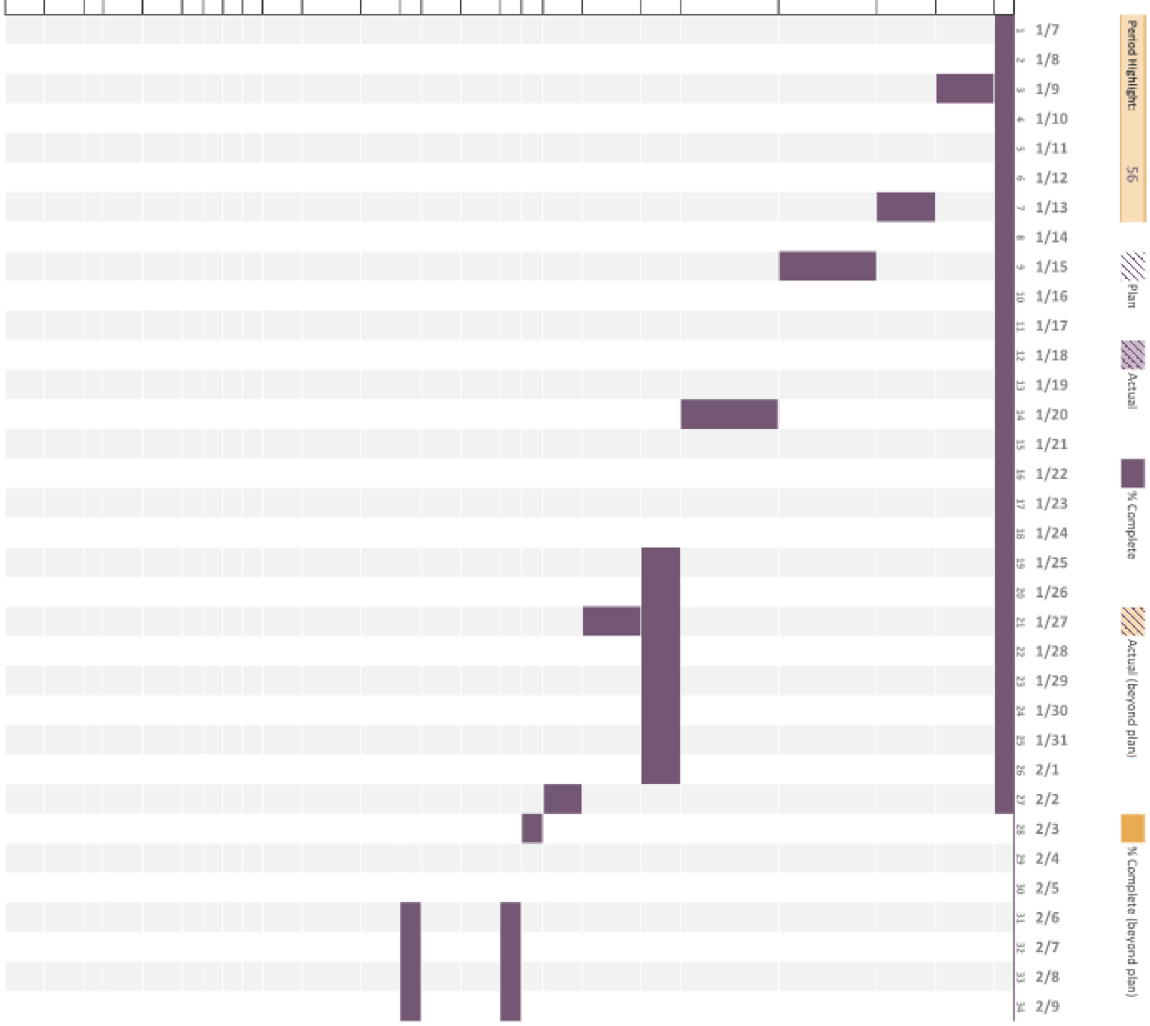
Appendix A – Gantt chart for Spring Semester

Spring Semester

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Analyze Phase	1	27	1	27	100%
Team Meeting 1 - Establishing New Meeting Day and Time	3	1	3	1	100%
Team Meeting 2 - Welcome Back; General Discussion	7	1	7	1	100%
Meeting - Discussing Expectations for Analyze Phase; Discussing Plan and Bill of Materials	9	1	9	1	100%
Team Meeting 3 - Assigning Paper Responsibilities; Discuss Jack Simulation Progress	14	1	14	1	100%
Write Analyze Phase Paper	19	8	19	8	100%
Team Meeting 4 - Paper Update & Clarification	21	1	21	1	100%
Proofread & Assemble Analyze Phase Paper	27	1	27	1	100%
Team Meeting 5	28	1	28	1	100%
Design Phase	31	26	31	26	100%
Write Design Phase Paper	47	8	47	8	100%
Proofread & Assemble Design Phase Paper	55	1	55	1	100%
Finalize Orders	31	7	31	21	100%
Parts Due: PVA Release Film	46	1	58	1	0%
Parts Due: Motor mounts, rotorcraft arms, propellers	46	1	60	1	0%
Parts Due: Motors and speed controllers	46	1	68	1	0%
Parts Due: All others	46	1	46	1	100%
Verify Phase	57	30	57	30	0%
Assembly	69	9	69	9	0%
Flight Testing	80	1	80	1	0%
Write Verify Phase Paper	77	8	77	8	0%
Proofread & Assemble Verify Phase Paper	85	1	85	1	0%
Final Report Phase	87	12	87	12	0%
Create Final Deliverable	87	6	87	6	0%
Proofread & Assemble Final Deliverable	93	1	93	1	0%



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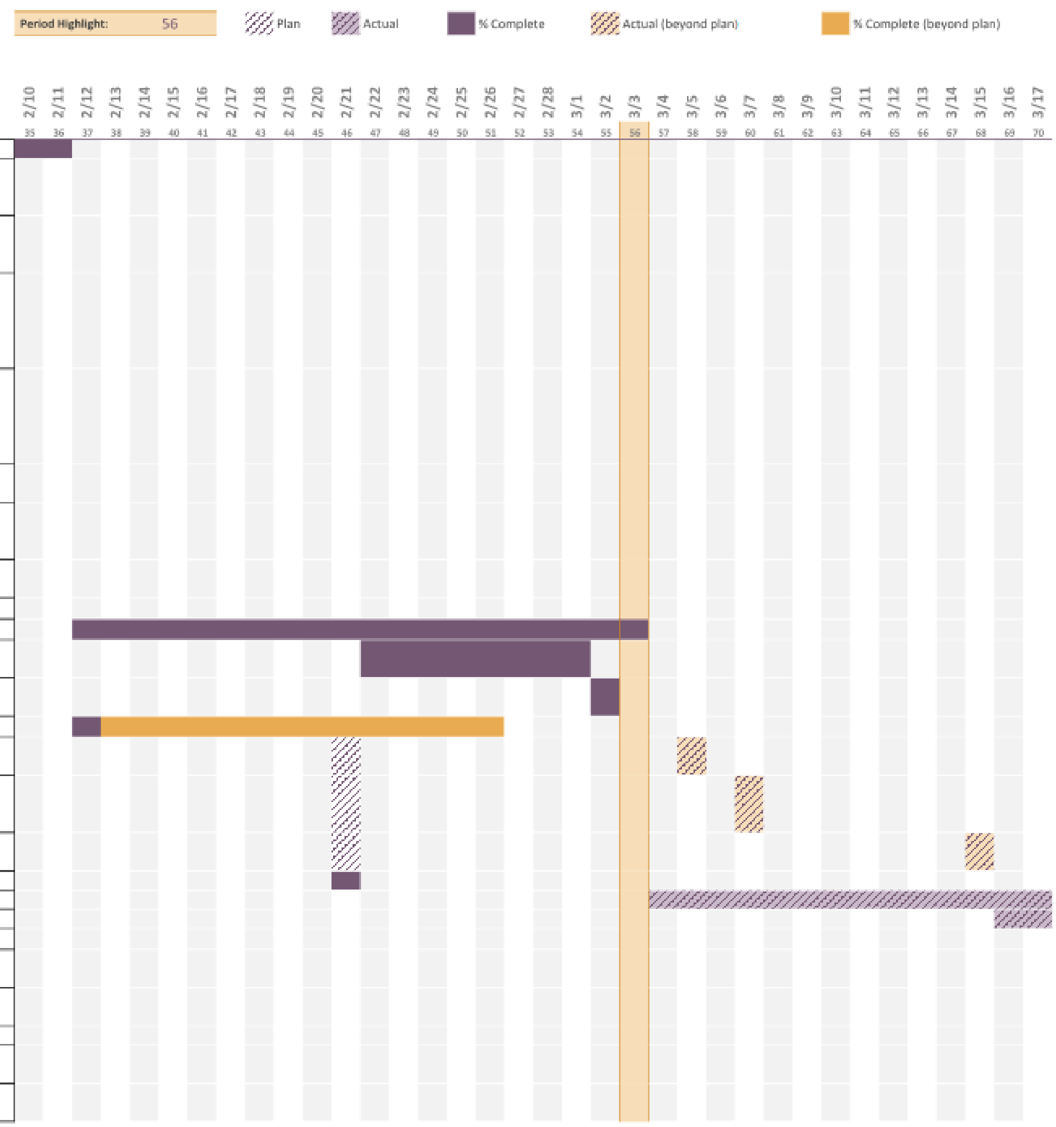

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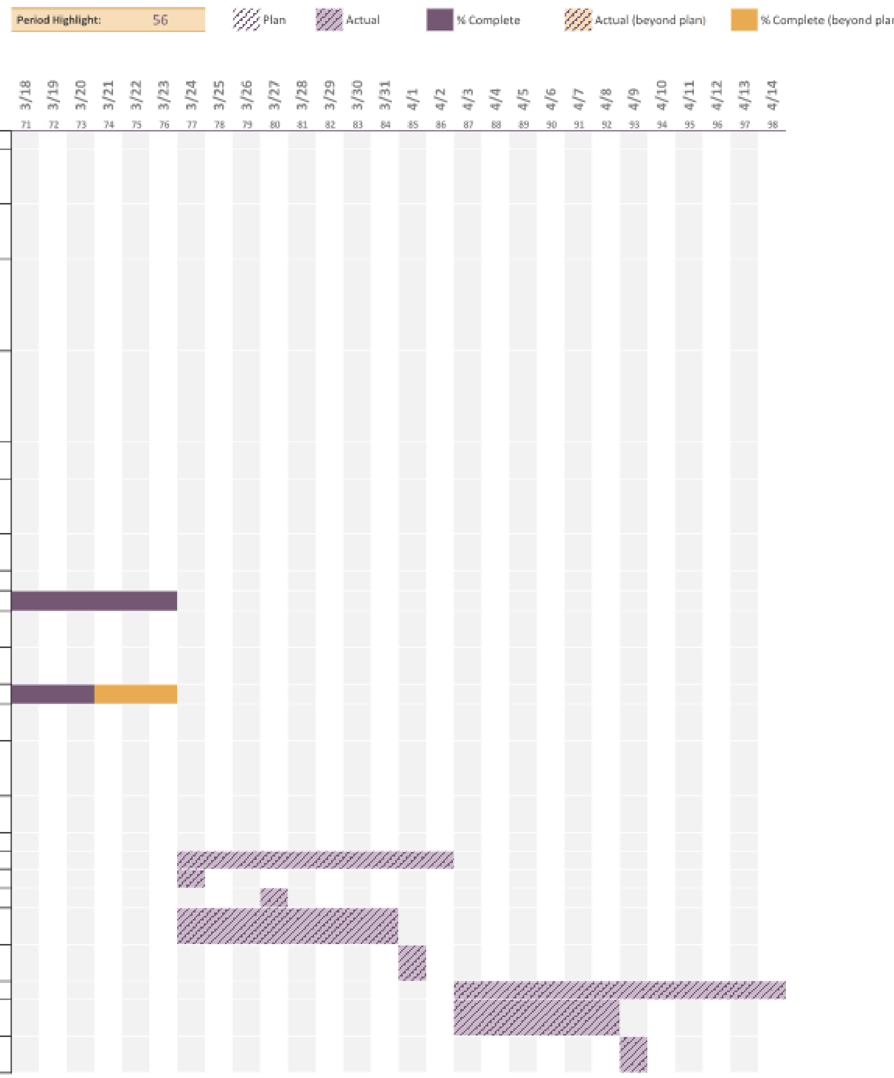

Appendix B – Motor dimensions

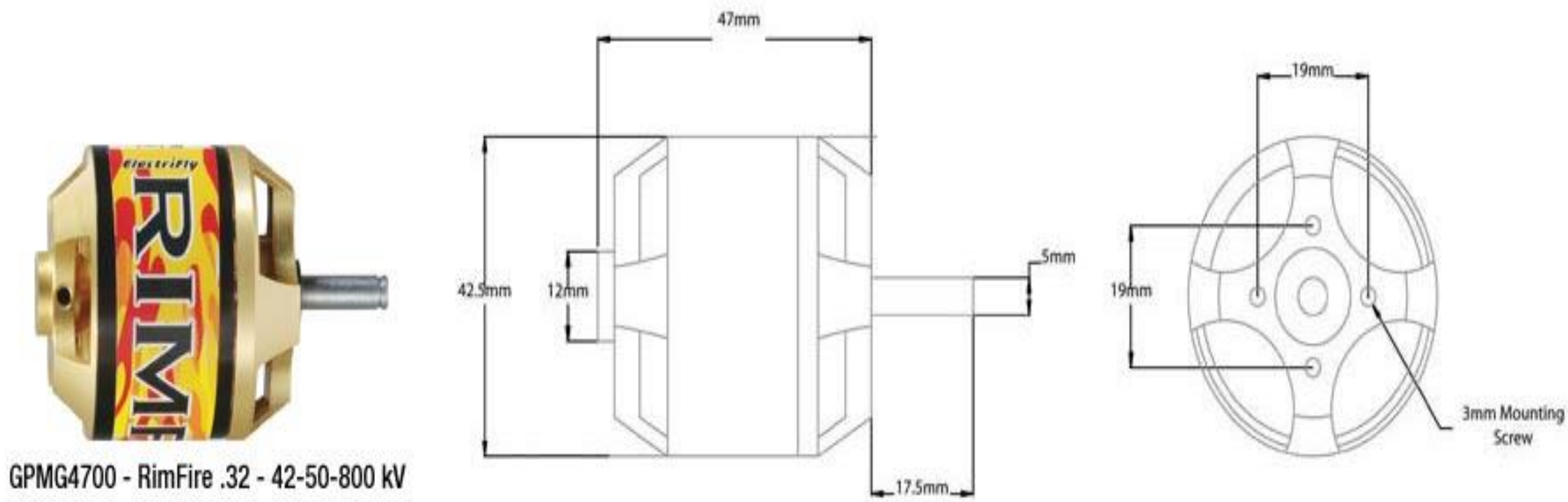

Figure 35. Electrifly Motor Dimensions