FAMU-FSU COLLEGE OF ENGINEERING

Design and Manufacture of a Rotorcraft for Military Applications

A report submitted to Dr. Okenwa Okoli
Industrial & Manufacturing Engineering Department

Authors: Chabely Amo, Louisny Dufresne, Robert Johnson, Mohammed Nabulsi, Taniwa Ndebele, Victoria Rogers, Kimberlee Steinman, and Mitchell Stratton

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This report is the fifth of five progress reports. It verifies the expected outcome determined in previous progress report following the Six Sigma methodology of “Define, Measure, Analyze, Design, Verify” (DMADV).

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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 fifth of five phases in this project. This phase is known as the Verify Phase, in which the performance measures previously calculated in Measure are supposed to be verified. Unfortunately, the team was unable to perform flight testing on the rotorcraft prototype within the time frame of this phase.

With the final design of the rotorcraft selected in the Measure Phase, mechanical, electrical, and ergonomic assessments done in the Analyze Phase, and all components ordered and explained in the Design Phase, this report focuses on providing a summary of the entire project and presenting work that needs to be completed by this team and possible areas for improvement for future teams assigned to continue this project.

1. Introduction

Rotary unmanned aerial vehicles often fall into one of two classifications: high portability with a low payload capacity or low portability with a high payload capacity. There is an increasing need however for rotorcrafts that are capable of transporting heavy payloads while still maintaining high portability. One reason for this need is military applications of unmanned aerial vehicle capable of carrying large payloads while being portable by a soldier on the ground. Due to this need by the military, the United States Air Force has sponsored this senior design project.

The objective of this project is to design and build a rotorcraft with high portability and high payload capacity. Specifically, a rotorcraft that can lift a payload of thirty pounds while still fitting into a standard military backpack. In order to achieve both goals for this project, a rotorcraft with high payload capabilities and compact size, the team focused on building a collapsible rotorcraft with arms that fold above the frame.

Due to the complexities of this project, multiple tools and phases were utilized to complete the rotorcraft. These programs and methods mentioned in the following paragraph will be discussed in more detail later in this report. This project is in the final of five project phases. First, in the Define Phase, customer requirements for the project were determined and a general approach for completing the project was established. Next, during the Measure Phase, eCalc was utilized to evaluate three proposed designs and a stress analysis was performed on major structural components in PTC Creo Parametric 2.0. Then, in the Analyze Phase the final components for the craft were selected with eCalc and an ergonomic assessment of the deployment of the rotorcraft, using Siemens Jack software, was done. In the most recent phase, the Design Phase, the detailed design and plan for manufacturing the rotorcraft was presented. Finally, the last and current phase of the project is the Verify Phase. In this phase the rotorcraft was assembled and tested by the team. The steps taken and results of this phase will be presented later in this report.

2. Project Charter

2.1 Overview

2.1.1 Background and History

This project is being sponsored by the Department of Industrial and Manufacturing Engineering for the United States Air Force. “The mission of the United States is to fly, fight, and win … in air, space, and cyberspace” [1] To those ends, the United States Air Force is interested in the study and development of various aircraft, included unmanned aerial vehicles (also known as UAVs).

One type of UAV is a rotorcraft, which is a heavier than air flying machine that uses lift generated by wings (also known as rotor blades) that revolve around a mass. The first rotorcraft was design by Louis Breguet in 1907 [2] Breguet’s four-rotor craft was able to fly a few feet above the ground. In the past century, unmanned aerial vehicles have advanced greatly thanks to the work of programs such as [2]:

- 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 applications, such as research in world-class engineering laboratories, military and law enforcement, and aerial imagery in commercial use [3]. However, these rotorcrafts all have one thing in common: they are large and carry large payloads or small and carry small payloads. This project is concerned with creating a rotorcraft that is small enough to fit in a military backpack while carrying a relatively sizeable payload, which has not yet been accomplished as far as this project’s team is aware.

More important than the improvement that this project’s rotorcraft will pose compared to previous rotorcraft designs is the improvement made compared to current military methods. The team objectives as originally planned lead to a payload of fifty pounds, which is on the scale of a sack of potatoes, six gallons of water, or two uncooked turkeys. These items are too small for an airdrop and thus would currently be delivered by a soldier on the ground. This is acceptable in non-combat situations, but in combat situations this could be hazardous or even fatal to a soldier.

Comparatively, the potential loss of a rotorcraft is much more preferable. From a utilitarian standpoint, the loss of a rotorcraft is less expensive (in terms of resources used to build a single unit) than the loss of a soldier (in terms of resources used to train a single unit). The loss of a soldier is even more tragic when one considers that the loss of a soldier means the unnecessary loss of human life.

This project is focused on the further development of existing UAV technology to mitigate some of the risks posed to human soldiers in combat situations.

2.1.2 Objectives and Expected Benefits

As originally assigned, the objectives for this project are as follows:

1. Design a rotorcraft that can:
    - Fit in a military backpack (23”x14.5”x15”)
    - Carry a payload of at least fifty pounds
    - Be made with commercial off the shelf (COTS) components
    - Travel up to a 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. Design the protocols for the operation and assembly of the rotorcraft.

Following the outcome of the Define and Measure Phases of the project, the payload objective was reduced from fifty pounds to thirty pounds. Altogether, the objectives listed above are the overall goals for 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 United States Air Force or by the College of Engineering as a means to further future projects or goals. The specific projects or goals desired by the United States Air Force beyond those described in section 2.1.1 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.

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 and local retailers	Rotorcraft components: rotors, propellers, battery, IMU sensors, microcontroller, RC transmitter	Build a prototype rotorcraft		United States Air Force
HPMI	Materials for the frame for the rotorcraft			

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 High Performance Materials Institute (HPMI).

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

The team organization among the project members is fairly flat. For the Verify Phase, team leadership responsibility is split evenly between Taniwa Ndebele and Kimberlee Steinman. All other members have equal input in decision making, but any final decisions are left to team leadership.

At the beginning of the project, the team organization was laid out differently. In this layout, there was a single team leader to whom a leader for each discipline reported and then each discipline's members reported to the discipline leader. Team roles are self-assigned based on comfort level with specific responsibilities. These roles and team members assigned to each role are:

- 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. Prior to the Verify Phase, the Team Leader was Mohammed Nabulsi.
- 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. This position rotates among the industrial engineering majors.

- 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. This position rotates among the mechanical engineering majors.
- 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. This position rotates among the electrical and computer engineering majors.
- 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 Financial Advisor for this project is Louisny Dufresne, in addition to any leadership responsibilities during his time as the Industrial Engineering Lead.
- The *Webmaster* is responsible for maintaining the team project website with up to date information and media according to the requirements of the Department of Mechanical Engineering. The Webmaster for this project is Kimberlee Steinman, in addition to any leadership responsibilities during their time as the Industrial Engineering Lead.
- The *Material Selection Engineer* is in charge of researching all the possible materials required for the design and manufacturing of the rotorcraft. The Material Selection Engineer is responsible for selecting the manufacturing process required to manufacture the parts. The Material Selection Engineer for this project is Chabely Amo, in addition to any leadership responsibilities during her time as the Industrial Engineering Lead.
- The *Power Systems Engineer* is responsible in particular for all power systems components of the project. This position rotates among the electrical and computer engineering majors – that is, one electrical and computer engineering student is the Electrical and Computer Engineering Lead while the other is the Power Systems Engineer.

- 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 Software Designer for this project is Taniwa Ndebele, in addition to any leadership responsibilities during his time as the Mechanical Engineering Lead.
- 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. The Mechanical Fabrication Engineer for this project is Victoria Rogers, in addition to any leadership responsibilities during her time as the Mechanical Engineering Lead.

2.2 Approach

2.2.1 Scope

This project is intended to result in an unmanned aerial vehicle that meets or exceeds the minimum requirements as stated in section 2.1.2. Any work that must be done to further these goals is within the scope of this project. This scope includes the design of said rotorcraft, building a prototype, and presenting progress reports and project updates on a regular basis. Throughout the project, the team shall ensure that the rotorcraft is in fact being built to the minimum standards set for this project using tools such as stress analysis in Creo Parametric 2.0, ergonomic analysis in Siemens Jack software, simulated flight analysis in eCalc, and other forms of analysis and verification. This work is also within the scope of the project

The scope does not include any work not related to building the UAV as described in section 2.1.2 or general project requirements. Out of scope work includes graduate level materials research, creating or designing custom electrical or mechanical components (with the exception of the plates included in the design), designing a rotorcraft that is intended to be used more than once, and designing a training manual or protocol for use other than in the most general terms.

2.2.2 Assumptions & Constraints

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

  - 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.
  - The net torque of the craft under steady state equilibrium conditions is equal to zero.
  - Wooden propellers are comparable in performance to the plastic propellers analyzed in eCalc.
- Electrical Assumptions
  - The microcontroller and sensor will be adequately protected from the weather by being inside the baseplates.
  - The wires and connections will stay intact while the craft is being moved in the backpack as well as in flight.
  - The batteries do not have to be removed or recharged after use because the rotorcraft will not return after its mission.
  - The batteries will discharge at full capacity the entire flight time.
  - The current will remain constant through the entire flight time.
  - All soldering will remain in usable condition throughout the entire usage of the rotorcraft.
- Quality Control Assumptions:
  - The quality control standards that each vendor utilizes are adequate and thus every component ordered for this project meets the requirements for the project.
  - Each motor is manufactured to be identical.
  - Purchased parts does not present any defects and need no assessment beyond rudimentary visual inspection by the team.
  - Parts manufactured by the project team (that is, the discs of the frame and the cut arms) are created without defects.
- Testing Assumptions:
  - The weight of the payload used in testing is accurately known and within the project parameters.
- Ergonomic Assumptions:

  - The ergonomic software Jack generates accurate and reliable results.
  - The ground on which the user is working is relatively stable and flat.
  - The user does not travel more than a meter when placing the rotorcraft on the ground.
  - 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).
  - 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.
  - The appropriate carrying limit for a soldier in pounds is not known, but the total weight of the payload and rotorcraft is assumed to be within these limits as testified by project team member Mitchell Stratton.

There are also constraints involved in this project. These constraints include the timeline of the project, the budget, and the project requirements as described in section 2.1.2. Additionally, companies located in the United States must manufacture all purchased components. This is because the project is being sponsored by the United States Air Force.

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

2.2.4 Milestones

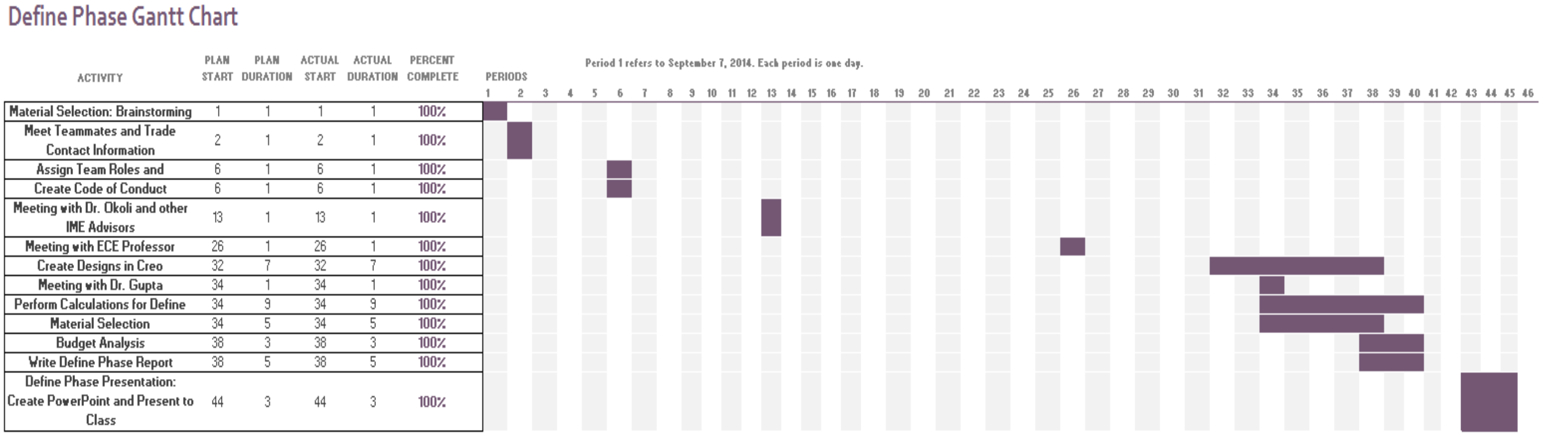
The team has already completed the six-sigma Define, Measure, Analyze, Design, and Verify (DMADV) process, and the milestones achieved per phase are the following:

- Define Phase:
    - Establish team organization
    - Meet with stakeholders to establish and define parameters for the project

    - Define the project scope, business case, need statement, goals and objectives, and other project charter elements
    - Create a House of Quality matrix representing the Voice of the Customer
    - Preliminary design research
- Measure Phase:
    - Finalize design of rotorcraft, along with component selection
    - Perform stress analysis of the design
- 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
- Verify Phase:
    - Build the rotorcraft prototype
    - Compare actual apparatus performance with simulations performed in previous phases
    - Write detailed mechanical and electrical assembly instruction manual
- Business Plan:
    - Finalize the project and establish a business plan

The milestones for the Design Phase (protocol for operation, assembly instructions, and a fully 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. As of the end of the Verify Phase, the rotorcraft should be fully built and has been flight-tested. Specific results of these tests can be found in section 7.

These milestones help to form a Gantt chart for this project. A Gantt chart is a project management tool that allows for scheduling and planning along a critical path. The Gantt chart generated for this project can be seen below in Figure 1, Figure 2, and Figure 3. An Excel file with this Gantt chart is available upon request, but is not print friendly.

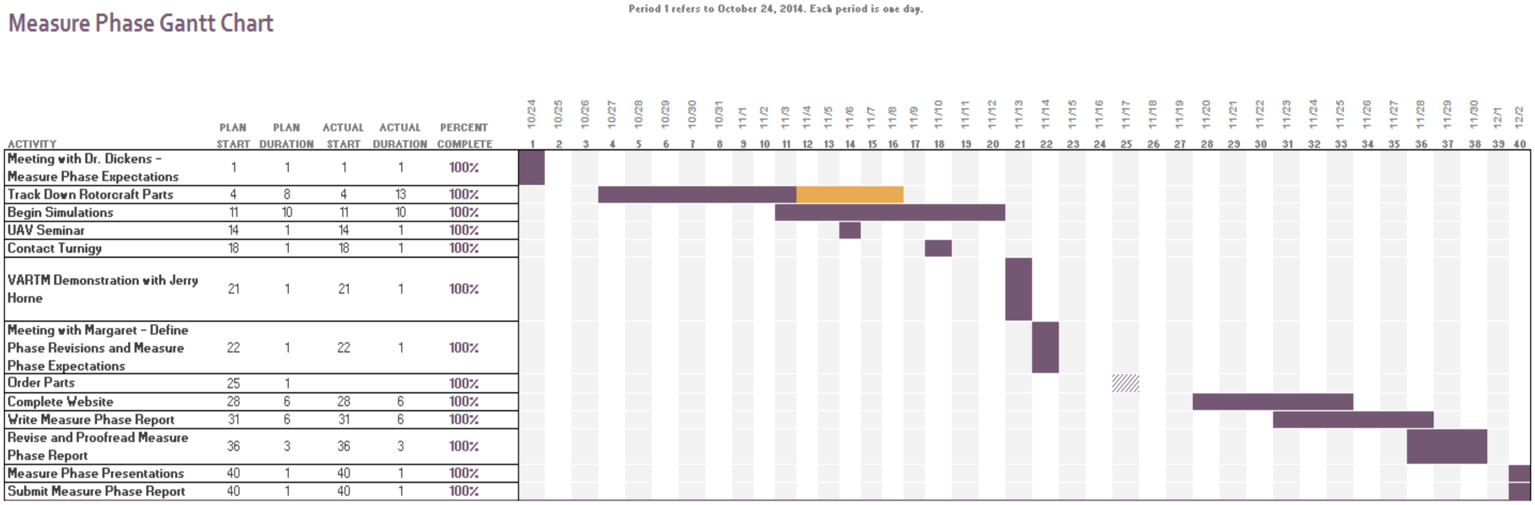


Define Phase Gantt Chart

Period 1 refers to September 7, 2014. Each period is one day.

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Material Selection: Brainstorming	1	1	1	1	100%
Meet Teammates and Trade Contact Information	2	1	2	1	100%
Assign Team Roles and	6	1	6	1	100%
Create Code of Conduct	6	1	6	1	100%
Meeting with Dr. Okoli and other IME Advisors	13	1	13	1	100%
Meeting with ECE Professor	26	1	26	1	100%
Create Designs in Creo	32	7	32	7	100%
Meeting with Dr. Gupta	34	1	34	1	100%
Perform Calculations for Define	34	9	34	9	100%
Material Selection	34	5	34	5	100%
Budget Analysis	38	3	38	3	100%
Write Define Phase Report	38	5	38	5	100%
Define Phase Presentation: Create PowerPoint and Present to Class	44	3	44	3	100%

Figure 1. Gantt chart for the Define Phase



Measure Phase Gantt Chart

Period 1 refers to October 24, 2014. Each period is one day.

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

Figure 2. Gantt chart for the Measure Phase

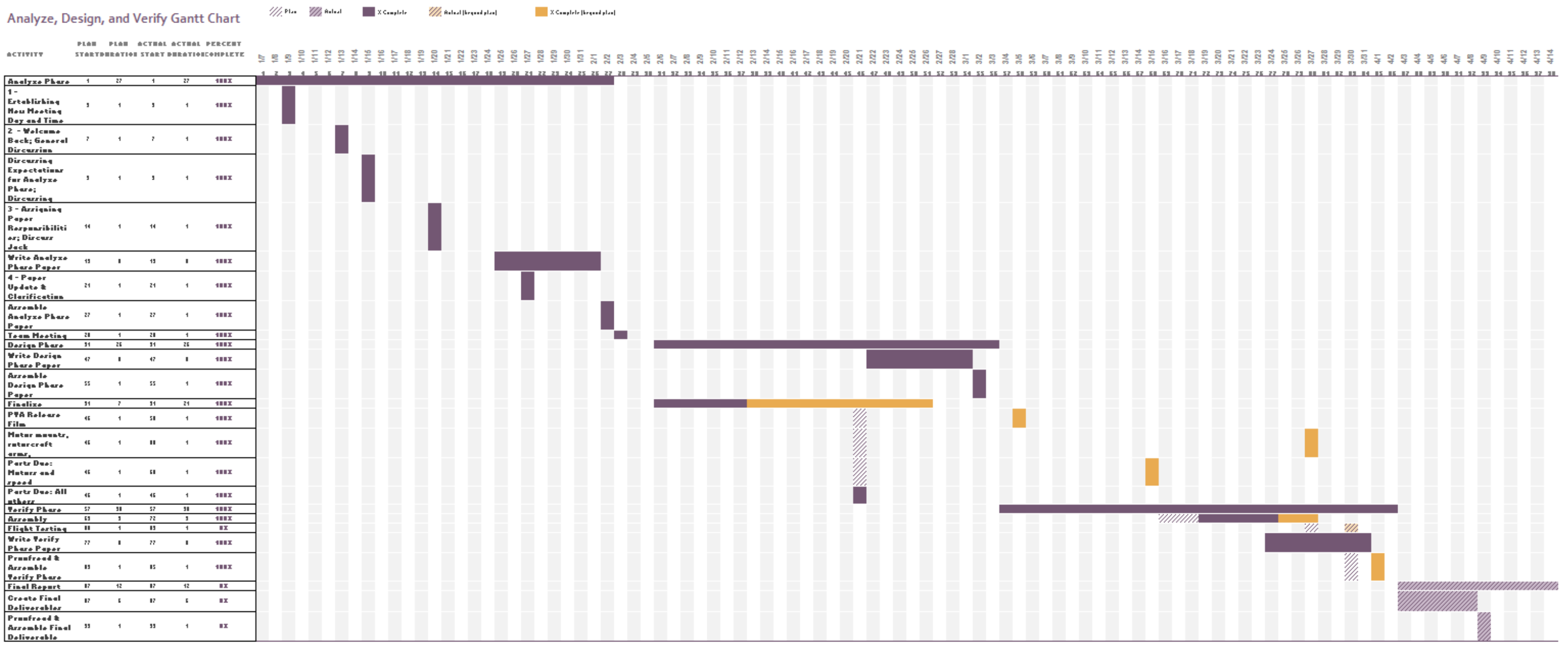


Figure 3. Gantt chart for the Analyze, Design, and Verify Phases

Even though the critical path is not explicitly clear in the figures above, the main elements of the critical path are prerequisites for each other and are as follows:

- Finalize a design choice
- Select components
- Order components
- Receive components
- Assemble rotorcraft prototype
- Fly rotorcraft prototype and report the results.

In January and February 2015, several delays were faced in ordering and receiving components. Delays were caused by issues such as unapproved purchase orders, long lead times on ordered components, ordering an incorrect component, requiring approval to go beyond budget, and so on. Because of the myriad delays, the majority of the components were not received until well into March 2015. The planned schedule above was already changed to account for when suppliers stated various components would arrive and even these were delayed in some cases, leading to a much delayed assembly and flight of the rotorcraft.

2.2.5 Bill of Materials

As the project progressed through the Verify Phase, various changes and additions to component selection were made due to problems regarding delivery time, component availability, and component incompatibility. Currently, the team has greatly surpassed the original budget of $2,500; in total the cost for the manufacture of the rotorcraft has been $5,207.21. Table 3 shows the final bill of materials with all the components required to build the rotorcraft and the purchaser for each of them. The High Performance Materials Institute (HPMI) donated all the materials required to manufacture the top plate and base plate composites of the rotorcraft; therefore, no payments were made for the creation of these components. However, the total payment made by the Department of Industrial and Manufacturing Engineering has been $3,093.30, the Department of Mechanical Engineering has paid $769.98, the Department of Electrical and Computer Engineering has paid $769.98, and the team members themselves have paid $573.95.

The Department of Mechanical Engineering and the Department of Electrical and Computer Engineering agreed to purchase the four batteries (two per department) required for the rotorcraft, because the team had already surpassed its budget and the price for the four batteries was too high. The team had to purchase last minute components due to the following issues:

- Failure to implement all components required early on the design, which resulted in parts not being ordered on time. For example: Screws, Pins, RC controller, and IMU.
- Failure to order components with necessary specifications. The APC propellers ordered through the Department of Industrial and Manufacturing Engineering were all counter clockwise propellers and the rotorcraft design requires four counter clockwise and four clockwise propellers.

Other issues that caused changes and additions of components were:

- Unavailability of components. The originally chosen speed controllers were discontinued, and new ones had to be ordered.
- Unapproved purchase orders. The motor mounts were not delivered on time due to problems regarding the approval of the purchase order.
- Incompatibility between components that resulted in returning and ordering new components. For example, the originally ordered carbon fiber tubes for the arms were incompatible with the motor mounts required.

Table 3. Rotorcraft Bill of Materials

Part Name	Description	Quantity	Unit Cost	Cost	Purchaser
Base Plates	Carbon Fiber Vinyl Ester Resin Composite	2	**	***	HPMI
Carbon Fiber Layers	3K Plain Carbon Fiber	3	**	***	
Vinyl ester Resin	Ivex c410	*	**	***	
Carbon Fiber Arms	High-Strength Carbon Fiber Tube, 1.000 in	2	$152.73	$305.46	SPONSOR
Motor Mounts	MOTOR MOUNT 25mm BOOM HEAVY LIFT COAX (PAIR)	4	$57.00	$228.00	
Speed Controller	120A HV Brushless Programmable ESC	8	$139.99	$1,119.92	
Motors	RimFire 1.60	8	$179.99	$1,439.92	
Battery	5000mAh 9-Cell/ 33.3V/ 45C/ LiPo	4	$384.99	$1,539.96	ME and ECE
Balsa Wood	1/8 X 6 X 36 in Balsa Wood Sheet	3	$5.51	$16.53	TEAM
	1/8 X 4 X 36 in Balsa Wood Sheet	4	$3.19	$12.76	
Propeller	Zinger Wood Propeller 18x10 in	8	$25.00	$200.00	
Flight Controller	Flight Controller	1	$50.00	$50.00	
RC Controller	Spektrum DX5e 5-Channel Transmitter with AR610 Receiver	1	$96.00	$96.00	
Pins	3/8 in Aluminum Pins	8	$4.57	$36.56	
Battery Charger	9s Lipo Charger	1	$50.00	$50.00	
AGW Wires	American Gage Wire	2 ft.	$7.00	$14.00	
Carbon Fiber Arms Holder	Cut from aluminum sheet	8	$1.25	$10.00	
Corner Brace	3 in. Zinc Plated Corner Braces	8	$3.77	$30.16	
IMU Sensor	Adafruit 10-DOF IMU Breakout - L3GD20H + LSM303 + BMP180	1	$29.95	$29.95	
Velcro Pack	12' x 3/4" Roll - Black	1	$7.99	$7.99	

Screws	¼ in diameter and 5/8 in long screws	16	$0.80	$12.80	
	¼ in diameter and 2 ½ in long screws	8	$0.90	$7.20	
			Total cost:	**$5,207.21**	

Moreover, the team had to return some of the components purchased by the Department of Industrial and Manufacturing Engineering because they were already provided by the HPMI or the specifications did not meet the design requirements. Table 4 shows the components that were returned.

Table 4. Returned Components

Part	Description	Quantity	Unit Cost	Cost
Propellers	18x10 APC Electric Prop	8	$11.40	$91.20
Epoxy Resin	With 2:1 Ratio Slow Epoxy Hardener (32 oz.)	1	$41.95	$41.95
Polyvinyl Alcohol	PVA Release Film (1 Gal)	1	$24.75	$24.75

The team surpassed the original budget of $2,500 and end up spending a total of $5,207.21, because of all the necessary components required to meet customer requirements. Since one of the team objectives is to lift a payload of thirty pounds, the team had to choose the optimal combination of motor, battery, speed controller, and propeller that would generate the require lift and thrust forces to make it possible. The components chosen by the team present a high cost; however, these components were tested together using the eCalc tool (which will be explained later in section 4.3) and they are all necessary to meet this requirement. Additionally, the top plate, bottom plate, motor mounts, and arms are made out of carbon fiber composites that also present a high cost, but are necessary for the success of the project.

3. Defining Customer & Technical Requirements

3.1 Critical Customer Requirements (CCR)

Defining 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 4 and each cause is explained by category below.

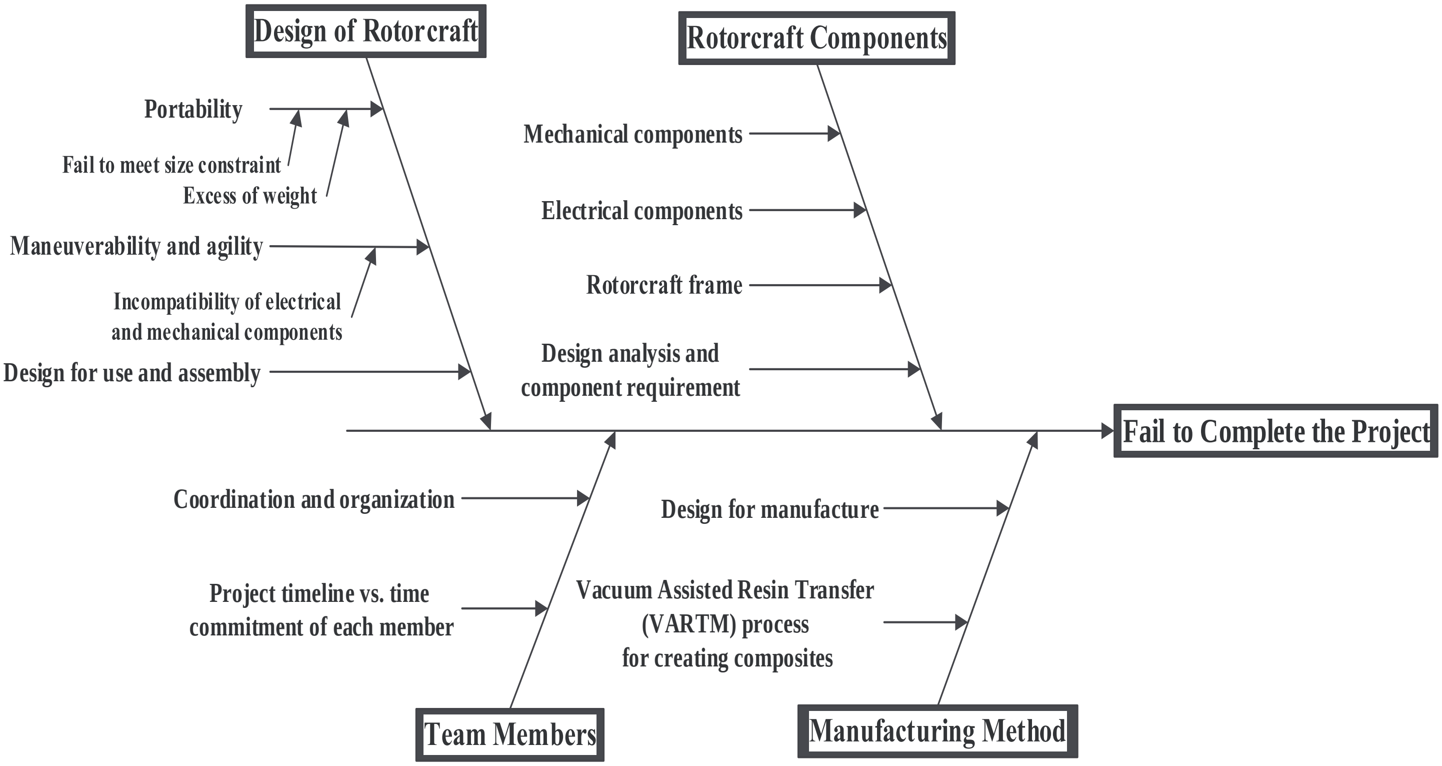


Figure 4. Fishbone Diagram

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 assumption 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 mechanical components with the largest potential to cause a problem 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 composite 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 team to meet all the customer requirements stated on section 3.2.1. 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. Gerald 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. Gerald Horne, to ensure the quality of the rotorcraft's base plates meet with specifications.

3.2 Meeting 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 5 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.

In order to lift the desired payload, the motors, 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.

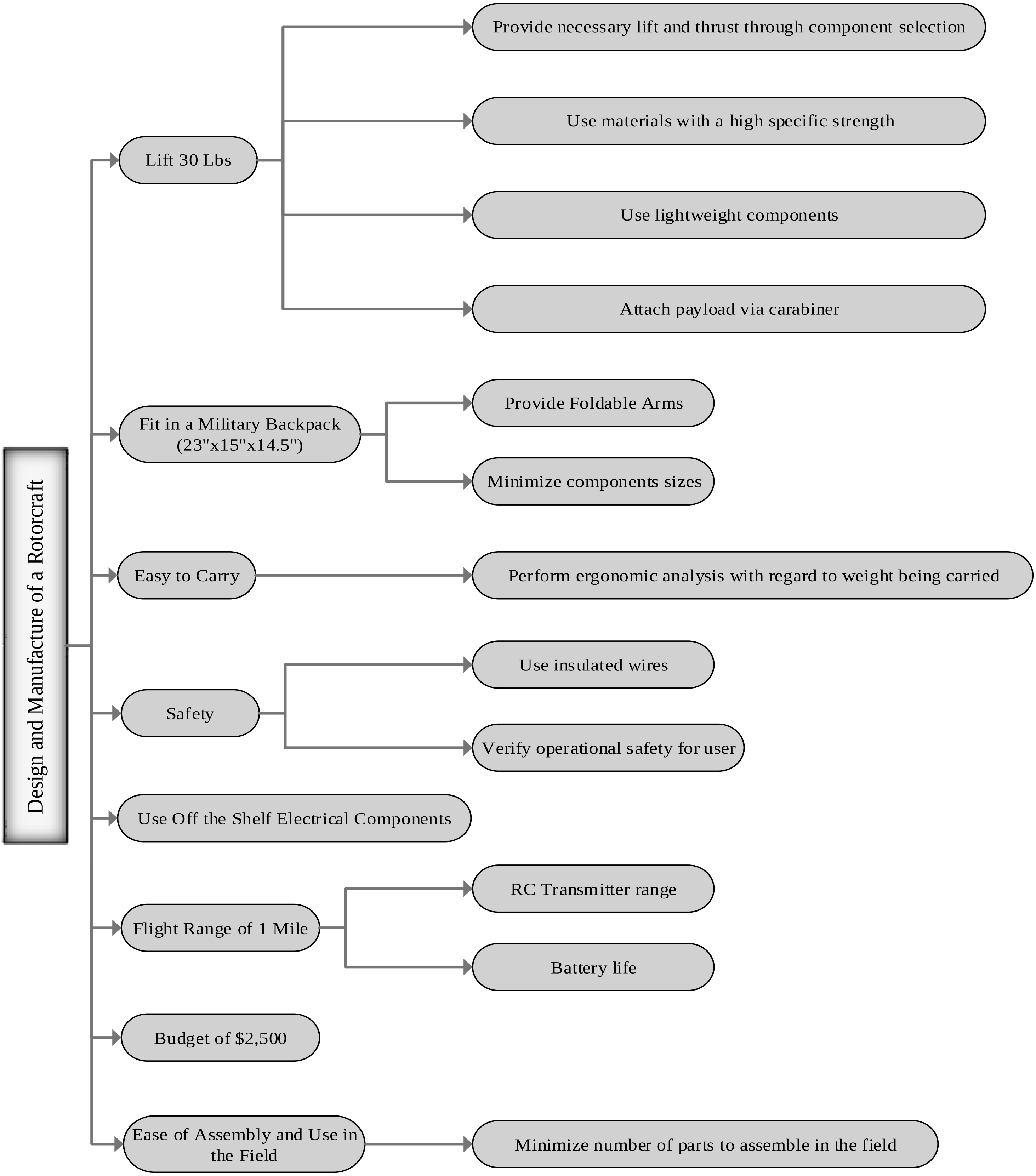


Figure 5. Voice of the Customer tree

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 6 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, **provide necessary lift and thrust forces** is strongly related to the customer requirement of **lift thirty-pound** payload, while the **number of rotors** is only moderately related. The relationship between the **provide necessary lift and thrust forces** and **lift thirty-pound** is assigned an index of 9, while the relationship between the **number of rotors** and **lift thirty-pound** 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.

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

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

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

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

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 **fitting in the military backpack** is nine (strong), and the relationship index between **foldable arms** and **ease of assembly and use in the field** is also nine (strong). Additionally, the customer requirement rating for both **fitting in the military backpack** and **ease of assembly and use in the field** is four. Therefore, multiplying nine times four and adding it to the product of, again, nine times four will result in the technical weight for that technical requirement. Moreover**, provide necessary lift and thrust forces** and **number of rotors** has 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.

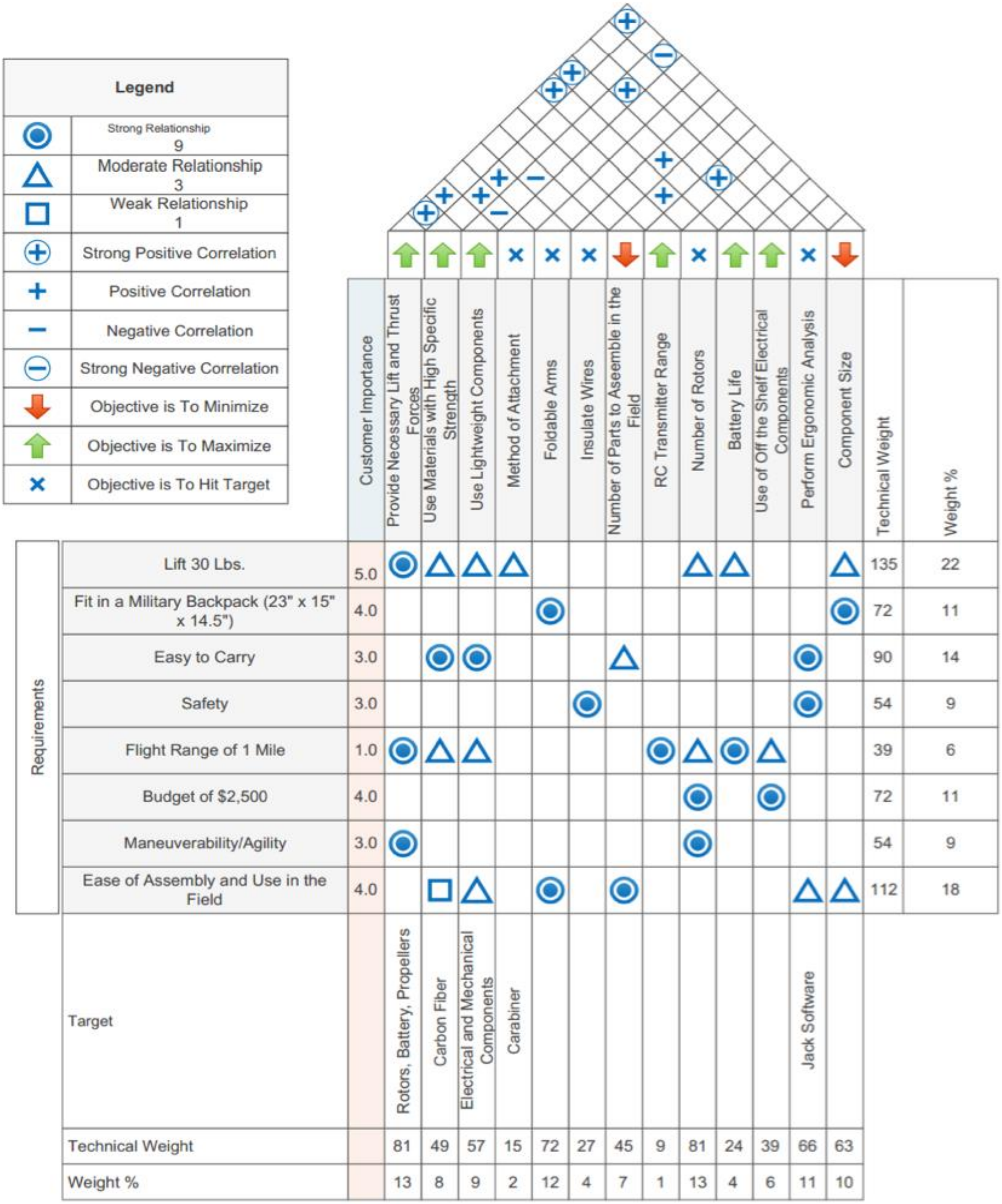
$$Technical\ Weights\ for\ Technical\ Requirements = \sum_{i=1}^{n}(R_i)(I_i) \qquad \text{Eq. (2)}$$

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

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

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

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.



Legend	
◎	Strong Relationship 9
△	Moderate Relationship 3
□	Weak Relationship 1
⊕	Strong Positive Correlation
+	Positive Correlation
−	Negative Correlation
⊖	Strong Negative Correlation
↓	Objective is To Minimize
↑	Objective is To Maximize
×	Objective is To Hit Target

Requirements	Customer Importance	Provide Necessary Lift and Thrust Forces	Use Materials with High Specific Strength	Use Lightweight Components	Method of Attachment	Foldable Arms	Insulate Wires	Number of Parts to Aseemble in the Field	RC Transmitter Range	Number of Rotors	Battery Life	Use of Off the Shelf Electrical Components	Perform Ergonomic Analysis	Component Size	Technical Weight	Weight %
		↑	↑	↑	×	×	×	↓	↑	×	↑	↑	×	↓		
Lift 30 Lbs.	5.0	◎	△	△	△					△	△			△	135	22
Fit in a Military Backpack (23" x 15" x 14.5")	4.0					◎								◎	72	11
Easy to Carry	3.0		◎	◎				△					◎		90	14
Safety	3.0						◎						◎		54	9
Flight Range of 1 Mile	1.0	◎	△	△					◎	△	◎	△			39	6
Budget of $2,500	4.0									◎		◎			72	11
Maneuverability/Agility	3.0	◎								◎					54	9
Ease of Assembly and Use in the Field	4.0		□	△		◎		◎					△	△	112	18
Target		Rotors, Battery, Propellers	Carbon Fiber	Electrical and Mechanical Components	Carabiner								Jack Software			
Technical Weight		81	49	57	15	72	27	45	9	81	24	39	66	63		
Weight %		13	8	9	2	12	4	7	1	13	4	6	11	10		

Figure 6. House of Quality matrix

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**, u**se 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.

House of Quality Overview

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. Measuring the Baseline Performance

4.1 How a Rotorcraft Works

Rotorcraft configurations vary depending on the type of task they are designed for. The rotorcraft configuration chosen for this project includes eight rotors and four arms in order to provide the necessary lift and thrust forces. This configuration will be achieved by placing two rotors per arm following a coaxial configuration, which will be explained later in this section.

To maintain balance, the rotorcraft must be continuously taking measurements from the sensors and making adjustments to the speed of each rotor to keep the body level. Usually these adjustments are done autonomously by a sophisticated control system on the rotorcraft in order to stay perfectly balanced. These rotors are aligned in a square, four rotors on opposite sides of the square rotate in a clockwise direction and the other four rotors rotate in a counterclockwise direction. If all the rotors were to turn in the same direction, the craft would spin. This spin can also be seen in normal helicopters that are without a functional tail rotor. Yaw is induced by unbalanced aerodynamic torques [4]. The aerodynamic torques of the clockwise rotors cancel out with the torque created by the counterclockwise rotors, so if all eight rotors apply equal thrust the rotorcraft will not spin. A rotorcraft has four controllable degrees of freedom: Yaw, Roll, Pitch, and Altitude [4]. These degrees can be seen in Figure 7. Adjusting the thrusts of each rotor can control each degree of freedom.

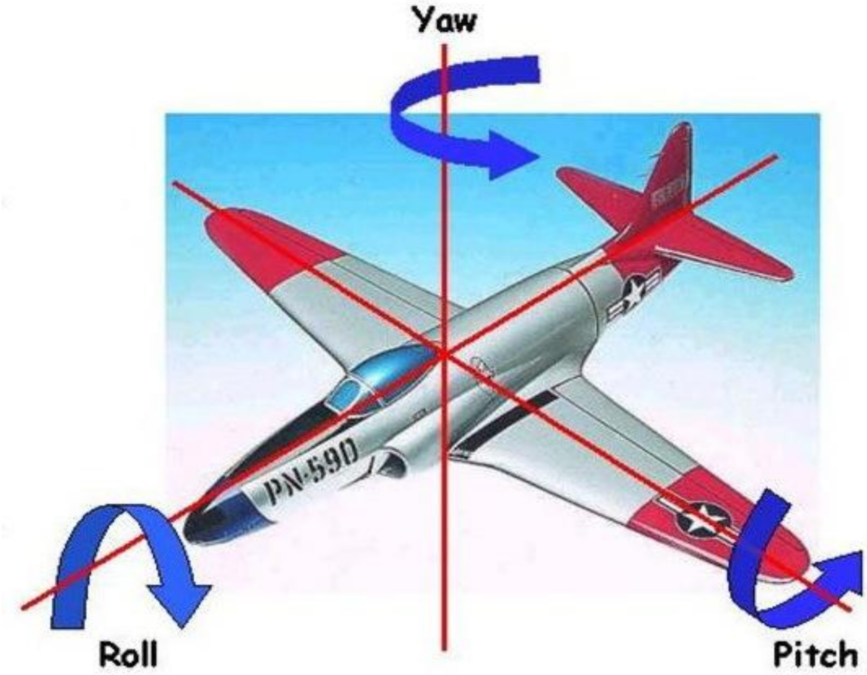


Figure 7. Orientations of a Rotorcraft

- Yaw is controlled by turning up the speed of the clockwise rotating motors and taking away power from the counterclockwise rotating motors. The yaw angle of the rotorcraft describes its bearing or rotation of the craft as it stays level to the ground. Rotation about the yaw axis is like when you shake your head to say “no”. Control becomes a matter of which motors get more power and which motors get less.
- Roll is achieved by increasing speed on one motor and lowering speed on the opposite one. The roll angle of the rotorcraft describes how the craft is tilted side to side. Rotation about the roll axis is like tilting your head towards one of your shoulders. Rolling the rotorcraft causes it to move sideways.

- Pitch is controlled the same way as roll, but using the second set of motors. This may be kind of confusing, but roll and pitch are determined from where the “front” of the rotorcraft is, and in a rotorcraft they are basically interchangeable but the “front” must be clearly and consistently defined or control of the rotorcraft may be lost. The pitch angle of the rotorcraft describes how the craft is tilted forwards or backwards. Rotation about the pitch axis is like tilting your head in order to look up or down. Rotation about the pitch axis is similar to nodding “yes”. Pitching the rotorcraft causes it to move forwards or backwards.
- Altitude is simply controlled by throttle. The more throttle applied to the rotorcraft the higher the altitude becomes.

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

There are a whole host of multi-rotor configurations. Essentially it boils down to number of booms and single or coaxial engine mounting. The number of booms will affect many aspects of the rotorcraft including: efficiency, lifting power, flight times, and stability. The number of physical engines present is also important, and this can affect the ability for the aircraft to cope should one engine be lost. Figure 8 shows the radial and coaxial configuration for a rotorcraft [5]:

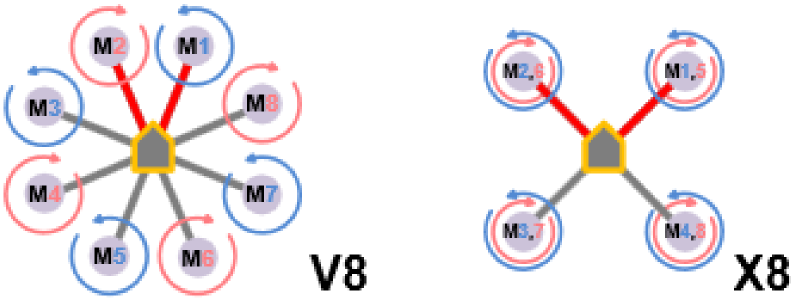


Figure 8. Radial and Coaxial Configurations of a Rotorcraft with Eight Motors

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

Moreover, in coaxial propulsion system shown in Figure 9, there is interference between the flows of the two propellers resulting in a total thrust that is lower than the case where the two propellers are isolated. This propulsion system is normally used because it presents a good thrust to volume ratio since the two engines are near and the total output thrust is higher than in a single engine. The pitch and diameter of the propellers are the main influence parameters of a coaxial propulsion system: the efficiency of the propulsion system decreases for lower pitches on the upper or lower propellers, higher pitch on the higher propeller or lower diameter on the lower propeller. Additionally, the efficiency is increased for a higher pitch on the lower propeller and lower diameter, also on the lower propeller. Finally, the efficiency was unchanged for a higher or lower diameter of the upper propeller.

Figure 9. Coaxial Configuration of Eight Motors on Four Booms

Before performing any test runs with the rotorcraft, the team had to decide if the two propellers were to be tested in a tractor or pusher configuration. A tractor propeller is characterized for pulling the UAV, the rotor axis is in tension. Contrarily, a pusher propeller is characterized for pushing the UAV, the rotor axis is in compression. Based on the Glauert's theory it was predicted that the most efficient coaxial system is the one were the lower propeller operates in the "far" wake of the upper propeller (at a distance approximately equal to the radius of the diameter). Therefore, in order to minimize the space occupied by the propulsion system, the experimental tests were conducted with an upper propeller in tractor configuration and with a lower propeller in pusher configuration, as shown in Figure 10 [6].

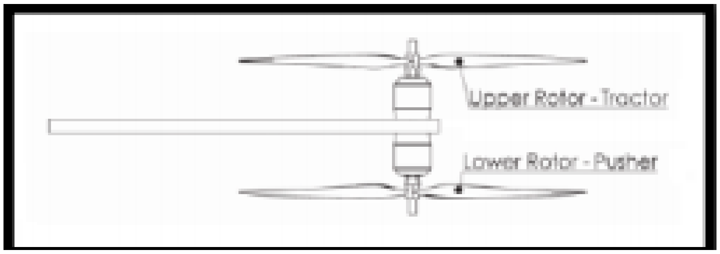


Figure 10. Upper Tractor and Lower Pusher

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

Force Equilibrium

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

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

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

Moment Equilibrium

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

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

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

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

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

Torque Equilibrium

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

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

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

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

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

4.2 Motor, Battery, and Propeller Selection

In order to provide the necessary lift and thrust forces to lift the specified payload, the correct combination of motor, battery, and propeller had to be researched. To help with the components selection, a membership with eCalc was acquired. Since 2004, eCalc has provided web-based quality services to calculate, evaluate and design electric motor driven systems for remote controlled models [7]. In essence, eCalc provides the outcome of the rotorcraft based on the combination of the battery, speed controller, motor, and propeller chosen. It will alert the user if there are any errors based on the components chosen, such as if the motor is drawing too much current, if the battery needs to be larger, or if the pitch needs to be increased. This membership was recommended by Dr. Chuy (Mechatronics professor) and Dr. Kumar (Fundamental of Aerodynamics professor) from the Mechanical Engineering department. Both Dr. Chuy and Dr. Kumar informed the team that eCalc was ninety percent accurate from firsthand experience. They continued to tell the team that the mechanical engineering department previously worked on building a rotorcraft that needed to carry five pounds and the test data gathered from their project as far as flight time, motor efficiency, current drawn, revolutions per minute of the propeller, and other characteristics matched identically to the eCalc website. Furthermore, eCalc guarantees all data has a margin of error of no greater than ±10% [7].

At the beginning of the Measure Phase the team was provided with a rotorcraft design proposed by Cameron Alexander. The team was challenged to compare Cameron Alexander's design with the design proposed by the team in order to choose the most optimal design that would satisfy customer requirements. Intern Cameron Alexander proposed Design #1, and the team proposed Design #2, Design #3, and Design #4. The reason for having three different designs proposed by the team will be explained in section 4.3. This section concentrates on describing the motors, batteries, and propellers chosen for each design.

Motor - Electric powered model rotorcrafts have gained popularity, mainly because the electric motors are more quiet, clean and often easier to start and operate than combustion motors. The selected motor must be lightweight and capable of rotating the propeller at the desired angular velocity. Selecting the correct motor is essential in producing the required thrust to lift the rotorcraft off the ground. The motor selection was based on several desired characteristics: low weight, high efficiency, and high power. In order to get these characteristics two classes of motors were examined. These classes are brushless motors and brushed motors. Brushless motors spin at a much higher speed and use less power at the same speed than brushed motors [8]. In addition, brushless motors don't lose power in the brush-transition like the brushed motors does, so they are more energy efficient [8].

These motors are slightly more expensive but they have a higher efficiency. This efficiency is typically between 80% and 90%. Due to these characteristics as well as the fact that brushed motors require some maintenance due to both the brushes and the commuter wearing after a while due to friction, a brushless motor was chosen. Brushless motors required an electronic speed controller (ESC) specially designed for the brushless motors, which converts the battery's DC voltage into three pulsed voltage lines that are 120^{o} out of phase [8]. The brushless motor's maximum RPM (rotations per minute) is dependent on the three-phase's frequency and on the number of poles:

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

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

In Table 6 a comparison of the E-Flite Power 110, E-Flite Power 360, E-Flite power 52, and the Electrifly Rimfire 1.6 motors can be viewed. The E-Flite Power 110, E-Flite Power 360, and the Electrifly Rimfire 1.6 are the motors proposed by the team, while the E-Flite power 52 motor is the motor proposed by Intern Cameron Alexander. The E-flite Power 110 motor has a 295Kv value as compared to 590Kv for the E-Flite Power 52 motor and 180 Kv for the E-flite Power 360 motor. The Electrifly Rimfire motor has a Kv value of 250. This is very significant because in order to generate more thrust, lower Kv values and larger propeller sizes are required. For the rotorcraft, the mass of the motors should be minimized. Since 8 motors are going to be used, the Power 110 motors would weigh 4kg (8.8 lbs.) in total, the Power 360 motor would weigh 9.81 kg (21.6 lbs.) in total, and the Power 52 motor would weigh 2.8kg (6.16 lbs.) in total. The heaviest motor is the Rimfire motor – eight of these weigh 5.8 kg (12.8 lbs.) in total.

Table 5. Motor Comparison for Each Design

Design	Motor	Kv (RPM/V)	Propeller Range	Weight (lbs.)	Maximum Current (A)	Max Voltage (V)	Power (W)	Cost ($)
Design #1	E-Flite Power 52 Brushless Outrunner [9]	590	12”x 8” to 14”x 7”	0.77	65	22	1650	109
Design #2	E-Flite Power 360 Brushless Outrunner [10]	180	24”x10” to 25”x12”	2.7	130	44.4	6000	359
Design #3	E-Flite Power 110 Brushless Outrunner [11]	295	17”x8” to 19”x10”	1.1	65	38.4	2000	139
Design #4	RimFire 1.60 Brushless Outrunner [12]	250	16” x 8” to 18” x 8”	1.4	80	44.4	2500	179

Further, the Power 110 and the Power 52 have the same max current, while the Power 360 has a max current of 130 amps. The maximum current for the Rimfire motor is 80 amperes. An important characteristic is the maximum voltage for each motor. The more voltage the motor can accept from the battery, the more thrust it will be able to generate to lift the required payload. The Power 360 and the Rimfire motors accept 44.4 volts, which is the most out of any motors under consideration. The cost of using eight E-Flite Power 110 motors is $1,112 as compared to $872 for the E-flight 52 power motor. The most expensive motor is the Power 360, which costs a total of $2,872 and puts the project over budget by itself. The Rimfire motor, which has similar characteristics to the Power 360 motor, is much cheaper and its cost for 8 motors is $1,432. Although the E-Flite power 360 motor is the most expensive motor, it is able to generate the necessary power required to lift this rotorcraft, which is demonstrated in section 4.3. Another indication that the motor can generate the necessary lift is the propeller range, which is an outstanding 24”x10” to 25”x12”. The motor that seems to have the least amount of lift capability is the Power 52 motor which only has a propeller range of 12”x 8” to 14”x 7”.

Battery Pack - The selected battery needs to be lightweight and provide the necessary power to the motor to run the propellers. The propulsion battery pack must supply high voltage per unit weight in order to minimize the required current draw by the motor [13]. With this in mind, the battery cells will be oriented in series to maximize the battery pack voltage and must be composed of cells with an appropriate electric charge. The battery pack must be composed of several individual cells oriented in a desired configuration to allow for easy installation and removal. The batteries that possess both a higher current capacity and electric charge typically have a higher weight and lower voltage. Battery packs with lower current capacity are lightweight with high pack voltage but have limited lifetime. The Pulse 5,000mAh (milli-ampere hour) 7S Lipo Pack battery has higher capacity during heavy discharge, longer cycle life, and faster charge capability compared to other batteries with low current capacity, which is a good fit for this project [13]. The second battery under consideration is the E-Flite 3,200 mAh 6S Lipo pack battery. This battery will have a high capacity during heavy discharge and charges relatively quickly. The last battery under consideration is the Thunder Power 5,000 mAh 9S Lipo pack battery. This battery supplies the highest voltage and the most power of all three batteries under consideration. The Thunder Power battery is the battery under consideration for both design #2 and design #4. There will be four batteries used, with each battery pack supplying power to two rotors.

Keeping the motor decision in mind, Table 7 shows the specifications on the Pulse battery proposed by the team, the Thunder battery also proposed by the team, and the E-Flite battery proposed by Intern Cameron Alexander. The most important thing here as far as generating enough power to have enough thrust to lift the aircraft is the capacity and the voltage supplied. The Pulse battery supplies 25.9 volts as compared to the E-Flite battery that supplies 22.2 volts. The Thunder battery however supplies an outstanding 33.3 volts. The Pulse battery has seven cells in series as compared to the E-Flite battery that has six cells in series and the Thunder battery has nine cells in series. Comparing the capacity, the Pulse battery, and the Thunder battery have a capacity of 5,000 mAh as compared to the capacity of 3,200 mAh for the E-flight battery. The current capacity measures how much current a battery will discharge over a specified period of time. Higher mAh ratings do not necessarily reflect how fast current can be drawn, but rather how long a current can be drawn. For this application, in order to travel a mile, a higher mAh rating is needed.

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

Table 6. Battery Comparison for Each Design

Design	Battery	Capacity (mAh)	Voltage (V)	Discharge (C)	Weight per battery (lbs.)	Cost ($)
Design #1	E-Flight Lipo Pack [14]	3,200	22.2	30	1.49	100
Design #2	Thunder Power Lipo Pack [15]	5,000	33.3	70	2.56	419
Design #3	Pulse Lipo Pack [16]	5,000	25.9	65	2.09	196
Design #4	Thunder Power Lipo Pack [15]	5,000	33.3	70	2.56	419

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

There are three main factors used to assess propeller effectiveness: thrust coefficient, power coefficient, and propeller efficiency [17]. Each of these factors is evaluated with respect to the advance ratio, which is a comparison of linear aircraft velocity to propeller blade velocity. It is desirable for the advance ratio to be larger as this indicates that fewer propeller rotations are needed to move a specified shape aircraft at a specified velocity. The propeller diameter-to-pitch ratio for this application should be approximately 2:1. This is because if the pitch is too high related to the diameter, the propeller becomes inefficient at low forward speed. This has the greatest effect during takeoff and climbing. At the other end of the scale, a propeller designed for greatest efficiency at takeoff and climbing (low pitch & large diameter), will accelerate the model very quickly from standstill but will give lower top speed.

The recommended propeller size is already determined based on the motor chosen earlier for each design. Foldable propellers were chosen so the propellers can be disassembled from the rotorcraft in order to fit in the backpack. An APC electric 18”x10” propellers, an APC electric 24”x12” propellers, and the Zinger Wood 18”x10” propellers are proposed by the team. These propellers can be taken off which does not affect the integrity of the prop. An APC electric 16.5”x10” propeller was proposed by Intern Cameron Alexander. The weight of these propellers is almost negligible. There are some minor differences when comparing these three propellers. The plastic propeller costs $7 as compared to the APC propeller in Design #1 that cost $8. The most expensive propeller is the one in Design #4 that cost $25.

Generally wood propellers are more expensive then plastic props. Wood propellers require the user to balance them and can be subjected to moisture/humidity issues as well as aging issues. Metal and plastic propellers can generally made thinner than wood propellers therefore making them a little more speed. However, for the application used for this project the speed of the wooden propellers is sufficient.

Again, the selection of the propeller is very critical when determining the necessary thrust generated to lift the rotorcraft. The selection of the propeller and its justification will be discussed in the next section of this report. Table 8 shows the propeller selections for the four designs.

Table 7. Propeller Comparison for Each Design

Design	Propeller	Propeller Size	Weight (lbs.)	Cost ($)
Design #1	APC Electric [18]	16.5”x10”	0.17	7
Design #2	APC Electric [19]	24”x12”	0.19	19
Design #3	APC Electric [20]	18”x10”	0.18	8
Design #4	Zinger Wood [21]	18”x 10”	0.19	25

4.3 Evaluation of Designs

Design #1 - As mentioned previously, eCalc was used to evaluate the selection of the propeller, motor, and battery. Figure 11 shows the multicopter calculator for Design #1, for which intern Cameron Alexander chose the parts. Beginning the evaluation of Cameron’s components, the number of rotors chosen to enter in eCalc was 2 even though Cameron’s design has six rotors. The reason for this is because eCalc does its calculations based on the number of rotors per battery. Because there will be three batteries used in Cameron’s design, there will be one battery for every two rotors. Next, the configuration of Cameron’s design is “flat”, meaning one rotor on each arm. This is similar to the V8 configuration in Figure 8.The model weight entered in eCalc for this design is entered at 12,100 grams (26.6 lbs.). The model weight is the sum of the weight for the entire system, including the battery, motor, propellers, and other components for which the **two rotors are expected to lift**. The components and design chosen for the entire system weights roughly 13.6kg (30 lbs.). Adding the payload of 22.7 kg (50 lbs.), the total weight of the system for this design is estimated to be at 36.3kg (80 lbs.)

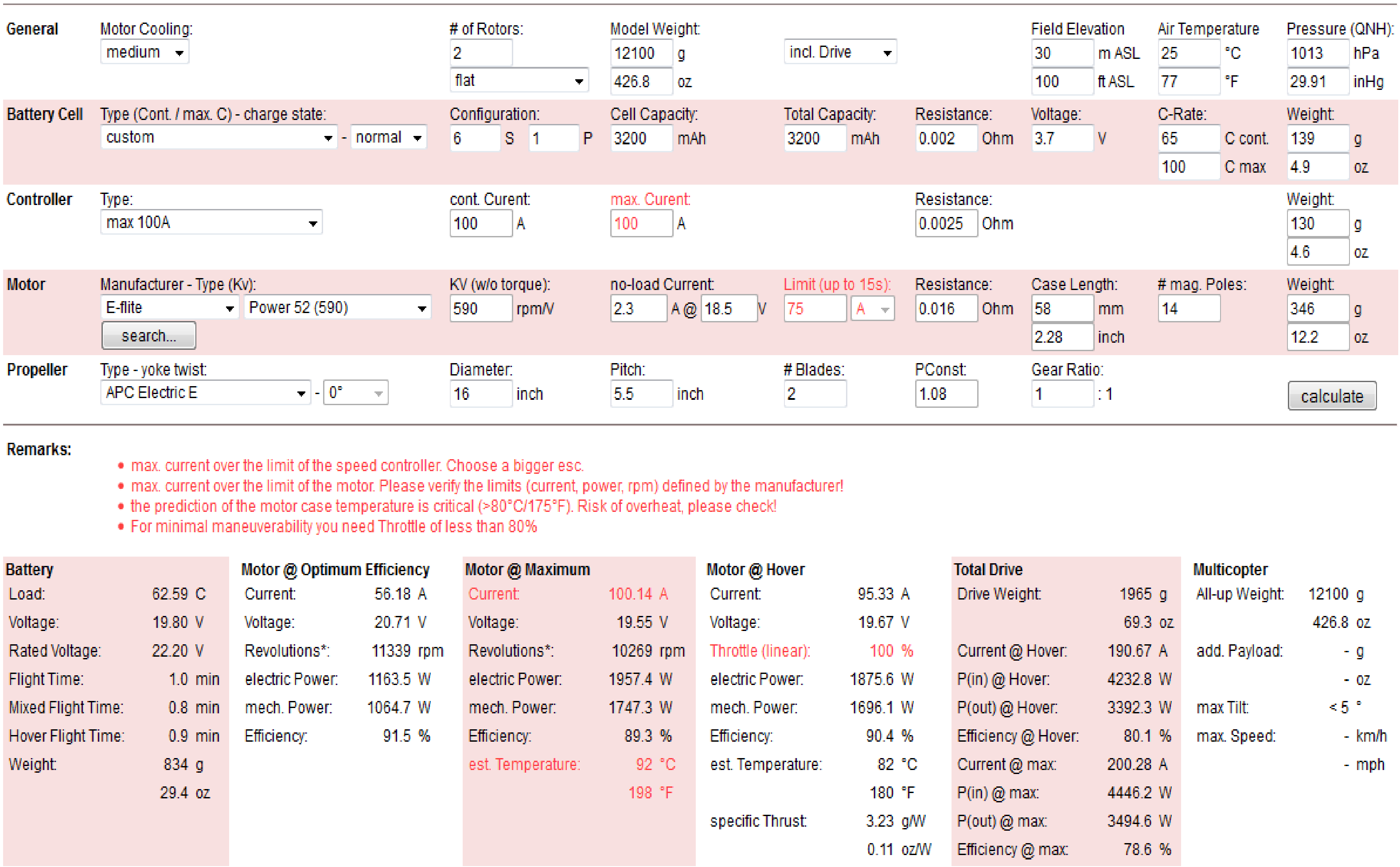
$$13.6\ kg + 22.7kg = 36.3\ kg \qquad \text{Eq. (8)}$$

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

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

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

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



General
Motor Cooling: medium
# of Rotors: 2 flat
Model Weight: 12100 g 426.8 oz incl. Drive
Field Elevation: 30 m ASL 100 ft ASL
Air Temperature: 25 °C 77 °F
Pressure (QNH): 1013 hPa 29.91 inHg

Battery Cell
Type (Cont. / max. C) - charge state: custom - normal
Configuration: 6 S 1 P
Cell Capacity: 3200 mAh
Total Capacity: 3200 mAh
Resistance: 0.002 Ohm
Voltage: 3.7 V
C-Rate: 65 C cont. 100 C max
Weight: 139 g 4.9 oz

Controller
Type: max 100A
cont. Curent: 100 A
max. Curent: 100 A
Resistance: 0.0025 Ohm
Weight: 130 g 4.6 oz

Motor
Manufacturer - Type (Kv): E-flite Power 52 (590) search...
KV (w/o torque): 590 rpm/V
no-load Current: 2.3 A @ 18.5 V
Limit (up to 15s): 75 A
Resistance: 0.016 Ohm
Case Length: 58 mm 2.28 inch
mag. Poles: 14
Weight: 346 g 12.2 oz

Propeller
Type - yoke twist: APC Electric E - 0°
Diameter: 16 inch
Pitch: 5.5 inch
Blades: 2
PConst: 1.08
Gear Ratio: 1 : 1
calculate

Remarks:

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

Battery	
Load:	62.59 C
Voltage:	19.80 V
Rated Voltage:	22.20 V
Flight Time:	1.0 min
Mixed Flight Time:	0.8 min
Hover Flight Time:	0.9 min
Weight:	834 g 29.4 oz

Motor @ Optimum Efficiency	
Current:	56.18 A
Voltage:	20.71 V
Revolutions*:	11339 rpm
electric Power:	1163.5 W
mech. Power:	1064.7 W
Efficiency:	91.5 %

Motor @ Maximum	
Current:	100.14 A
Voltage:	19.55 V
Revolutions*:	10269 rpm
electric Power:	1957.4 W
mech. Power:	1747.3 W
Efficiency:	89.3 %
est. Temperature:	92 °C 198 °F

Motor @ Hover	
Current:	95.33 A
Voltage:	19.67 V
Throttle (linear):	100 %
electric Power:	1875.6 W
mech. Power:	1696.1 W
Efficiency:	90.4 %
est. Temperature:	82 °C 180 °F
specific Thrust:	3.23 g/W 0.11 oz/W

Total Drive	
Drive Weight:	1965 g 69.3 oz
Current @ Hover:	190.67 A
P(in) @ Hover:	4232.8 W
P(out) @ Hover:	3392.3 W
Efficiency @ Hover:	80.1 %
Current @ max:	200.28 A
P(in) @ max:	4446.2 W
P(out) @ max:	3494.6 W
Efficiency @ max:	78.6 %

Multicopter	
All-up Weight:	12100 g 426.8 oz
add. Payload:	- g - oz
max Tilt:	< 5 °
max. Speed:	- km/h - mph

Figure 11. Design #1 Multicopter Calculator Results

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

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

- The maximum current is over the limit of the speed controller.
- The maximum current is over the limit of the motor.

- The prediction of the motor case temperature is over 175 °F that risks overheating.
- The throttle needs to be at least fewer than 80% for minimal maneuverability, and with this design throttle is at 100 %.

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

Another factor to note is the "add Payload" in Figure 11. "Add. Payload" states the maximum additional payload possible to hover with 80% throttle to guarantee maneuverability. As can be seen from Figure 11, these components cannot withstand any additional payload. Furthermore, even if the maximum current by the speed controller were changed to 70 amps, the motor would still not be able to draw the proper amount of current. Another significant factor is that, with the components chosen by the Intern Cameron Alexander, there is no maximum speed. The reason for this is there are no specifications or submitted data about maximum velocity in the eCalc web base that was tested for the components chosen. The maximum speed is the theoretical maximum attainable forward speed in level flight at maximum tilt. The maximum tilt is the theoretical maximum possible tilt of the copter to maintain level flight. The maximum tilt would be less than 5° for this design. Another interesting fact about this design is it cannot lift even a 5lbs payload. With these components the rotorcraft can barely lift its own weight at 99% throttle. This design was eliminated moving forward because it cannot meet the criteria of lifting any payload. Due to all the reasons discussed above, Design #1 would have failed.

Design #2 - Figure 12 shows the rotorcraft eCalc calculations for the components chosen by the team. The number of rotors chosen to enter in eCalc was 2 and not 8. The reason for this is because eCalc does its calculations based on the number of rotors per battery. There will be four batteries in the rotorcraft design, meaning that each battery will power two rotors. Next, the configuration of the rotorcraft design is "coaxial" meaning two identical counter-rotating motors using the same propeller on each arm. This is similar to the X8 configuration in Figure 8. The model weight for this design was found to be 10,680 grams (23.4 lbs.). Again, this is the sum of the weight for the entire system, which the **two rotors** are expected to lift. The components and design chosen weighs roughly 20kg (44lbs.). Adding the payload of 22.7 kg (50 lbs.), the total weight of the system is estimated to be 42.7kg (94 lbs.)

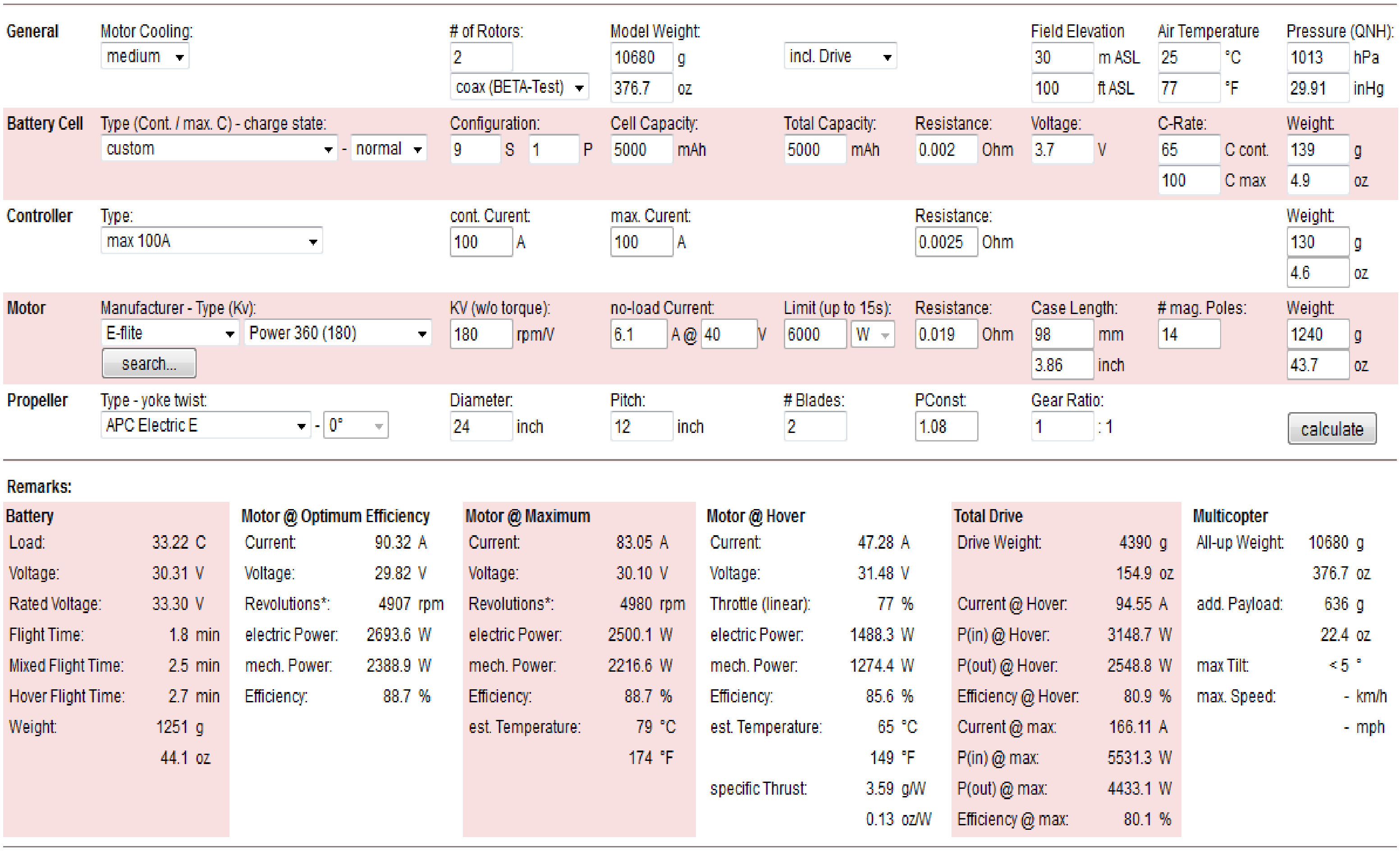
$$20\ kg + 22.7kg = 42.7\ kg \qquad \text{Eq. (11)}$$

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

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

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

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



General
Motor Cooling: medium
# of Rotors: 2
coax (BETA-Test)
Model Weight: 10680 g, 376.7 oz
incl. Drive
Field Elevation: 30 m ASL, 100 ft ASL
Air Temperature: 25 °C, 77 °F
Pressure (QNH): 1013 hPa, 29.91 inHg

Battery Cell
Type (Cont. / max. C) - charge state: custom - normal
Configuration: 9 S 1 P
Cell Capacity: 5000 mAh
Total Capacity: 5000 mAh
Resistance: 0.002 Ohm
Voltage: 3.7 V
C-Rate: 65 C cont., 100 C max
Weight: 139 g, 4.9 oz

Controller
Type: max 100A
cont. Curent: 100 A
max. Curent: 100 A
Resistance: 0.0025 Ohm
Weight: 130 g, 4.6 oz

Motor
Manufacturer - Type (Kv): E-flite Power 360 (180)
search...
KV (w/o torque): 180 rpm/V
no-load Current: 6.1 A @ 40 V
Limit (up to 15s): 6000 W
Resistance: 0.019 Ohm
Case Length: 98 mm, 3.86 inch
mag. Poles: 14
Weight: 1240 g, 43.7 oz

Propeller
Type - yoke twist: APC Electric E - 0°
Diameter: 24 inch
Pitch: 12 inch
Blades: 2
PConst: 1.08
Gear Ratio: 1 : 1
calculate

Remarks:

Battery
Load: 33.22 C
Voltage: 30.31 V
Rated Voltage: 33.30 V
Flight Time: 1.8 min
Mixed Flight Time: 2.5 min
Hover Flight Time: 2.7 min
Weight: 1251 g, 44.1 oz

Motor @ Optimum Efficiency
Current: 90.32 A
Voltage: 29.82 V
Revolutions*: 4907 rpm
electric Power: 2693.6 W
mech. Power: 2388.9 W
Efficiency: 88.7 %

Motor @ Maximum
Current: 83.05 A
Voltage: 30.10 V
Revolutions*: 4980 rpm
electric Power: 2500.1 W
mech. Power: 2216.6 W
Efficiency: 88.7 %
est. Temperature: 79 °C, 174 °F

Motor @ Hover
Current: 47.28 A
Voltage: 31.48 V
Throttle (linear): 77 %
electric Power: 1488.3 W
mech. Power: 1274.4 W
Efficiency: 85.6 %
est. Temperature: 65 °C, 149 °F
specific Thrust: 3.59 g/W, 0.13 oz/W

Total Drive
Drive Weight: 4390 g, 154.9 oz
Current @ Hover: 94.55 A
P(in) @ Hover: 3148.7 W
P(out) @ Hover: 2548.8 W
Efficiency @ Hover: 80.9 %
Current @ max: 166.11 A
P(in) @ max: 5531.3 W
P(out) @ max: 4433.1 W
Efficiency @ max: 80.1 %

Multicopter
All-up Weight: 10680 g, 376.7 oz
add. Payload: 636 g, 22.4 oz
max Tilt: < 5 °
max. Speed: - km/h, - mph

Figure 12. Design #2 Multicopter Calculator Results

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

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

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

If the lift produced by the rotorcraft is greater than the force of gravity, the craft will gain altitude. If the opposite is true, that is, if the lift produced by the rotorcraft is less than the force of gravity acting on the rotorcraft, then the rotorcraft will fall. The maximum attainable forward speed in level flight is not presented in Figure 12. The reason for this is there are no specifications or submitted data about maximum velocity in the eCalc web base that was tested for the components chosen in the co-axial frame. However, if the components selected were put in the “flat” configuration, the maximum speed would be 35.4 miles per hour (mph).

As stated earlier in the report, brushless motors operate at nearly 90% efficiency and the Power 360 motor operates at a maximum efficiency of 88.7%. However, there are a few drawbacks to using this design. Although the rotorcraft can lift the necessary weight with these components, it cannot fit in a standard size military backpack and the cost of this design is well beyond the budget of this project. Due to the budget constraints this design is also eliminated, and will not be pursued by the team.

Design #3 - Figure 13 shows the rotorcraft eCalc calculations for Design #3. As in Designs #1 and 2, the number of rotors entered in eCalc is 2. The reason for this is because eCalc does its calculations based on the number of rotors per battery as stated earlier. The configuration of this design is “co-axial” meaning one rotor on each arm. The model weight entered in eCalc for this design is 9,090 grams (19.9 lbs.). As stated earlier, the model weight is the sum of the weight for the entire system for which the **two rotors are expected to lift**. The components and design chosen for the entire system weights roughly 13.6kg (30 lbs.). Adding the payload of 22.7 kg (50 lbs.), the total weight of the system for this design is 36.3kg (80 lbs.)

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

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

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

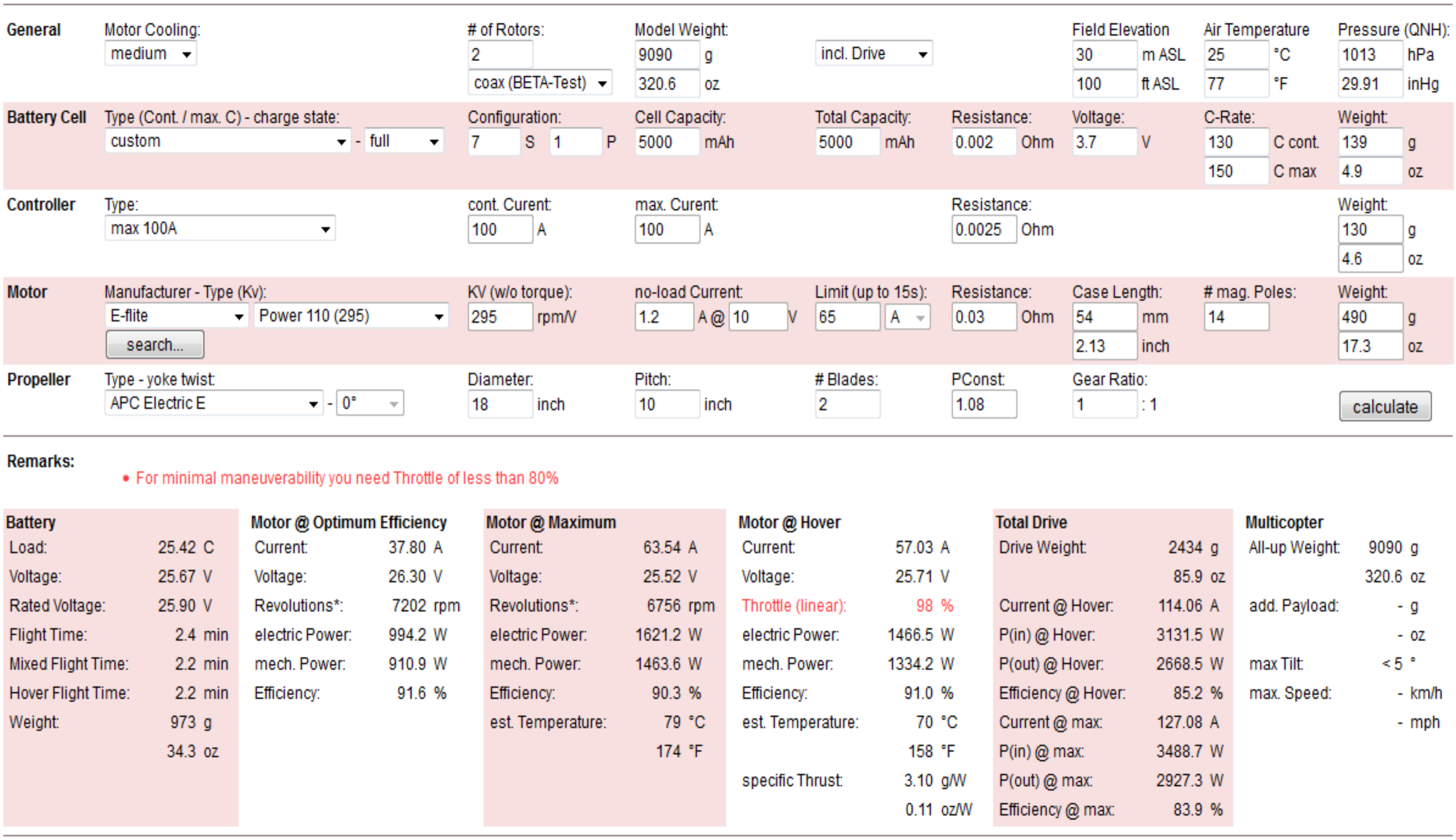
This means that **each** rotor is expected to be able to lift at least 4.54kg (10 lbs.). Finally, since there are two rotors being analyzed for each battery as stated earlier, the model weight found in Equation 15 is multiplied by 2 and simply becomes 9,090 grams (19.9 lbs.).

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

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

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

For this reason, Design #3 would not necessarily fail but would be inefficient. There is no good reason to build a rotorcraft that could lift the necessary payload but cannot move to the desired location. Also, these components cannot withstand any additional payload, as can be seen in Figure 13. This implies that if any more weight was to be added to the payload, there will not be enough power to lift the rotorcraft at all.



General
Motor Cooling: medium
# of Rotors: 2 coax (BETA-Test)
Model Weight: 9090 g 320.6 oz incl. Drive
Field Elevation: 30 m ASL 100 ft ASL
Air Temperature: 25 °C 77 °F
Pressure (QNH): 1013 hPa 29.91 inHg

Battery Cell
Type (Cont. / max. C) - charge state: custom - full
Configuration: 7 S 1 P
Cell Capacity: 5000 mAh
Total Capacity: 5000 mAh
Resistance: 0.002 Ohm
Voltage: 3.7 V
C-Rate: 130 C cont. 150 C max
Weight: 139 g 4.9 oz

Controller
Type: max 100A
cont. Curent: 100 A
max. Curent: 100 A
Resistance: 0.0025 Ohm
Weight: 130 g 4.6 oz

Motor
Manufacturer - Type (Kv): E-flite Power 110 (295)
KV (w/o torque): 295 rpm/V
no-load Current: 1.2 A @ 10 V
Limit (up to 15s): 65 A
Resistance: 0.03 Ohm
Case Length: 54 mm 2.13 inch
mag. Poles: 14
Weight: 490 g 17.3 oz

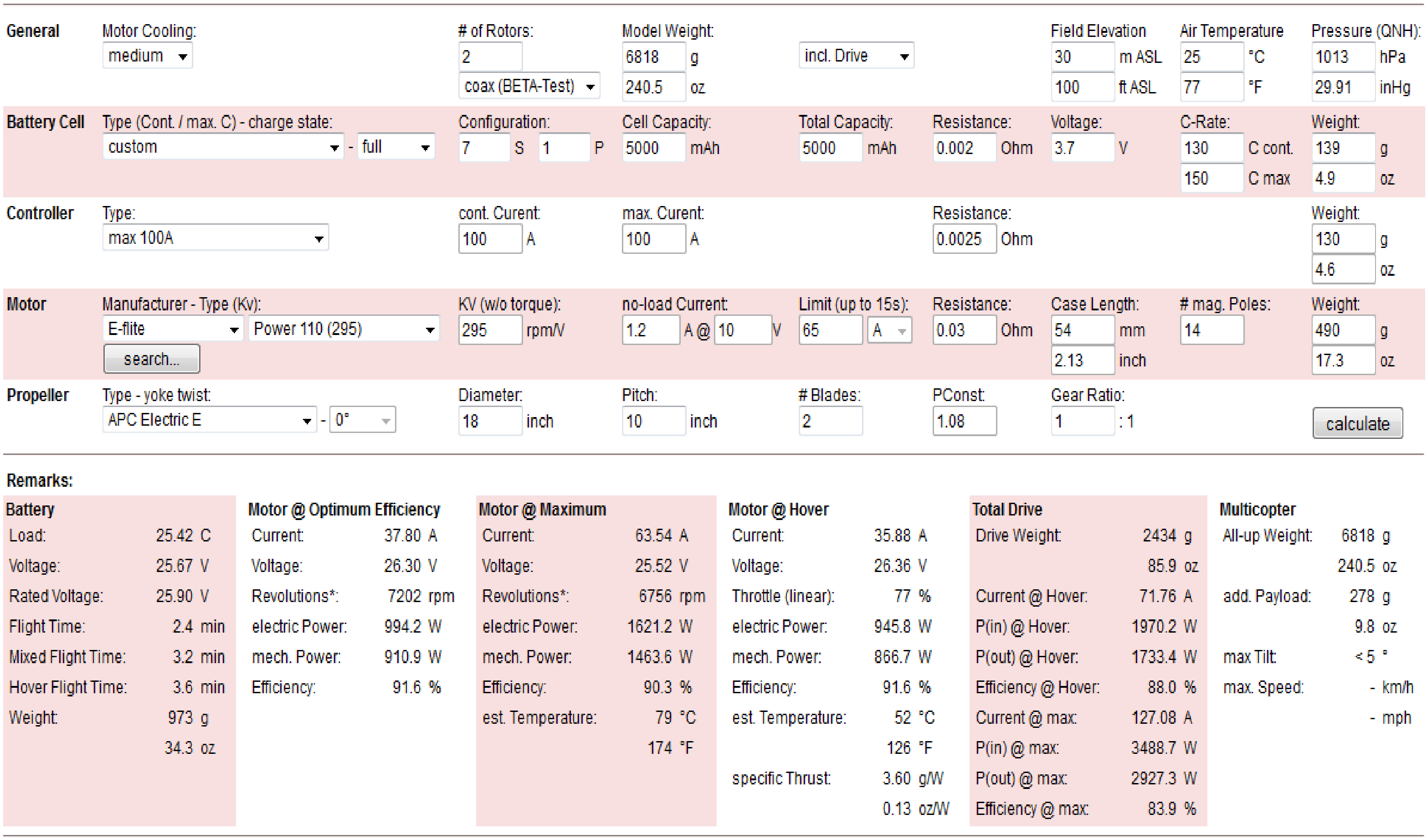
Propeller
Type - yoke twist: APC Electric E - 0°
Diameter: 18 inch
Pitch: 10 inch
Blades: 2
PConst: 1.08
Gear Ratio: 1 : 1

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

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

Figure 13. Design #3 Multicopter Calculator Results (50 Pound Payload)

However, using these components and attempting to lift a payload of 11.3 kg (30 lbs.), produced very favorable results. Design #3 would be able to carry this payload as can be seen in Figure 14. It should be noted that with the components chosen, the expected flight time for this design at maximum throttle (100 % discharge of battery) is 2 minutes and 24 seconds The mixed flight time is the expected flight time based on the all-up weight when moving (85% discharge of battery) and is expected to be 3 minutes and 12 seconds. The hover flight time is the expected flight time based on the all-up weight when hovering only (85% discharge of battery). The hover flight time expected for the components chosen with a 13.6kg (30 lbs.) payload is 3 minutes and 36 seconds. Out of the first three designs this is by far the best alternative.



General
Motor Cooling: medium
# of Rotors: 2
coax (BETA-Test)
Model Weight: 6818 g
240.5 oz
incl. Drive
Field Elevation: 30 m ASL
100 ft ASL
Air Temperature: 25 °C
77 °F
Pressure (QNH): 1013 hPa
29.91 inHg

Battery Cell
Type (Cont. / max. C) - charge state: custom - full
Configuration: 7 S 1 P
Cell Capacity: 5000 mAh
Total Capacity: 5000 mAh
Resistance: 0.002 Ohm
Voltage: 3.7 V
C-Rate: 130 C cont.
150 C max
Weight: 139 g
4.9 oz

Controller
Type: max 100A
cont. Curent: 100 A
max. Curent: 100 A
Resistance: 0.0025 Ohm
Weight: 130 g
4.6 oz

Motor
Manufacturer - Type (Kv): E-flite Power 110 (295)
KV (w/o torque): 295 rpm/V
no-load Current: 1.2 A @ 10 V
Limit (up to 15s): 65 A
Resistance: 0.03 Ohm
Case Length: 54 mm
2.13 inch
mag. Poles: 14
Weight: 490 g
17.3 oz

Propeller
Type - yoke twist: APC Electric E - 0°
Diameter: 18 inch
Pitch: 10 inch
Blades: 2
PConst: 1.08
Gear Ratio: 1 : 1

Remarks:

Battery
Load: 25.42 C
Voltage: 25.67 V
Rated Voltage: 25.90 V
Flight Time: 2.4 min
Mixed Flight Time: 3.2 min
Hover Flight Time: 3.6 min
Weight: 973 g
34.3 oz

Motor @ Optimum Efficiency
Current: 37.80 A
Voltage: 26.30 V
Revolutions*: 7202 rpm
electric Power: 994.2 W
mech. Power: 910.9 W
Efficiency: 91.6 %

Motor @ Maximum
Current: 63.54 A
Voltage: 25.52 V
Revolutions*: 6756 rpm
electric Power: 1621.2 W
mech. Power: 1463.6 W
Efficiency: 90.3 %
est. Temperature: 79 °C
174 °F

Motor @ Hover
Current: 35.88 A
Voltage: 26.36 V
Throttle (linear): 77 %
electric Power: 945.8 W
mech. Power: 866.7 W
Efficiency: 91.6 %
est. Temperature: 52 °C
126 °F
specific Thrust: 3.60 g/W
0.13 oz/W

Total Drive
Drive Weight: 2434 g
85.9 oz
Current @ Hover: 71.76 A
P(in) @ Hover: 1970.2 W
P(out) @ Hover: 1733.4 W
Efficiency @ Hover: 88.0 %
Current @ max: 127.08 A
P(in) @ max: 3488.7 W
P(out) @ max: 2927.3 W
Efficiency @ max: 83.9 %

Multicopter
All-up Weight: 6818 g
240.5 oz
add. Payload: 278 g
9.8 oz
max Tilt: < 5 °
max. Speed: - km/h
- mph

Figure 14. Design #3 Multicopter Calculator Results (30 Pound Payload)

However, this design was eliminated due to the fact that when the team contacted the manufacture of the E-flite motor to order the motor, the manufacturer said it would take four months to be received. The manufacturer said the motor was on backorder, and due to a strike on the West Coast the motor was not being made anytime soon. Another reason for eliminating Design #3 was due to the fact that APC electric propellers do not make 18”x10” clockwise propellers. This was also discovered when the team proceed to order from the manufacturer. The manufacturer only makes counterclockwise 18”x10” propellers. For this application, both a pusher and a tractor propeller are required on each boom as stated earlier in the report. The final reason this design was eliminated from further consideration was the batteries. When the team contacted the manufacturer of Pulse batteries in December, the manufacturer informed the team that the 7-cell battery is a special custom made battery. This also had would have took 2-3 months to arrive and so the team did not want to risk having a crucial component of the rotorcraft come in so late. For these reasons, Design #3 was eliminated from further consideration.

Design #4- Figure 15 shows the evaluation of the final components chosen for a 50 pound payload. The number of rotors chosen to enter in eCalc was two, even though the final design has eight rotors. The reason for this is because eCalc does its calculations based on the number of rotors per battery as stated earlier. Because there will be four batteries used in this design, there will be one battery for every two rotors. The propulsion battery pack must supply high voltage per unit weight in order to minimize the required current draw by the motor [22]. With this in mind, the battery cells will be oriented in series to maximize the battery pack voltage and must be composed of cells with an appropriate electric charge. The battery pack must be composed of several individual cells oriented in a desired configuration to allow for easy installation and removal.

The model weight entered in eCalc for this design is 9,090 grams (19.9 lbs.). As stated earlier, the model weight is the sum of the weight for the entire system, including the battery, motor, props, and all other rotorcraft components for which the two rotors are expected to lift. The components and design chosen for the entire system weighs roughly 13.6 kg (30 lbs.). Adding the payload of 22.7 kg (50 lbs.), the total weight of the system for this design is estimated to be at 36.3kg (80 lbs.)

$$13.6\, kg + 22.7kg = 36.3\, kg \qquad \text{Eq. (17)}$$

Dividing this total weight of the system by 8 rotors in order to determine how much weight each rotor is expected to lift, the model weight becomes 4.54kg (10 lbs.).

$$\frac{36.3\, kg\ (total\ weight)}{8\, rotors} = 4.54\frac{kg}{rotor} \qquad \text{Eq. (18)}$$

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

$$4.54\frac{kg}{rotor} \times 2\, rotors = 9.08\, kg \qquad \text{Eq. (19)}$$

The field elevation for which this rotorcraft is expected to fly at is set at 100 feet. The standard temperature of 77 °F and standard pressure of 101.3 kPa (kilopascals) is also entered in the multi-copter calculator. Next, the information for the final design's chosen components are entered, these include: Thunder 5,000 mAh (mille Ampere Hour) 9S Lipo battery, 120 Amp ESC controller, ElectriFly RimFire, and Zinger wood 18"x10" propeller chosen. The results from eCalc state that the throttle needs to be less than a maximum of 80% for minimal maneuverability, and with this design the throttle is at 93%.

General Motor Cooling: medium | # of Rotors: 2 coaxial | Model Weight: 9090 g 320.6 oz | incl. Drive | Field Elevation 500 m ASL 1640 ft ASL | Air Temperature 25 °C 77 °F | Pressure (QNH): 1013 hPa 29.91 inHg

Battery Cell Type (Cont. / max. C) - charge state: custom - normal | Configuration: 9 S 1 P | Cell Capacity: 5000 mAh | Total Capacity: 5000 mAh | Resistance: 0.002 Ohm | Voltage: 3.7 V | C-Rate: 65 C cont. 100 C max | Weight: 139 g 4.9 oz

Controller Type: max 120A | cont. Curent: 120 A | max. Curent: 120 A | Resistance: 0.002 Ohm | Weight: 155 g 5.5 oz

Motor Manufacturer - Type (Kv): ElectriFly RimFire 1.60³ (242) search... | KV (w/o torque): 242 rpm/V | no-load Current: 1.04 A @ 10 V | Limit (up to 15s): 2500 W | Resistance: 0.0225 Ohm | Case Length: 62 mm 2.44 inch | # mag. Poles: 14 | Weight: 635 g 22.4 oz

Propeller Type - yoke twist: custom - 0° | Diameter: 18 inch | Pitch: 10 inch | # Blades: 2 | PConst: 1.3 | Gear Ratio: 1 : 1 | calculate

Remarks:

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

Battery	
Load:	24.65 C
Voltage:	31.08 V
Rated Voltage:	33.30 V
Capacity:	5000 mAh
Energy:	166.5 Wh
Flight Time:	2.4 min
Mixed Flight Time:	2.5 min
Hover Flight Time:	2.6 min
Weight:	1251 g 44.1 oz

Motor @ Optimum Efficiency	
Current:	44.98 A
Voltage:	31.59 V
Revolutions*:	7178 rpm
electric Power:	1420.9 W
mech. Power:	1332.0 W
Efficiency:	93.7 %

Motor @ Maximum	
Current:	61.64 A
Voltage:	30.96 V
Revolutions*:	6941 rpm
electric Power:	1908.1 W
mech. Power:	1781.6 W
Efficiency:	93.4 %
est. Temperature:	63 °C 145 °F

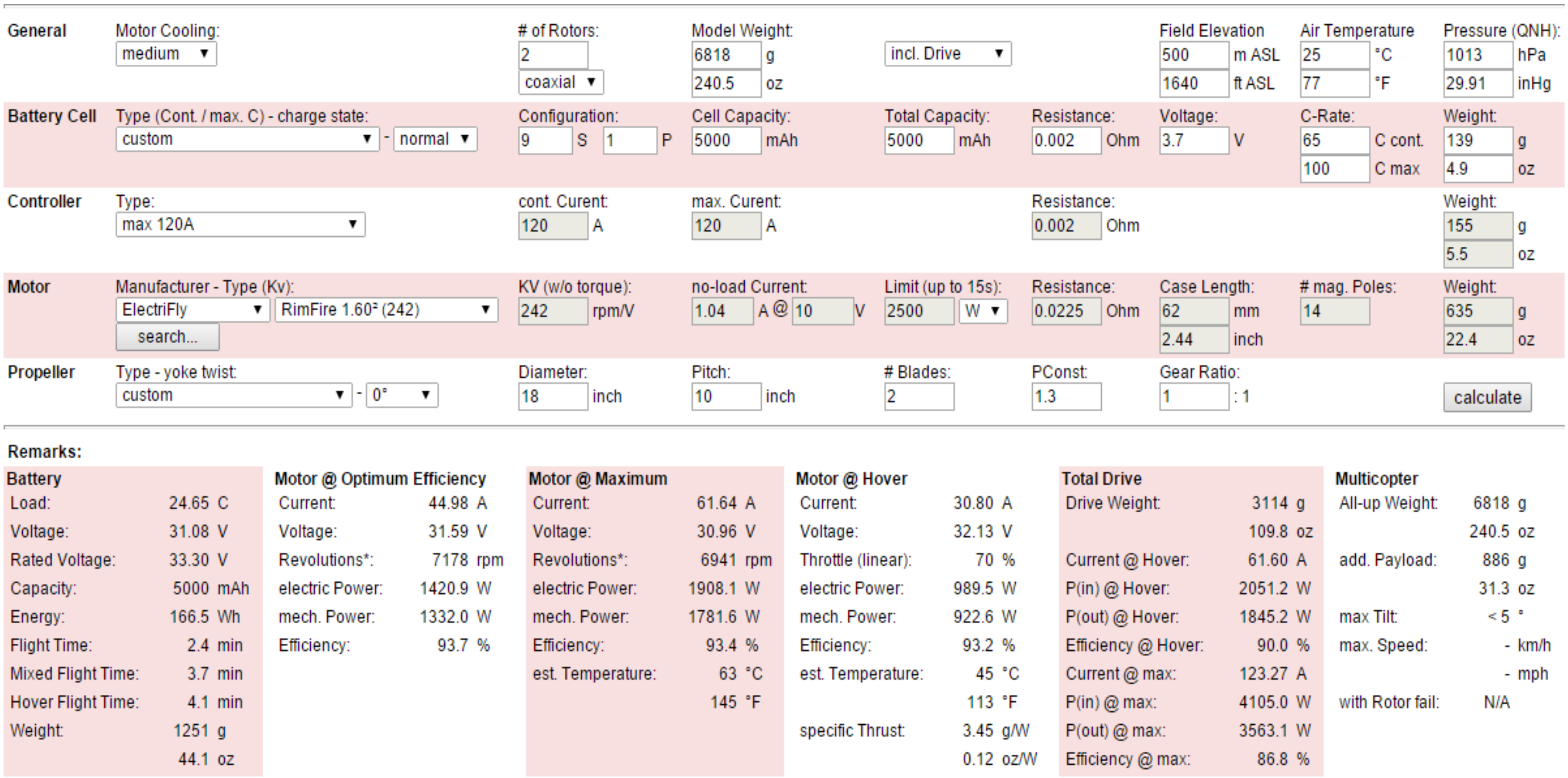
Motor @ Hover	
Current:	48.12 A
Voltage:	31.47 V
Throttle (linear):	93 %
electric Power:	1514.4 W
mech. Power:	1420.3 W
Efficiency:	93.8 %
est. Temperature:	53 °C 127 °F
specific Thrust:	3.00 g/W 0.11 oz/W

Total Drive	
Drive Weight:	3114 g 109.8 oz
Current @ Hover:	96.24 A
P(in) @ Hover:	3204.8 W
P(out) @ Hover:	2840.5 W
Efficiency @ Hover:	88.6 %
Current @ max:	123.27 A
P(in) @ max:	4105.0 W
P(out) @ max:	3563.1 W
Efficiency @ max:	86.8 %

Multicopter	
All-up Weight:	9090 g 320.6 oz
add. Payload:	- g - oz
max Tilt:	< 5 °
max. Speed:	- km/h - mph
with Rotor fail:	N/A

Figure 15. Design #4 Multicopter Calculator Results (50 Pound Payload)

Using these components and attempting to lift a payload of 11.3 kg (30 lbs.), much more favorable results are produced and the project scope was changed as stated earlier in the report. As seen in Figure 16, the design would be able to carry this payload with a throttle of only 70%. Another result with this combination of components is that the expected flight time for this design at maximum throttle (100% discharge of battery) is 2 minutes and 24 seconds. The mixed flight time is the expected flight time based on all-up weight when moving (85% discharge of battery) and is expected to be 3 minutes and 42 seconds. The hover flight time is the expected flight time based on all-up weight when hovering only (85% discharge of battery). The hover flight time expected for the components chosen with a 13.6kg (30 lbs.) payload is 4 minutes and 6 seconds.



General
Motor Cooling: medium
# of Rotors: 2 coaxial
Model Weight: 6818 g 240.5 oz incl. Drive
Field Elevation: 500 m ASL 1640 ft ASL
Air Temperature: 25 °C 77 °F
Pressure (QNH): 1013 hPa 29.91 inHg

Battery Cell
Type (Cont. / max. C) - charge state: custom - normal
Configuration: 9 S 1 P
Cell Capacity: 5000 mAh
Total Capacity: 5000 mAh
Resistance: 0.002 Ohm
Voltage: 3.7 V
C-Rate: 65 C cont. 100 C max
Weight: 139 g 4.9 oz

Controller
Type: max 120A
cont. Curent: 120 A
max. Curent: 120 A
Resistance: 0.002 Ohm
Weight: 155 g 5.5 oz

Motor
Manufacturer - Type (Kv): ElectriFly RimFire 1.60² (242)
search...
KV (w/o torque): 242 rpm/V
no-load Current: 1.04 A @ 10 V
Limit (up to 15s): 2500 W
Resistance: 0.0225 Ohm
Case Length: 62 mm 2.44 inch
mag. Poles: 14
Weight: 635 g 22.4 oz

Propeller
Type - yoke twist: custom - 0°
Diameter: 18 inch
Pitch: 10 inch
Blades: 2
PConst: 1.3
Gear Ratio: 1 : 1
calculate

Remarks:

Battery	
Load:	24.65 C
Voltage:	31.08 V
Rated Voltage:	33.30 V
Capacity:	5000 mAh
Energy:	166.5 Wh
Flight Time:	2.4 min
Mixed Flight Time:	3.7 min
Hover Flight Time:	4.1 min
Weight:	1251 g 44.1 oz

Motor @ Optimum Efficiency	
Current:	44.98 A
Voltage:	31.59 V
Revolutions*:	7178 rpm
electric Power:	1420.9 W
mech. Power:	1332.0 W
Efficiency:	93.7 %

Motor @ Maximum	
Current:	61.64 A
Voltage:	30.96 V
Revolutions*:	6941 rpm
electric Power:	1908.1 W
mech. Power:	1781.6 W
Efficiency:	93.4 %
est. Temperature:	63 °C 145 °F

Motor @ Hover	
Current:	30.80 A
Voltage:	32.13 V
Throttle (linear):	70 %
electric Power:	989.5 W
mech. Power:	922.6 W
Efficiency:	93.2 %
est. Temperature:	45 °C 113 °F
specific Thrust:	3.45 g/W 0.12 oz/W

Total Drive	
Drive Weight:	3114 g 109.8 oz
Current @ Hover:	61.60 A
P(in) @ Hover:	2051.2 W
P(out) @ Hover:	1845.2 W
Efficiency @ Hover:	90.0 %
Current @ max:	123.27 A
P(in) @ max:	4105.0 W
P(out) @ max:	3563.1 W
Efficiency @ max:	86.8 %

Multicopter	
All-up Weight:	6818 g 240.5 oz
add. Payload:	886 g 31.3 oz
max Tilt:	< 5 °
max. Speed:	- km/h - mph
with Rotor fail:	N/A

Figure 16. Design #4 Multicopter Calculator Results (30 Pound Payload)

eCalc also allows the team to measure the maximum tilt and the maximum speed of the rotorcraft. As can be seen in Figure 16 does not show the maximum tilt and maximum speed for the rotorcraft because there is no submitted data for the maximum tilt and maximum speed with the components chosen. The maximum tilt is the maximum angle from the horizontal that the rotorcraft can tilt before falling.

Next, in order to help measure the performance of the motor, the motor characteristics were plotted versus the amount of current being supplied to it. As stated earlier, the Thunder Power battery can supply a minimum of 45 amperes of continuous current to the motor. Due to some of the losses in current, the battery will supply 50 amperes of continuous current to the motor. The cabling wires that connect the power supply to the load terminals introduce current-resistance loss. The amount of current-resistance loss is determined by the resistance of the cabling wire (a property of the wire gauge and length) and the amount of current flowing through the wire. Current-resistance loss results in a voltage drop between the power supply and the load. To minimize voltage drop caused by cabling, it is best to keep each wire pair as short as possible and use the thickest wire gauge appropriate for each application.

Looking at the right hand side of Figure 17, one can see there is a number 1 through 5 associated with each line on the graph. These numbers correlate with the legend, which can be seen at the top left portion of the graph. Looking at number 1 (yellow line), at 50 Amperes the power supplied to the motor is $155 \times 10 Watts = 1550 Watts$. By examining the efficiency of the motor by looking at the number 2 line (blue line), it can be seen that at 50 amperes the motor will have an efficiency of 94%. This is because the Electrifly motor has no brushes; there is less friction and virtually no parts to wear apart from the bearings.

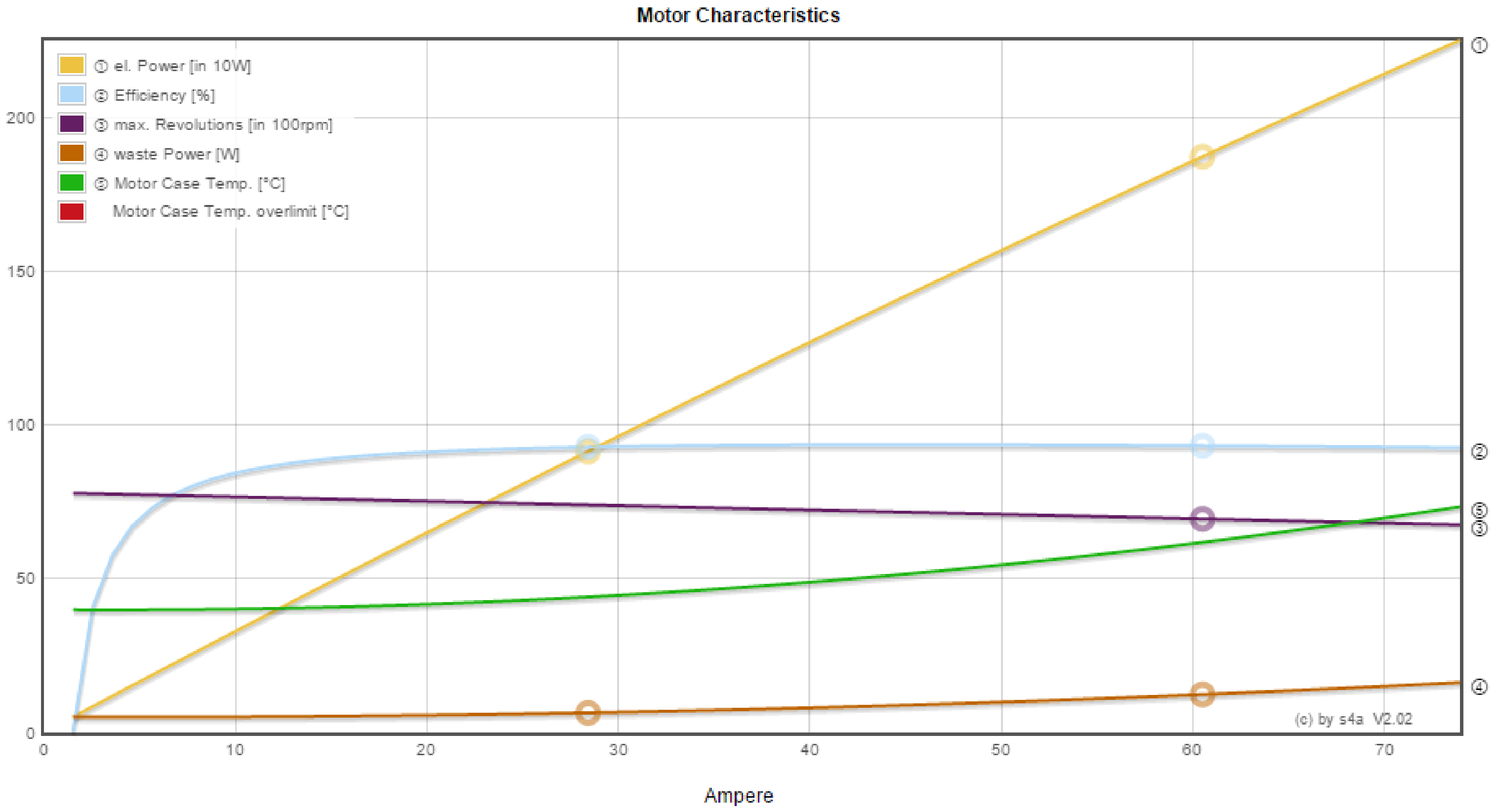


Figure 17. Motor Characteristics

Unlike the DC brushed motor, the stator of the brushless motor has coils while the rotor consists normally of permanent magnets. The stator of a conventional brushless motor is part of its outer case, while the rotor rotates inside it [23]. The metal case acts as a heat sink, radiating the heat generated by the stator coils, thereby keeping the permanent magnets at lower temperature. This is verified by examining line number 5 (green line) that plots the motor case temperature in degree Celsius. Looking at 50 Amperes, the motor case temperature is only 55℃. This is important to note because higher motor case temperature can result in permanent damage to the motor.

Through Figure 17, the revolutions per minute (Rpm) and the wasted power for the craft can be seen. Examining line number 3 (purple line) of the motor at 50 Amperes, the motor reaches 7,100 revolutions per minute. Examining line number 4 (orange line), there is only a minimum of 8 watts wasted when 50 amperes are supplied to the motor.

Design Review- Design #1 does not have enough power to lift a 22.4 kg (50lbs.) payload, and therefore was eliminated from further analysis. Design #2 does have enough power to lift the 22.4 kg (50 lbs.) payload, but was eliminated from further analysis due to high cost. Design #3 provides the highest amount of lift while still being cost effective. However, due to the problems with the manufactures it was eliminated. Design #4 presented the most lift capability while still being cost effective and there were only minor problems with the manufacture. Design #4 can fit in the backpack via adding an extra flap on the backpack as can be seen in the next section of this report, which also made this design even more appealing. A 13.6kg (30lbs.) payload is still substantial considering how few previous rotorcrafts have been able to carry such a payload given the size constraints. A summary of the designs chosen can be seen in Table 8.

Table 8. eCalc Calculator Summary for All Four Designs

Design	Lift Payload of 30 Lbs.	Comments
Design #1	No	➢ Max current over limit for speed controller and motor ➢ Motor overheat potential ➢ Throttle at 100% (minimal maneuverability)
Design #2	Yes	➢ Throttle at 67% (full maneuverability)
Design #3	Yes	➢ Throttle at 79% (minimal maneuverability)
Design #4	Yes	➢ Throttle at 70% (full maneuverability)

As seen in Table 8, Design #1 cannot lift the 13.6kg (30lbs.) payload. This is because the maximum current is over the limit of the speed controller and the motor, the motor has the possibility to overheat, and the throttle is at 100% so maneuverability is going to be difficult. Design #2 is able to lift the 13.6kg (30lbs.) payload and has full maneuverability of the rotorcraft, but was not chosen due to budget constraints and propeller size. Design #3 was able to lift the payload at 98% throttle meaning maneuverability is minimal. Also, this design is able to lift a

13.6kg (30 lbs.) payload, however again due to components unavailability problems it was eliminated. Design #4 can lift the 13.6 kg (30 lbs.) payload with a throttle of 70% meaning full maneuverability. This design is still cost effective compared to the other three designs. Design #4 still has the opportunity to fit in a backpack as will be in the next coming section from the report. This design with the Thunder 9s Lipo battery, Electrifly Rimfire 1.6 motor, Zinger wood 18”x10” propellers, and 120 amp electronic speed controller were chosen as the optimal design to manufacture.

4.4 General Rotorcraft Design

After comparing four different designs and choosing Design #4, the team was able to draw the rotorcraft in Creo Parametric 2.0. 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. However, 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 18. 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.

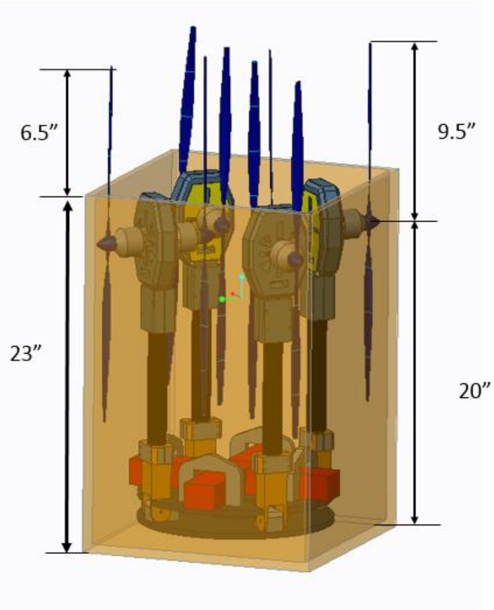


Figure 18. Rotorcraft Displayed in the Backpack

The rotorcraft will have a total height of 20 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 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 arrangement as can be seen in Figure 19. As mention before the rotorcraft will present coaxial configuration. Therefore, the arms will be equipped with motor mounts that, as the name implies, mount two motors to each arm. The motor mounts and arms will be rotated 90^o so that the motor shafts are vertically aligned. There will be groove markings to ensure that they are positioned properly because if the motor shafts are placed incorrectly the flight of the rotorcraft will be greatly affected. Finally, pins will be used to control the position of the arms, vertical position when the rotorcraft is placed on the backpack or horizontal position when the rotorcraft is arranged for deployment, and the top and base plates will be screwed together. Detailed description and illustration of components and assembly of the rotorcraft will be explained in section 6.2.

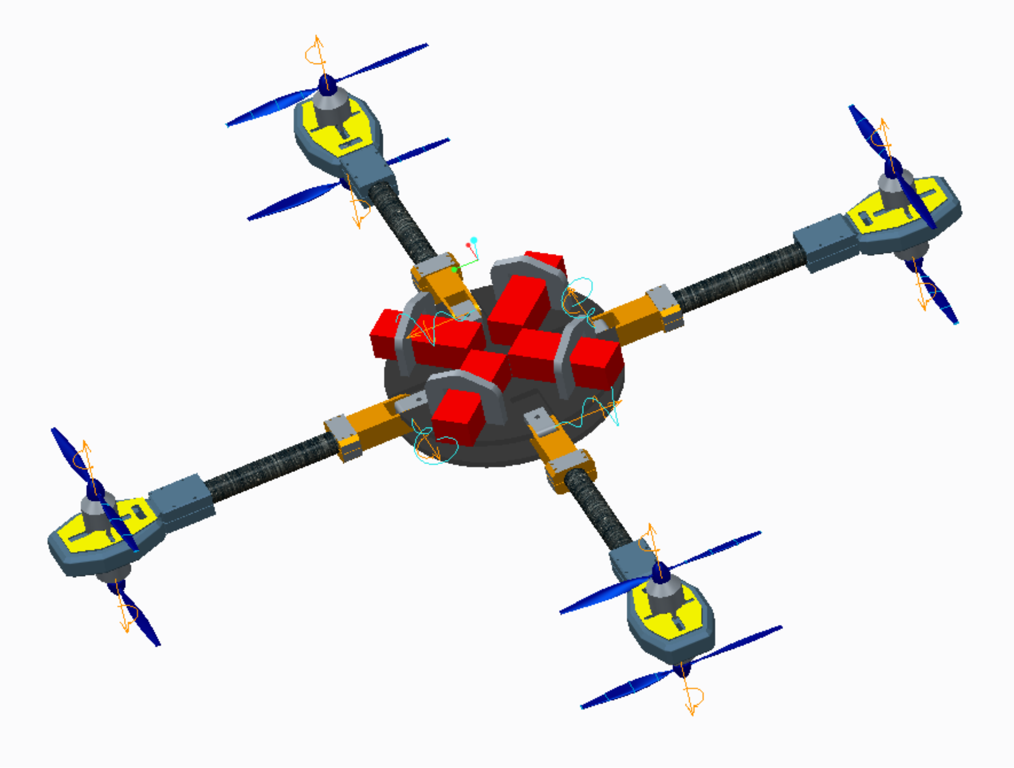


Figure 19. Rotorcraft before Take-Off

4.5 Speed Controller, IMU, and RC Transmitter Component Selection

Electronic Speed Controller (ESC) – An Electronic Speed Controller does several things. First, it converts your battery voltage down to 5v which is what your receiver runs off. An ESC will have a power limit. To handle more power, the ESC needs to be larger, heavier, and is more expensive. It's important to know the peak current the motor is going to pull at full throttle. This determines the current rating you should look for in an ESC. It's advised to choose an ESC with a current rating that is higher than what is needed. If the motor is going to pull 12A, a 25A-rated ESC is a much better choice than a 10A-rated one. The 10A ESC will probably overheat and cook, even if you only fly at half throttle. ESCs are relatively light and maintain great resale value, so this is one item in the power system where skimping isn't worthwhile. Choosing the correct type and identifying the minimum current rating are the two big steps. Table X shows a list of each ESC chosen for each design and is explained in more detail in the next several paragraphs.

Design #1 has a 40 amp lite pro switch mode brushless ESC. This ESC would be compatible with the motor chosen for design number one because the ESC current rating is 10 amps higher than that of the motor. This speed controller has a pre-wired connectors for E-flite EC3 connectors on battery input and a 3.5 mm female gold bullets on motor output leads [24].

Design #2 has a Hobbywing ESC which has a continuous current of 90 amps. This is more than the motor current rating by 20 amps so it will not over heat. The total weight of 8 electronic speed controllers would be 648 grams (1.4 lbs.) This speed controller works well with an input of 2- 6 cells of Lipo battery. The low cut off voltage for this ESC is adjustable between 2.8 volts and 3.4 volts per cell [25].

Design #3 has an E-flite 80 amps pro switch mode brushless ESC. This speed controller has pre wired connectors E-flite EC5 on battery input and 4.0 mm female gold bullets on motor output leads. A neat feature about this ESC is it has an auto motor shut down if signal is lost or if there is interference. The E-flite speed controller can operate without the need for a separate receiver battery to power the servos and receivers, which saves on weight of the rotorcraft [26].

Design #4 has a 120 Amp OPTO Brushless ESC. This speed controller is suitable for the use of a 6-12 Lipo cells battery. This is compatible with design number 4 because the battery chosen for design #4 is a 9 cell Lipo battery. The OPTO Brushless ESC has a large aluminum finned heat sink for reliable operation [27]. All functions for this battery can be programmed through the transmitter chosen. Also this electronic speed controller comes with 3.5mm bullet connectors which will plug directly into the motors. The weight of eight ESC's for design #4 would be 1184 g (2.6 lbs.). Table 9 compares the different speed controllers chosen for each design.

Table 9.Electronic Speed Controllers Comparison

Designs	Motor Current Rating (Amps)	ESC Current Rating (Amps)	ESC Weight (grams)
Design #1	30	40	48
Design #2	70	90	81
Design #3	65	80	76
Design #4	70	120	145

IMU (Inertial Measurement Unit) Sensor - Another component that must be considered is the IMU sensor. This component is able to measure and report the velocity, orientation, and gravitational forces 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. There are varying degrees of freedom in IMU sensors [28]. This project requires at least six degrees, because that allows for movement in all three dimensions. The degrees of freedom relate to the components which are part of the rotorcraft. Along with the set-up of the rotors the ICU will also prevent the craft from spinning on its all of its axes without user input. 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 and the Adafruit. These brands use analog outputs on their sensors, which can be plugged directly 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. This does not relate to the number of pins. Pins are solid objects that can be turned on or off based on necessity, and also can be set as inputs or outputs [28].

RC Transmitter- The last 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. The selection will be based on the range and the size of the device. 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, because the rest of the frequencies in the Tallahassee area are used for First Responders, and other government. Higher than that are military frequencies that are strictly off limits to civilians. The transmitter that is used must not only have a frequency that is approved for usage, but it also must be fairly unique so that other civilians cannot tap into this rotorcraft's frequency and control the rotorcraft without user permission. It's also important to have a unique frequency because other RC users such as small planes, helicopters, and cars can overlap with this rotorcraft's frequency and offset the inputs the team is trying to use, ultimately crashing the craft [29].

There is also a requirement for the project that the transmitter sends and the receiver receives signals effectively for a mile. There are two brands that can be used to accomplish this task that the project requires that can also meet the frequency and size requirements needed by the team. The first is the XTend 900 1W RPSMA transmitter. This has a range for 40 miles, which easily covers the project requirement. Another potential option is the XBee-Pro 900 XSC S3B transmitter. This module covers 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 than the XBee board. The XBee board has a smaller antenna. Also, it should be noted the cost of the XTend board is around $200, while the XBee board is around $70.

4.6 Rotorcraft's Top and Base Plates Material Selection

In order to lift a thirty pound payload and meet customer requirements, the rotorcraft's weight must be reduced as much as possible. Additionally, the rotorcraft's top and base plates must present high strength in order to carry all the mechanical and electrical components and endure stress forces the rotorcraft might experience. Therefore, high specific strength materials must be implemented in order to satisfy these conditions. Composite materials offer these characteristics, as they are lighter than alternative materials, such as aluminum, used in rotorcrafts. Composites are defined as two or more constituent materials combined by an interface. This combination results in a material with better properties that cannot be achieved by either of the constituents on their own [30]. Composite materials typically have a lower density, and so are lighter than other materials used in rotorcrafts. For example, the density of carbon fiber is about 1.55 g/cm^3 while aluminum's density is 2.7 g/cm^3.

There exist different types of composite materials that can be distinguished depending on the type of matrix and reinforcement used. The particulate reinforced material that will be used for the manufacture of the top and base plates is a polymer matrix. Carbon fiber or glass fiber will be used as the reinforcement material in an epoxy resin matrix. The following paragraphs include comparisons between carbon fiber and glass fiber; however, the manufacture process that will be implemented to manufacture the rotorcraft's plates will be explained in section 6.1.

First, a comparison of carbon fiber and glass fiber is necessary to select the better material for the plates of the rotorcraft. The rotorcraft has to tolerate a wide range of stresses from changing frequency vibrations, heat, centrifugal forces, and hard landings. Therefore, the material has to be strong and stiff to endure all those factors. Table 10 compares properties and characteristics of carbon and glass fiber.

Table 10. Mechanical Properties and Price of Carbon Fiber and Glass Fiber

Material	Tensile Strength (MPa)	Young Modulus (GPa)	Density (g/cm^3)	Price/Yard ($)
Carbon Fiber [31,32]	4127	125 – 181	1.58	30 - 40
Glass Fiber [33]	3450	30 – 40	2.66	5

It should be mentioned that the numbers shown in Table 10 are estimations and actual values vary from sample to sample. Because there are many types of carbon and glass fibers, including E-glass and S-glass, the manufacturing process and after treatments can affect the properties displayed in Table 10, even for a particular type of glass fiber. However, the values in Table 10 are suitable to make comparison between carbon fiber and glass fiber.

Table 10 shows that carbon fiber is stronger than glass fiber. Carbon fiber has a tensile strength of 4127 MPa, while glass fiber has a tensile strength of 3450 MPa. The difference between their strengths is nearly 18 percent, the stronger the material the greater the durability of the rotorcraft. Also, carbon fiber presents a young modulus of 125-181 GPa and glass fiber of 30-40 GPa. As such, carbon fiber is much stiffer than glass fiber, which is another important factor enabling the resistance of stresses in the rotorcraft.

Another aspect to be taken into consideration is density. The rotorcraft needs to be as light as possible in order to minimize the thrust and lift forces needed to maintain flight. Because carbon fiber has a density of 1.58 g/cm3 while glass fiber of 2.66 g/cm3, it is favorable to use carbon fiber because a higher amount of strength can be obtained for a lesser weight of material. The denser a material is the heavier it will feel for an equal sized volume. If glass fiber were chosen as the material to move forward with this project, then the mechanical components chosen for the different designs discussed in section 4.3 would not be able to carry the payload.

Finally, budget is an important constraint in this project. Carbon fiber price per yard ranges from $ 30-40 while glass fiber price is between $3 and $6 for the same amount. Carbon fiber is significantly more expensive than glass fiber, however its greater strength and lower density make the difference in price worth the expense. Because of all these factors, carbon fiber was selected for the manufacture of the top and base plates of the rotorcraft.

5. Identifying the Root Causes

5.1 Ergonomic Analysis

In order to prove the operation and carry of the rotorcraft will be safe for the user and determine the time it would take to deploy the rotorcraft, an ergonomic simulation was performed on Siemens Jack software. The simulation created demonstrates the default male, Jack, lifting a cylinder representing the rotorcraft out of a rectangular prism representing the military backpack and setting it on the ground nearby. The rotorcraft cylinder was named "Hermes" by the team analyst in order to easily differentiate any files related to the simulation. The dimensions of the backpack and of Hermes match the real life dimensions of the objects they represent. The default male, Jack, represents an average man (that is, a man with all anthropometric measurements matching the 50th percentile in each measurement category). The typical user of the rotorcraft would be a soldier, and the average soldier is expected to be above average when compared to the total population of men. However, the default Jack was used to represent the lower bound of all users.

In the simulation, Jack begins slightly behind the backpack as can be seen in the top left picture of Figure 20. This is to simulate the soldier having taken off the backpack to place it in front of him. Jack walks to where the backpack is set and removes the rotorcraft from the backpack. Jack turns and walks away from the backpack in order to bend over and set the rotorcraft on the ground. At this point, the soldier would begin field assembly of the rotorcraft, which is not included in this simulation.

The key points of the screenshots in Figure 20 are as follows:

- Top left: initial context.
- Top right: walking to the backpack.
- Center left: Jack bending over to reach into the backpack.
- Center right: Jack lifting the rotorcraft out of the backpack.
- Bottom left: Jack walking to set down the rotorcraft.
- Bottom right: Jack bending over to place the rotorcraft on the ground.

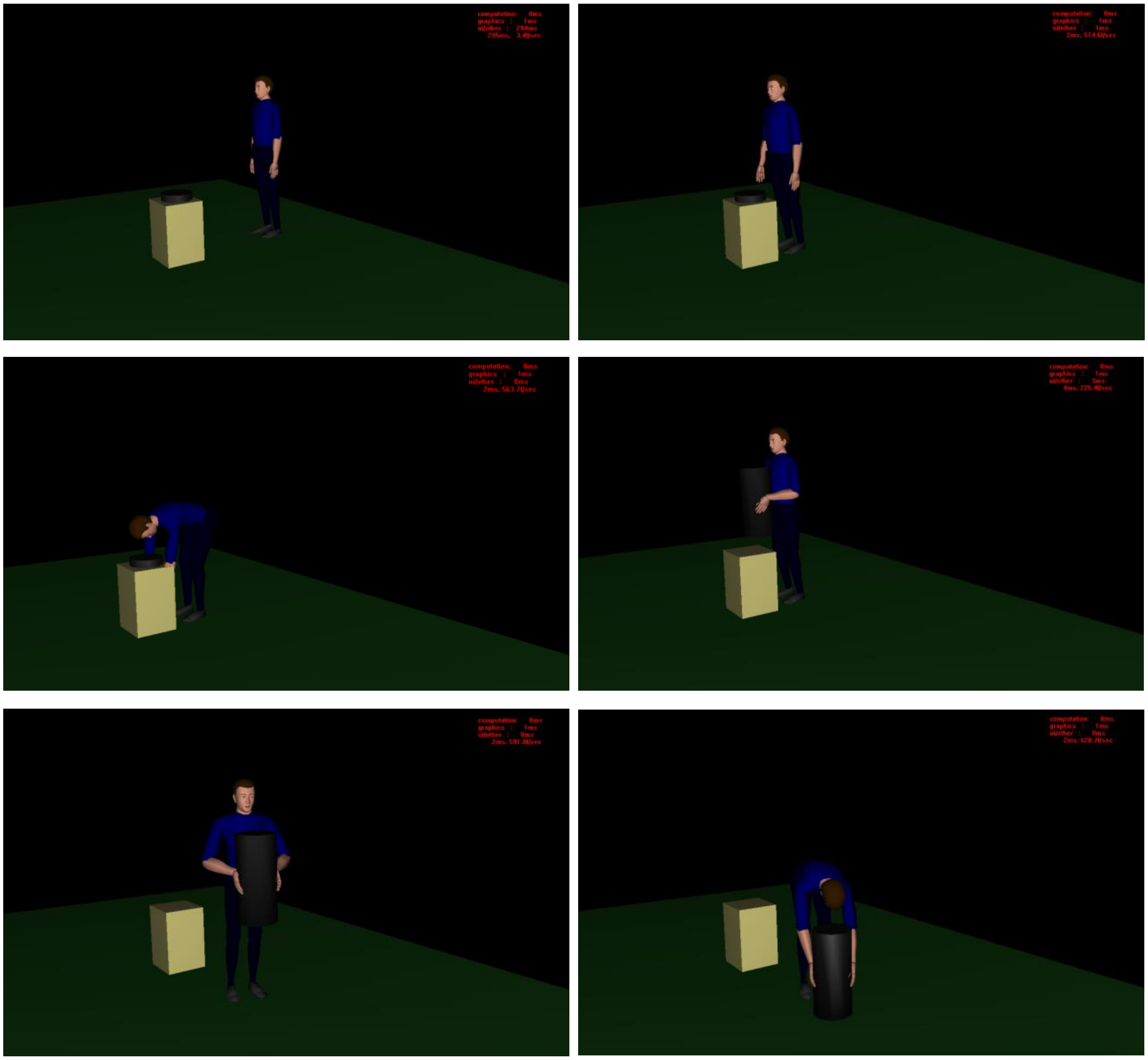


Figure 20. Six Key Points of the Ergonomic Simulation

The timing report represents how long it should take the average man to remove the rotorcraft from the backpack and place it on the ground. A few assumptions are carried through this report:

1) The timing begins from the moment the user places the backpack on the ground
2) The ground on which the user is working is relatively stable and flat
3) The user does not travel exceedingly far when placing the rotorcraft on the ground
4) The rotorcraft is symmetrical and thus it does not matter which way the rotorcraft is placed on the ground as long as it is upright

In total, the operation should take up to 8.07 seconds. A large portion of this time is spent in the Arise_From_Bend and Bend_And_Reach actions of the task Put_hermes. Combined, these actions take 3.41 seconds. When added to the Walk action from the same task, a total of 4.85 seconds is spent standing from the backpack, walking, and bending to place the rotorcraft on the ground. As such, up to 4.85 seconds could be shaved off the operation, leading to a minimum operation time of 3.22 seconds. The simulation will retain the upper bound operation for simplicity. The full timing report can be seen in Appendix B.

The ergonomic analysis also includes 2 analyses. One is the Lower Back Analysis (LBA) and "uses a complex biomechanical low back model to evaluate the spinal forces that act on the lower back under an unlimited number of posture and loading conditions", while the other is the Static Strength Prediction (SSP) and "evaluates the percentage of a worker population that has the strength to perform a task based on posture, exertion requirements and anthropometry, including wrist strength calculations"[34].

The highest value in the LBA analysis for the spinal compression forces occurs at 3.433 seconds into the simulation. This value is 2,335.494 Newton. The guidelines for spinal compression establish low risk activities as those with a spinal compression less than 3,400 Newton, medium risk as those with a spinal compression less than 6,400 Newton, and high risk as those with a spinal compression above 6,400 Newton [35]. Since the spinal compression forces are 2,336 Newton or lower throughout the entire simulation, this entire task is assumed to be low risk based on the spinal compression forces.

Another qualifier for a low risk activity is one with AP shear forces lower than 750 Newton. A medium risk activity includes AP shear forces lower than 1,000 Newton. The highest AP shear forces in this simulation occur at 3.233 seconds into the simulation. This corresponds to when Jack is lifting the rotorcraft from the backpack. The high shear values in this portion of the simulation push this task just above the lower bound for a medium risk activity. The easiest way to return this activity to a low risk activity would be to limit the twisting incurred during the bend and lift of the rotorcraft.

The lowest value in the SSP analysis for the percent of a population capable of performing a given task is 82.72%, which corresponds to the left ankle flex during the Walk action of the task Put_Hermes. All other values are higher than this - that is, 82% or more of the population is expected to be capable of performing the required operation. Since the user is expected to be at or above the 50th percentile with regards to the total male population, there is no task that should cause difficulty or fatigue to the user during the process of removing the rotorcraft out of the backpack and placing it on the ground. The data for the SSP analysis is not included in this report, but is available upon request.

5.2 Stress Analysis

Stress analyses were performed on this design to ensure its safety and efficiency. In order to perform a stress analysis on the team's design in Creo Parametric 2.0, first the attachment system for the payload had to be modified from the previous report. Previously, the design included a hook at the bottom of the rotorcraft's baseplate. However, due to the inability to find an attachment method for the hook that could withstand the required payload, a new attachment system was designed. For this system, two metal wires (made of bright wire rope with a ¼ inch steel core) attached in the center of the baseplate go across the diameter of the plate. These wires are of a length such that when the payload is attached the wires are at a twenty-degree angle to the top surface plane of the baseplate. A visual representation of the new load attachment system can be seen in Figure 21.

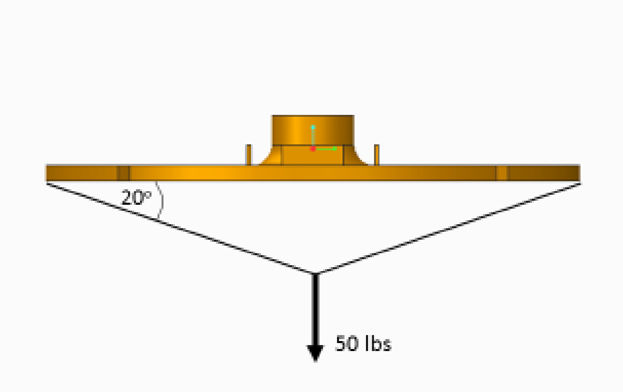


Figure 21. Payload Attachment Design

Also, a stress analysis was performed on the baseplate in Creo Parametric 2.0. First, the center of the baseplate was constrained to prevent any movement under the payload. Then, a fifty pound payload was placed on each notch to ensure that the maximum possible load on each notch was tested. This takes into account a scenario where the weight of the payload shifts, and one notch must be able to support more than its share of the weight. This load was then put at an angle of twenty degrees, the maximum anticipated angle from the horizontal. The results from the stress analysis done on the baseplate can be seen in Figure 22 from two different views.

In Figure 22, the displacement under the load is measured in millimeters. The maximum anticipated deformation is 0.14 mm, at the edges of the plate. The maximum deformation at the point of contact between the plate and the wires is 0.11 mm. In Figure 23 a stress von Mises analysis can be seen. This stress analysis indicates the minimum stress for yielding to occur at specific points on the plate due to the load. The two highest regions of stress are at the notches and the points where the wires are connected to the plate. As can be seen in Figure 23, the plate never comes close to approaching the critical yield stress. This shows that the plate does 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.

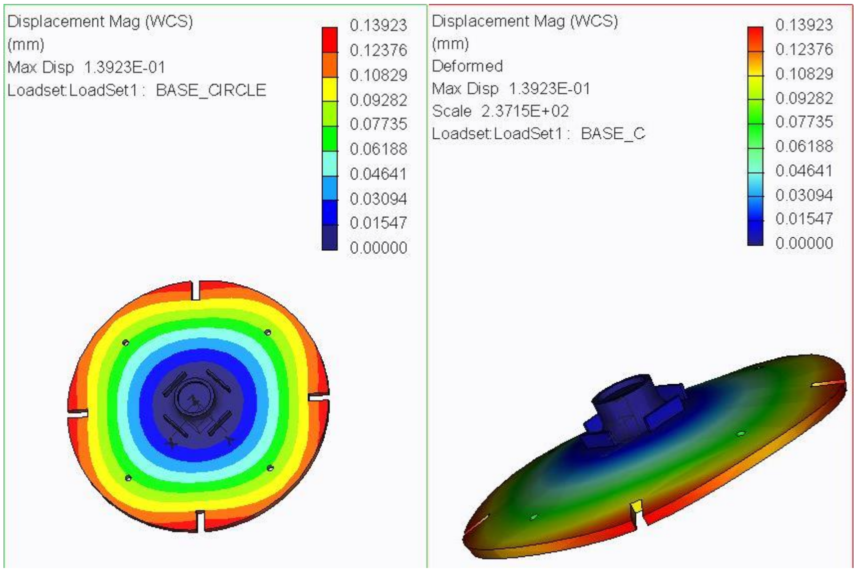


Figure 22. Baseplate Deformation Analysis

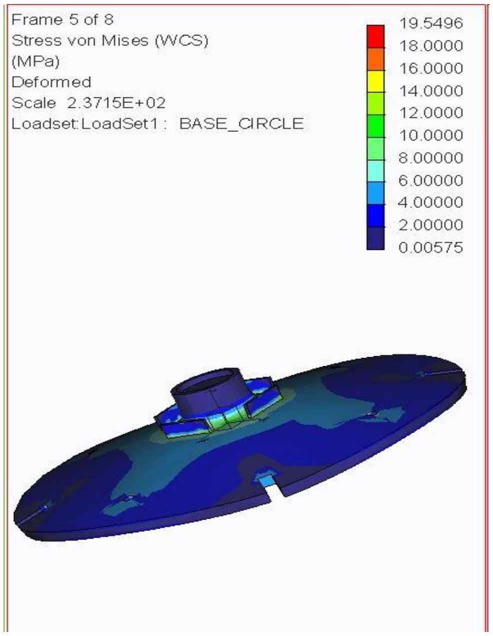


Figure 23. Baseplate Stress Von Mises Analysis

Next, a stress analysis was performed on the arms of the team's rotorcraft design. This was done by putting the entire fifty pound payload on the end of an individual arm of the craft. This is the worst-case scenario for any arm because as a force is moved from the center of a body to the farthest and least constrained point, in this case the end of an arm, the deformation will increase to a maximum. Figure 24 shows the displacement map from the stress analysis of an arm. The pink outline above the arm represents the original location of the arm before the 50 lbs. load and the colors on the arm represent the amount of displacement that occurred. As expected the maximum deformation occurs at the end of the arm where the displacement is 0.72 mm while no displacement of the arms occurs where the arms are attached to the base of the rotorcraft. Only elastic deformation occurs on the arms. Based on the stress analysis performed on the arms, the carbon fiber is anticipated to not have any permanent deformation and so the carbon fiber is an appropriate material for this application.

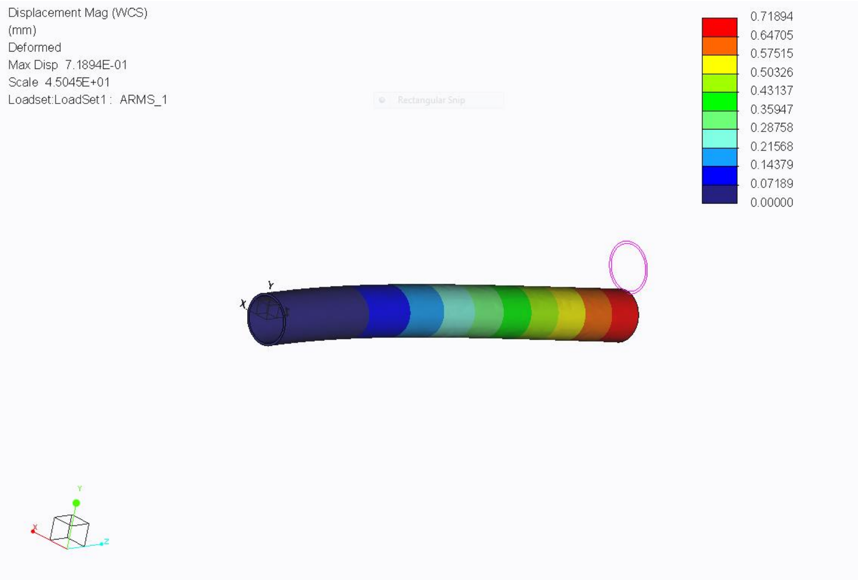


Figure 24. Arm Stress Analysis

5.3 Electrical Hardware Analysis

The importance of the hardware analysis is ensuring that the components of the rotorcraft do not overheat or burn out. If the components fail from a hardware standpoint, other components of the flight with also overheat and instigate a total malfunction. For this project, it is essential to verify that the batteries supply enough power to all of the motors for them to be functional and efficient, without supplying too much power and burning out the motors.

The voltage of the batteries being used in this project is 33.3V, while the maximum voltage allowed by the propellers is 44.4V. This means that burning out the resistor is a non-issue and that the team can focus on supplying as much power to the motor as possible. The simplest way to do this is with a simple series circuit, with a 1K Ω resistor in parallel with each of the motors. This will mean that the full 33.3V will be going through the resistor, but the current will be low enough to ensure the motors do not burn out. Figure 25 shows an example of the circuit that can be used so that one battery can power both of the motors of one of the arms. Moreover, the other component that needs to be powered is the flight controller. In order to power the flight controller, there is a power cord on the ESCs that supplied a voltage of 5V. This voltage is acceptable to power the flight controller without burning it out.

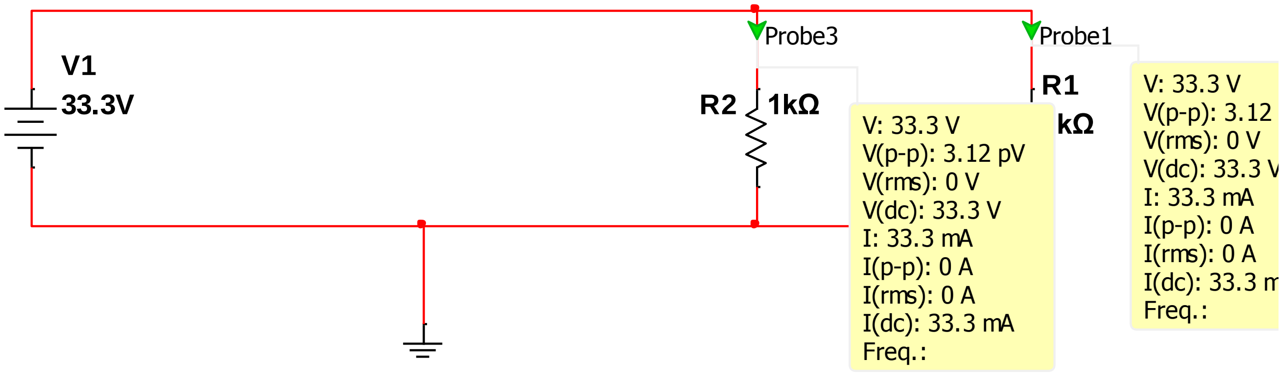


Figure 25. Parallel Power Connection for the Motors

6. Improving the Current Process (Design Phase)

6.1 Manufacture of Rotorcraft's Top and Base Plates

In order to manufacture the rotorcraft's base plates the team decided to use 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 fiber fabrics, 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 was not 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 [36]:

- 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, 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 does not 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 it is well placed to avoid any leaks.
3. Apply PVA across the glass surface using a brush and wait about 20 min 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 26 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 [36]. 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 27. 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.

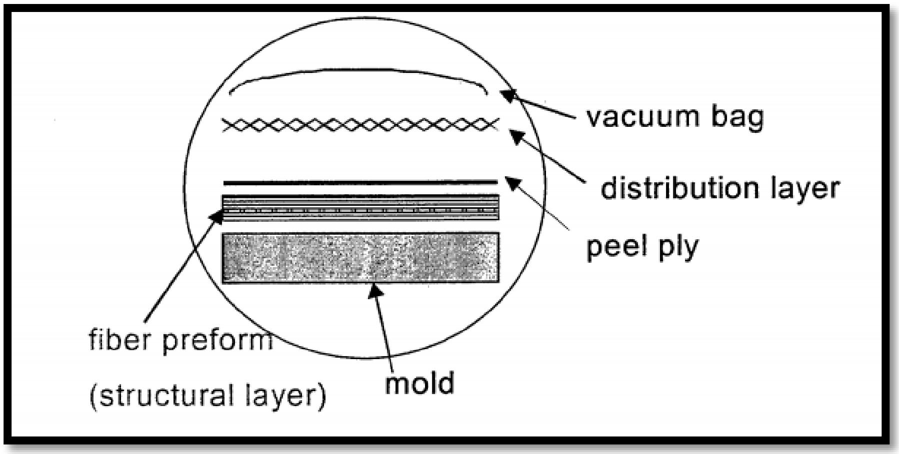


Figure 26. Layup of Materials in VARTM Process

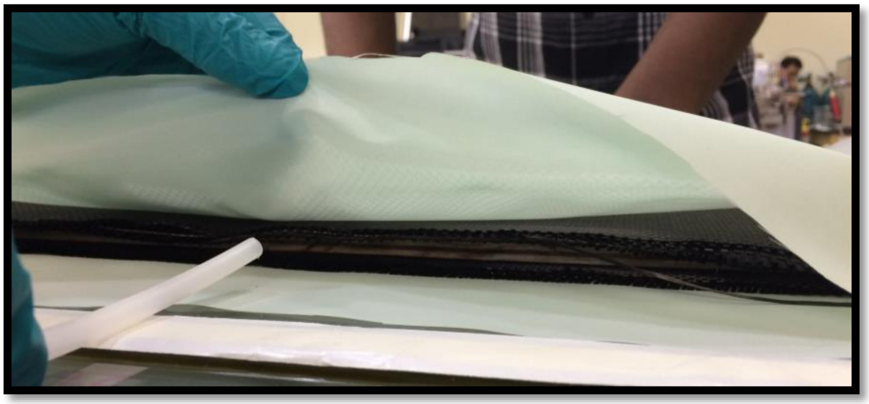


Figure 27. Layup of Materials for the Manufacture of the Base Plates

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 28 shows the composite layup before resin infusion.

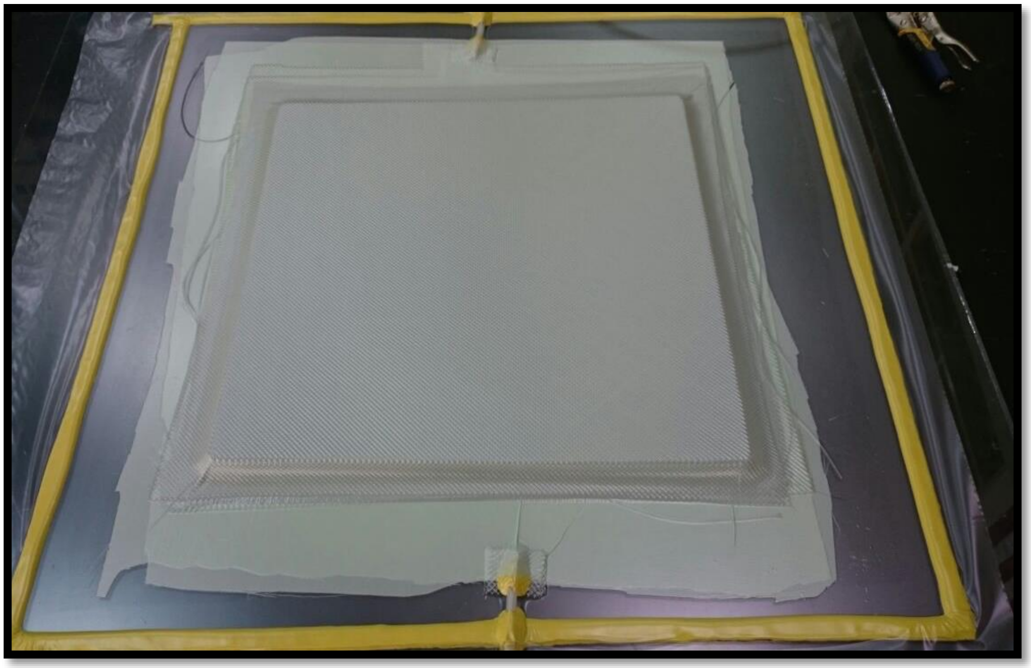


Figure 28. Composite Layup before Resin Infusion

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 29.

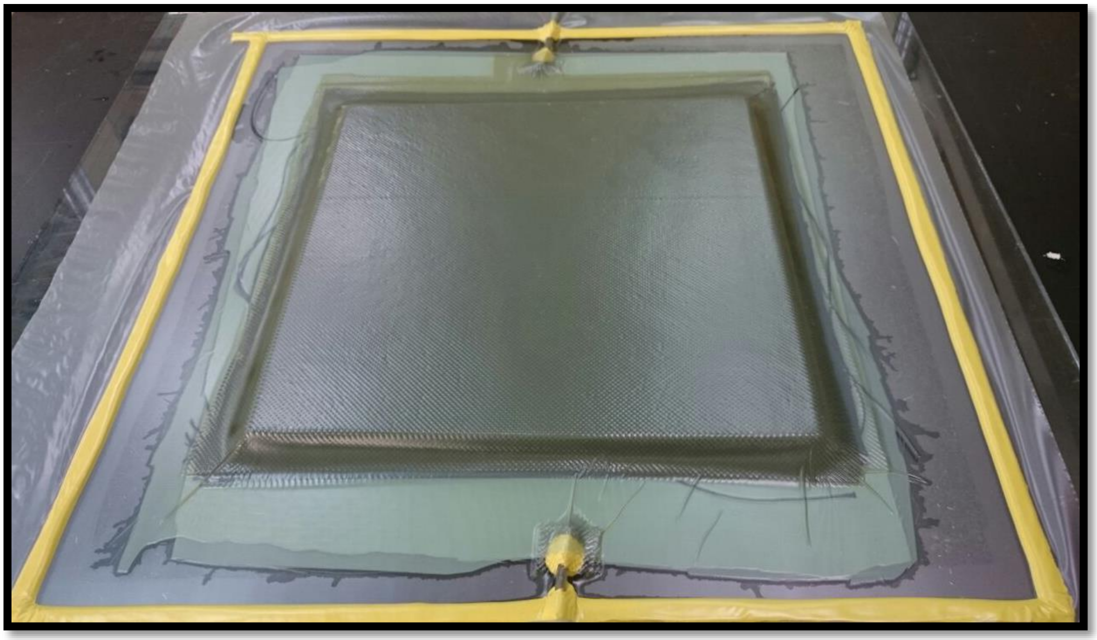


Figure 29. Resin Infusion Process

10. Clamp the vent and gate tubes and let the composite cure 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.

6.2 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 propellers 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 Zinger 18x10 (diameter x pitch) inch and there will be four propellers rotating clockwise and four rotating counter clockwise. The team’s design follows a coaxial configuration and four arms, therefore, there must be eight Electrifly Rimfire 1.60 motors, eight propellers, and eight 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 Zinger propellers, Electrifly Rimfire motor, and motor mounts can be seen in Figure 30.

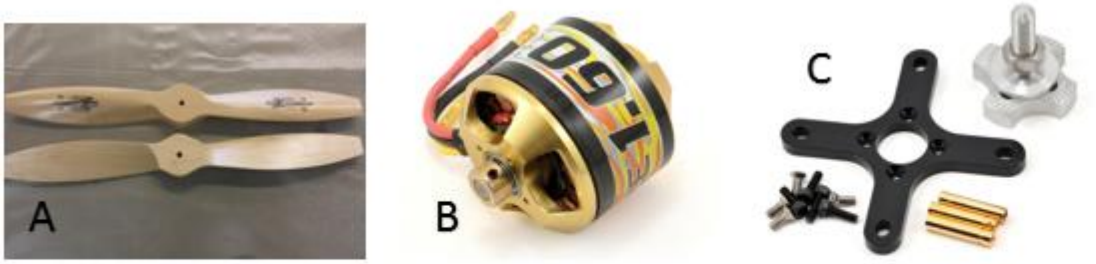


Figure 30. Propellers, Motors, and Motor Mounts

A. Zinger Wood Propeller 18x10 inch (CW & CWW) **(Quantity 4 Each)**
B. Electrifly Rimfire 1.60 Motors **(Quantity 8)**
C. Prop, Motor Mount Set, and Motor Bullet Connectors **(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 31.

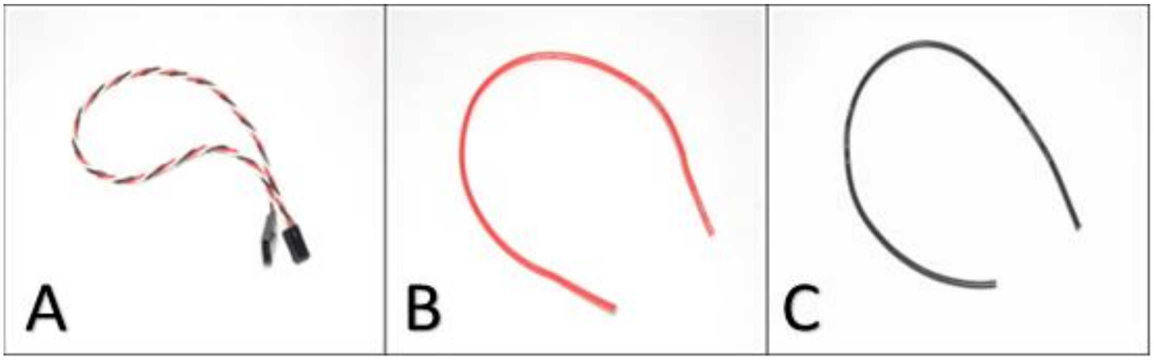


Figure 31. AWG Wires and Servo Extension

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 and wood. 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 32 shows the bottom base plate and Figure 33 shows the 12.75 in carbon fiber arms that will be used in this assembly.

Figure 32. Bottom Base Plate

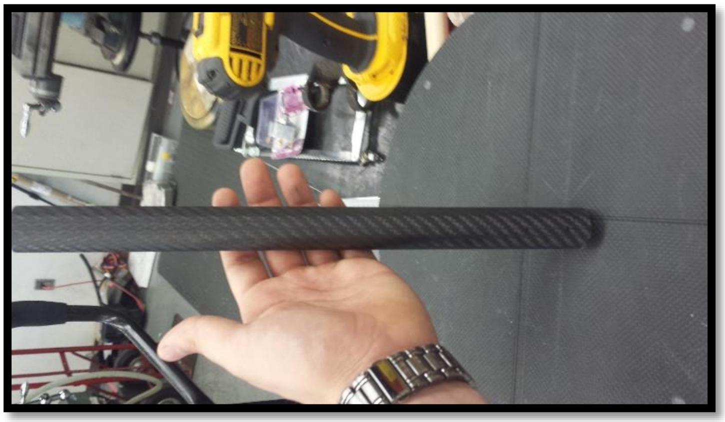


Figure 33. Carbon Fiber Arms

Moreover, eight corner braces 3 inches long will be required and can be seen in Figure 34 (A) [6]. These will be placed on the bottom center plate. Figure 34 (B) shows an aluminum piece of metal that will hold the corner brace in the first two holes to the left and the carbon fiber arm in the other three holes.

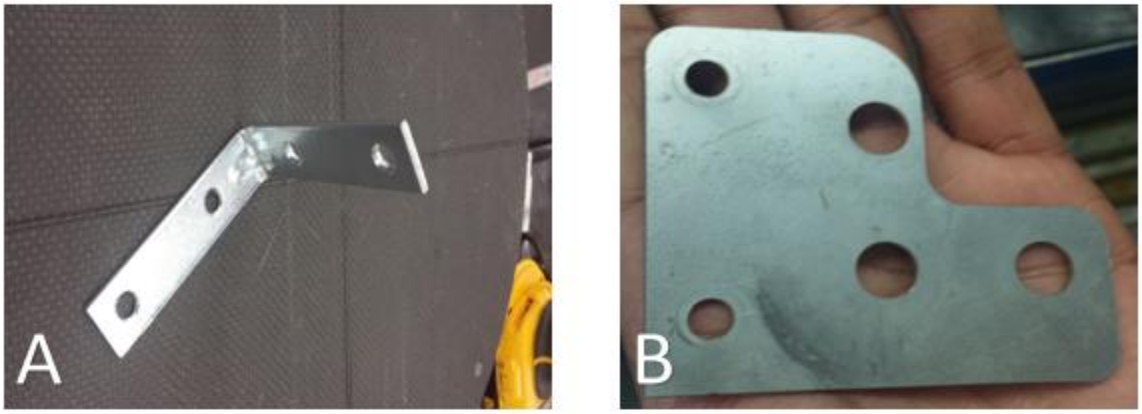


Figure 34. Corner Brace and Carbon Fiber Arm Holder

Also, there will be ¼ in 5/8in long screws used to mount the corner braces onto the base plate. Each corner brace requires two screws to hold it in place. Since there are 8 corner braces then there will be 16 of the ¼ in 5/8in long screws used. Also, there should be 8 pins used to hold the carbon fiber arms in place. Figure 35 shows the screws and pins require for the assemble of the rotorcraft.

Figure 35. Screws and Pins

Figure 36 shows the rotorcraft's heavy lifter motor mount pair needed to finish building the frame assembly. 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.

Figure 36. Motor Mounts

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 37. 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 37. ESC, Bullet Connector, and Connector for Batteries and Microcontroller

A) 120 amp Electric Speed Controller SC (33.3V 9S)

B) 3mm Bullet Connector (Female)

C) Connector for Batteries and Microcontroller

Figure 38 shows the Thunder Power 33.3 volt 9S (cells) lithium polymer battery and it also shows the 9s Lipo charger needed for building this Rotorcraft [15]. The Thunder Power battery has a capacity of 5,000 milli-Ampere per hour (mAh) and four will be required 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.

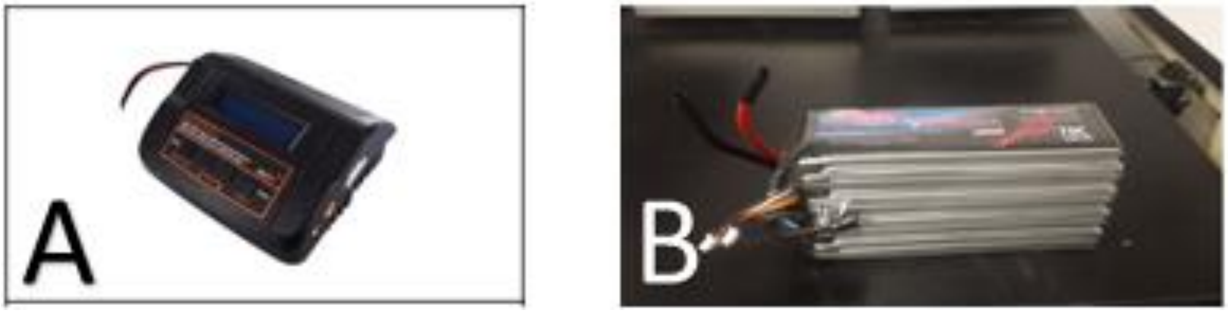


Figure 38. Thunder Power 33.3 V 9S Lipo Battery and 9S Lipo Charger

There are two more components needed as part of the checklist including the RC transmitter, which can be seen in Figure 39. This DSMX controller combines superior data capacity and interference resistance of a wideband single with the agility of frequency shifts. Compared to the wideband signal of DSMX, the narrow band signal of other frequency hopping 2.4 transmitter is more likely to suffer data loss in the event of on-channel interference. Think of it as a river vs. a stream. It takes more interference to dam a river than it does a stream. As more and more 2.4 transmitters vie for the same number of available channels, there is more interference and more risk for data loss. By adding the agility of frequency shifts to the superior interference resistance of a wideband signal, DSMX is far less likely to suffer significant data loss from on-channel interference. The result is quicker connection times and superior response in even the most crowded 2.4GHz (Giga Hertz) environment.

Figure 39. DSMX Remote Control

The last component on the checklist is the flight controller and the hook up connections, and can be seen in Figure 40. This component well allow for gyro stabilization. This simply means it will give the Rotorcraft the ability to easily keep the copter stable and level under the pilot's control. It also gives the ability to self-level by letting go of the pitch and roll stick on the transmitter and having the copter stay leveled. It also allows for altitude hold, giving the rotorcraft the ability to hover a certain distance from the ground without having to manually adjust the throttle.

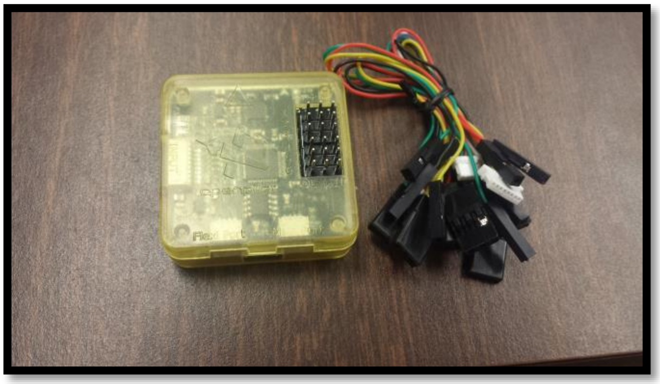


Figure 40. Flight Controller

Assembly Steps- Frame Assembly

The frame assembly includes all the parts of the rotorcraft not including any electrical components such as the motor, speed controller, battery, etc.…

Step 1- Begin with drilling four holes on the bottom base plate. These holes were found by finding the center of the 13inch diameter base plate first. Then draw a "plus" sign down the middle in order to find the optimum location for where the arms need to be placed. Once these locations are found then proceed by placing the corner brace 1 inch from the center of the plus sign on each side and mark it with a sharpie. Then using a drill press, drill the 16 holes using a ¼ inch drill bit as shown in Figure 41.

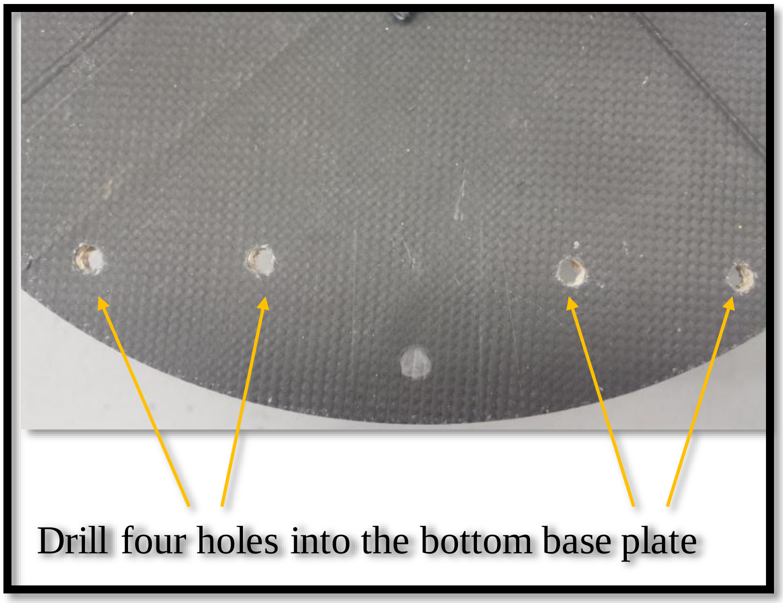


Figure 41. Drill the Base Plate

Step 2- Line up the corner braces over the holes and place the ¼ inch screw into the corner brace. Next tighten down the bolts using a ¼ inch wrench, and place a lug nut on the bottom of the plate to tighten down the screws as seen in Figure 42. Repeat this step for three other sides.

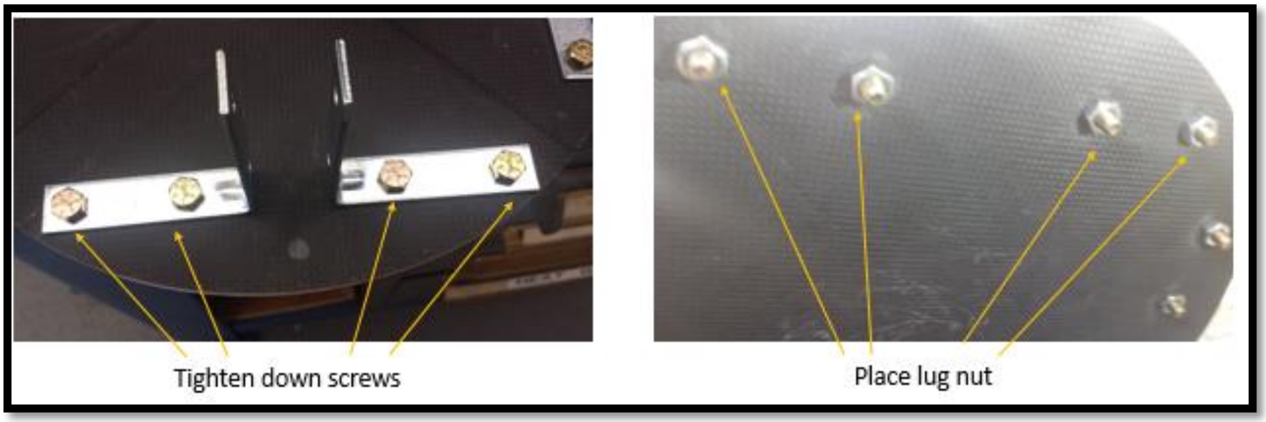


Figure 42. Place the Corner Brace

Step 3- Next place the arm and corner brace holder on the outside of the corner brace, and place two ¼ in screws in the holes as seen in Figure 43. Once the screws have been placed in the appropriate holes, place a lug nut on the end of the screw to hold it in place.

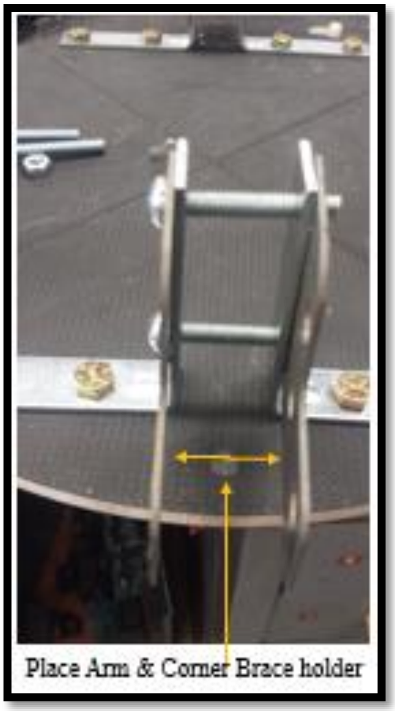


Figure 43. Arm and Corner Brace Holder

Step 4- Slide the pins through the carbon fiber & corner brace holder. Then wrap the safety pin around the corner brace towards the center of the plate and place on the other side of the pin as seen in Figure 44. When the Rotorcraft is in the upward position there should be a pin place on the hole directly vertical over the pin it pivots on. When the Rotorcraft is in flight condition, the pin should be placed in hole directly horizontal to the pin it pivots on.

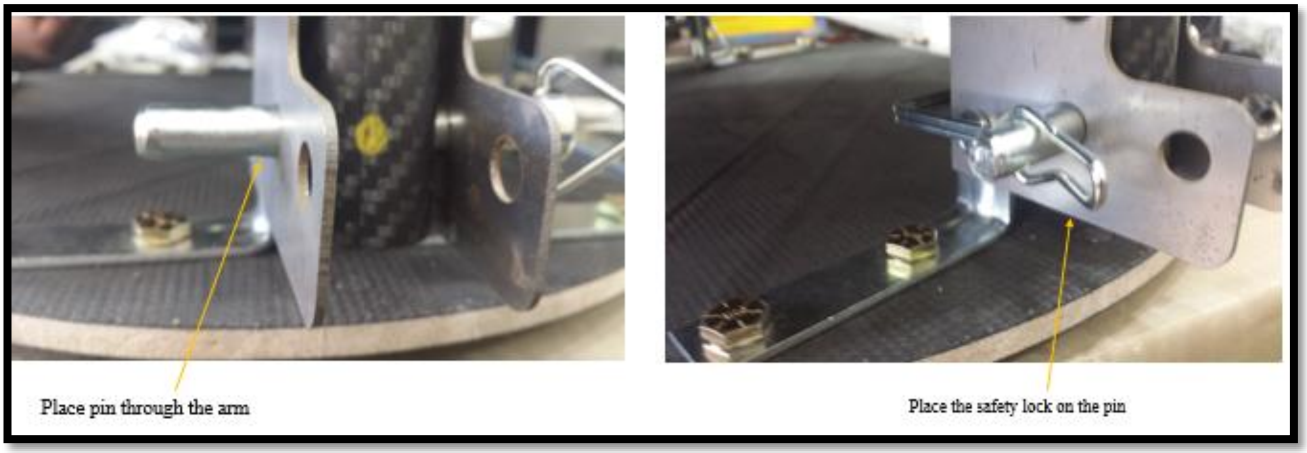
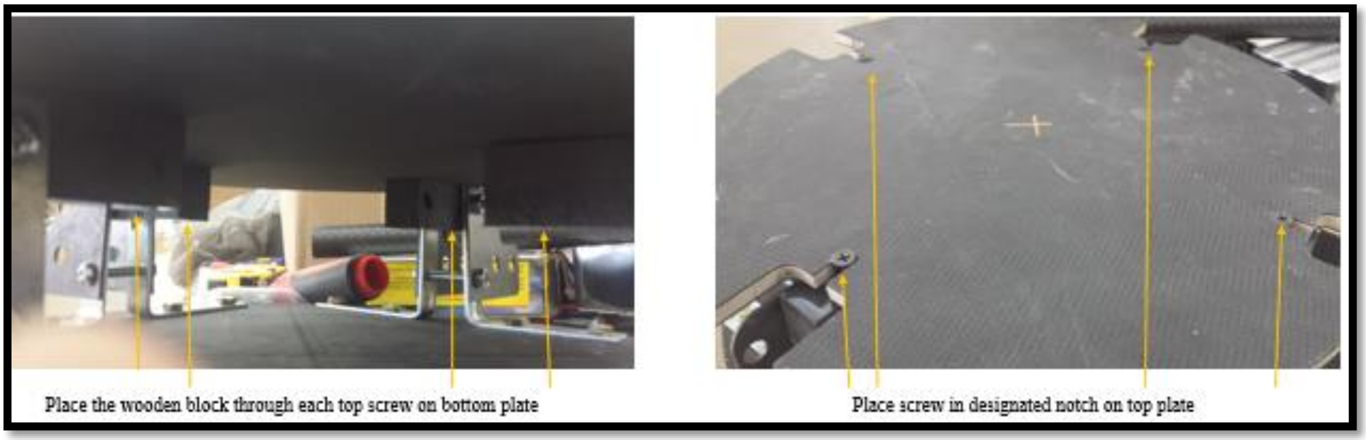


Figure 44. Place Pins on the Arms

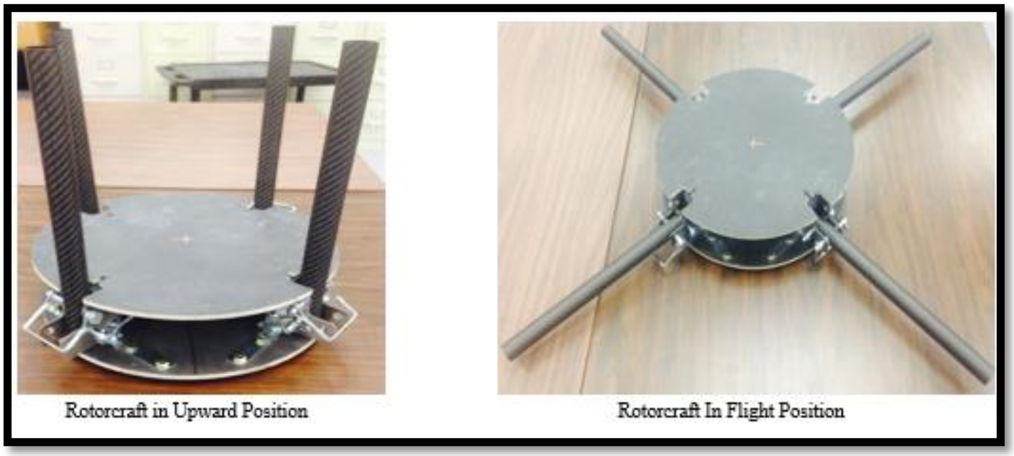
Step 5- Attach the top plate to the bottom plate by placing a two by two inch wooden block to the top plate. This is done by screwing the wooden block through the arm & brace holder and putting a ¼ in screw from the top plate directly into the wooden block as seen in Figure 45. This needs to be placed on each arm.


Place the wooden block through each top screw on bottom plate

Place screw in designated notch on top plate

Figure 45. Attach Top and Bottom Plates

Once these first five steps have been completed Figure 46 shows the rotorcraft in its upward position and its take off flight position. It should be noted that the arms should be very rigid and should not be able to move with ease. This will help reduce harmonic vibrations during flight. There should be at no time of the assembly pins having to be forced into their position. Again Figure 46 shows the rotorcraft assembly without any of the electrical components, as that will be discussed in the next section.


Rotorcraft in Upward Position

Rotorcraft In Flight Position

Figure 46. Rotorcraft in Storage/Upward Position (left) and Active/Flight Position (right)

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 the rotorcraft assembly has not been completed yet.

Step 1- Begin with soldering all 8 ESCs, so that the 3mm Bullet Connector can be attached as seen in Figure 47 [25].

Figure 47. Solder Connections

Step 2- Install the propeller mount to the motor using 3mm mounting screw as seen in Figure 48 [24].

Figure 48. Mount Propeller 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 49 [24].

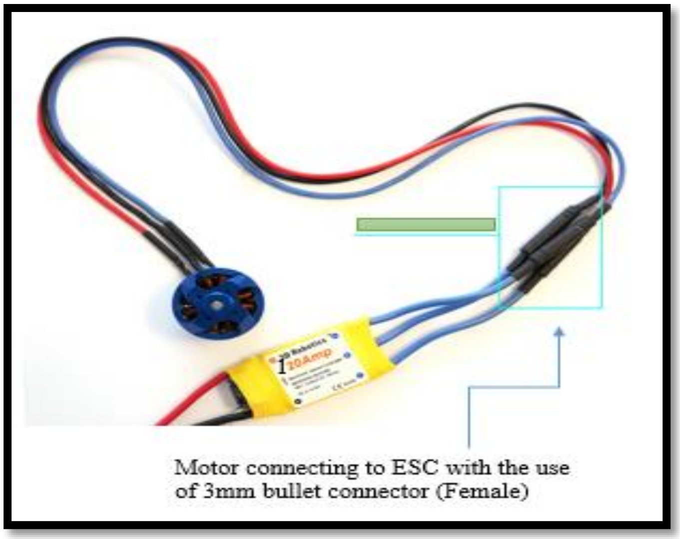


Figure 49. Connect the Electrical Speed Controller to the Motor

Step 4- Connect ESC dean connector to microcontroller board connectors that are attached to the IMU sensor. Connect ESC for motor one to PDB pins marked M1, motor two to PDB pin marked M2, and so on as shown in Figure 50 [24].

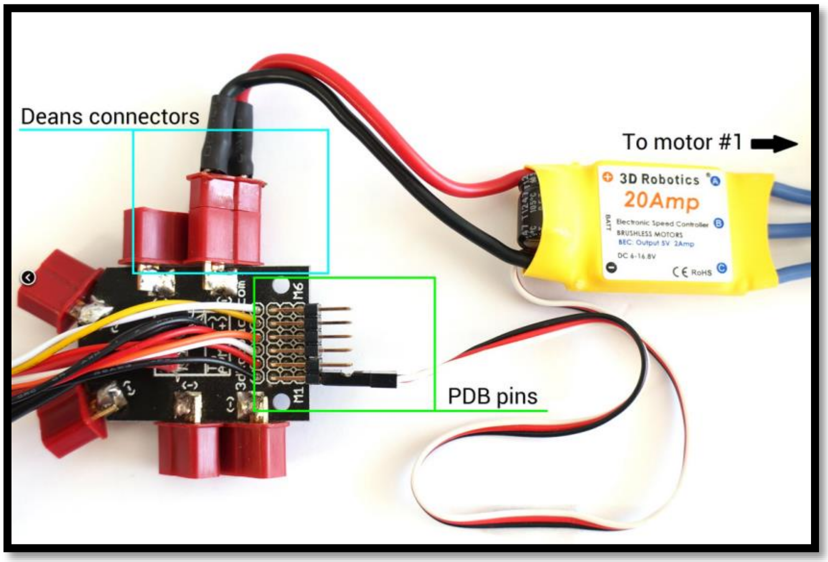


Figure 50. Connect the Electrical Speed Controller to the Motor

Step 5- Connect the ESC to the battery by sliding the female connector inside the male connector as shown in Figure 51 [27].

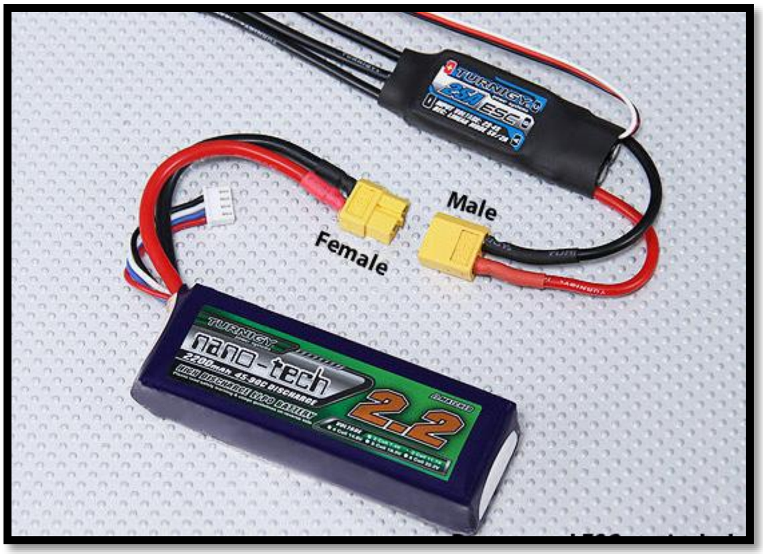


Figure 51. Connect the Electrical Speed Controller to the Battery

As a review of the first five steps a general layout can be seen in Figure 52 to better help understand how the layout is supposed to be [27]. The general layout for this rotorcraft includes two motors being powered by one battery. 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.

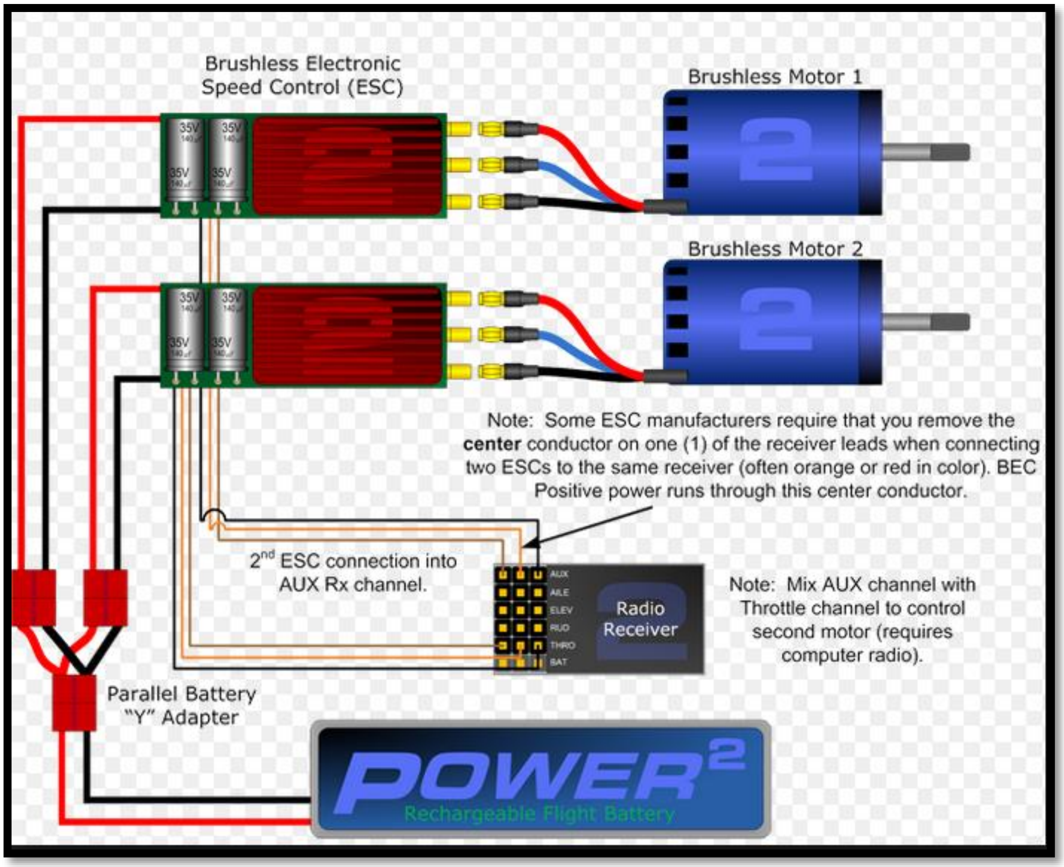


Figure 52. General Layout of the ESC, Battery, IMU Sensor, and Motor Connections

Assembly Steps- Motors and Propellers

Step 6- Secure the motor mount to the carbon fiber arms using four M3x6 screws as shown in Figure 53 [37].

Figure 53. Secure Motor Mount to Carbon Fiber Arm

Step 7- Secure the Electrifly motor to the motor mount as seen in Figure 54 [37].

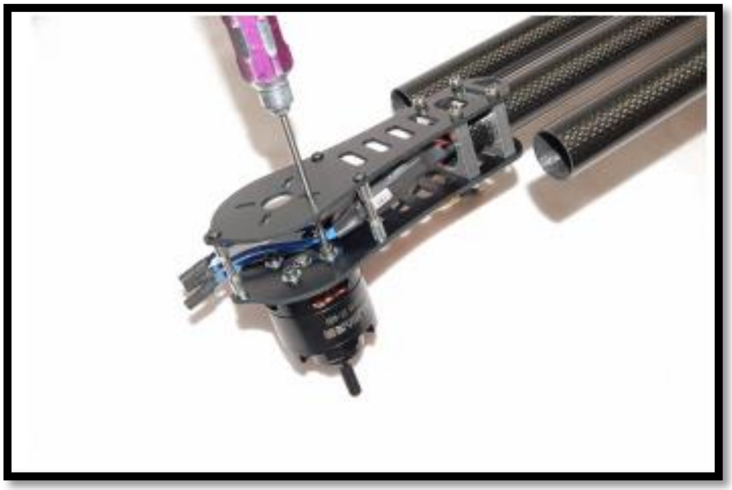


Figure 54. Secure the Motor to the Motor Mount

Step 8- After ensuring the motors are running in the correct direction, prepare the 18x10 inch Zinger Wood propellers and propeller mounting screw and washer from the motors.

Step 9- Install the propeller to the motor and secure it with the propeller mount screw and washer as seen in Figure 55 [37].

Figure 55. Install Propeller on Motor

Battery Straps

Step 10- Attach the Velcro straps over the batteries tightly as shown in Figure 56 in order to minimize battery movements.

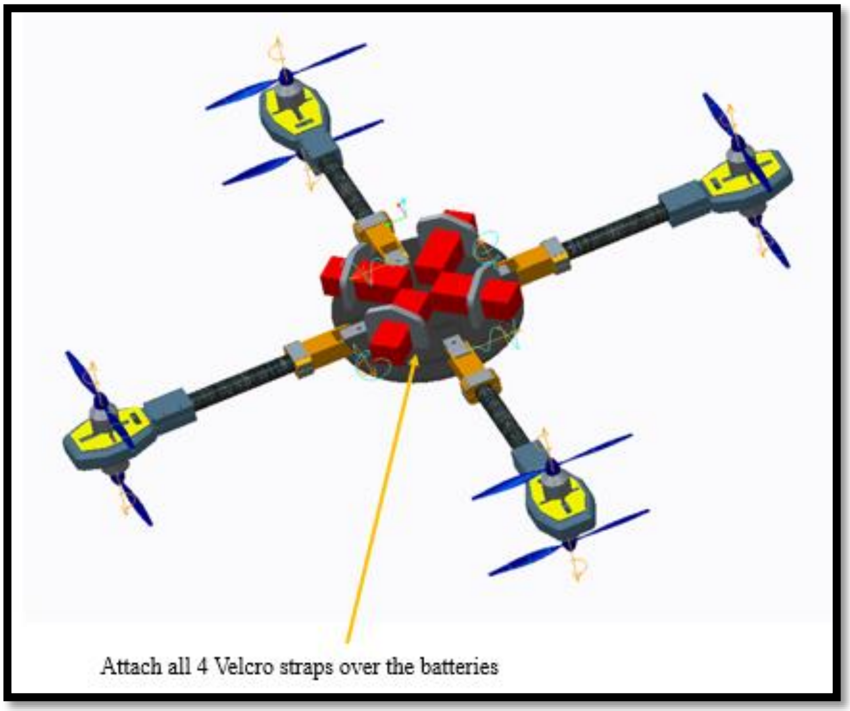


Figure 56. Place Velcro Straps Over Batteries

7. Controlling Process Improvement (Verify Phase)

7.1 Protocol for Operation of the Rotorcraft

Step 1- First, the soldier removes the rotorcraft from the backpack and places the rotorcraft onto the ground. At this point the arms are locked into the vertical, more compact position. A close up view of a locked vertical arm on the rotorcraft can be seen in Figure 57.

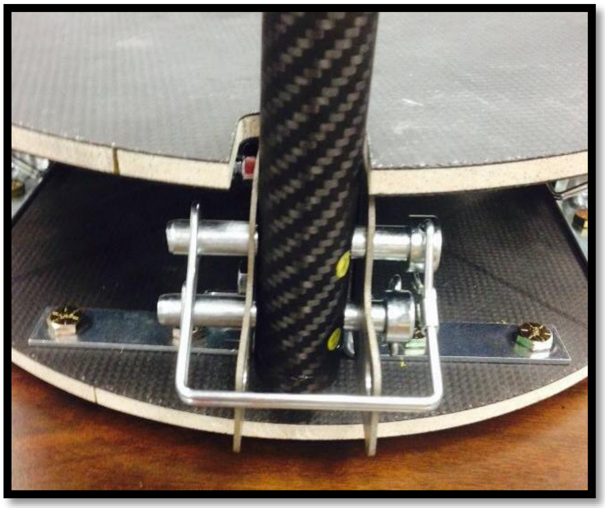


Figure 57. Lock Arm into its Vertical Position

Step 2- Then, working with one arm at a time, the soldier disconnects the safety mechanism of the upper pin. The detached safety mechanism of the pin can be seen in Figure 58.

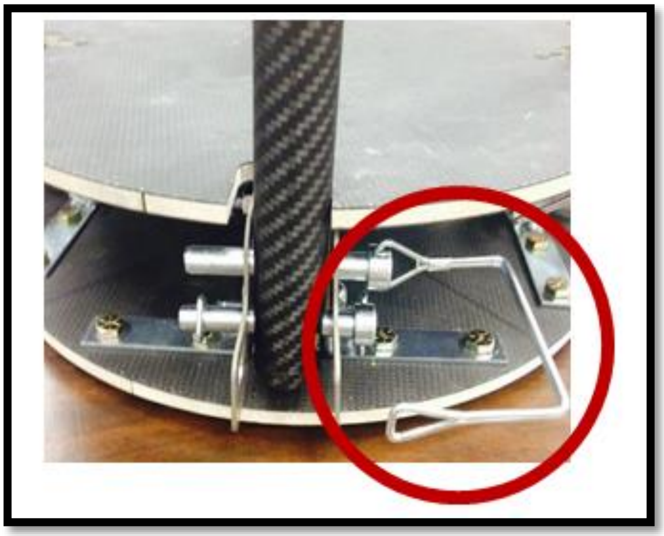


Figure 58. Remove Safety Mechanism of the Pin

Step 3- Next, the entire pin is removed from the arm. This can be seen in Figure 59.

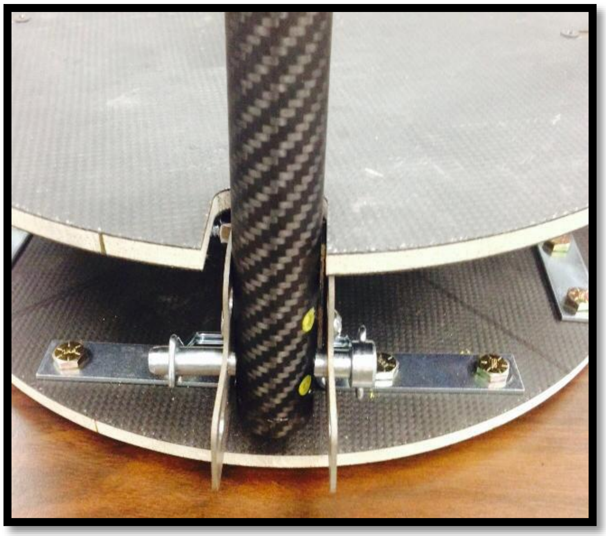


Figure 59. Remove Pin

Step 4- Following step 3, the arm is lowered into its horizontal position. Then, the pin is slid through the arm and the lower holes on the two L brackets. This can be seen in Figure 60.

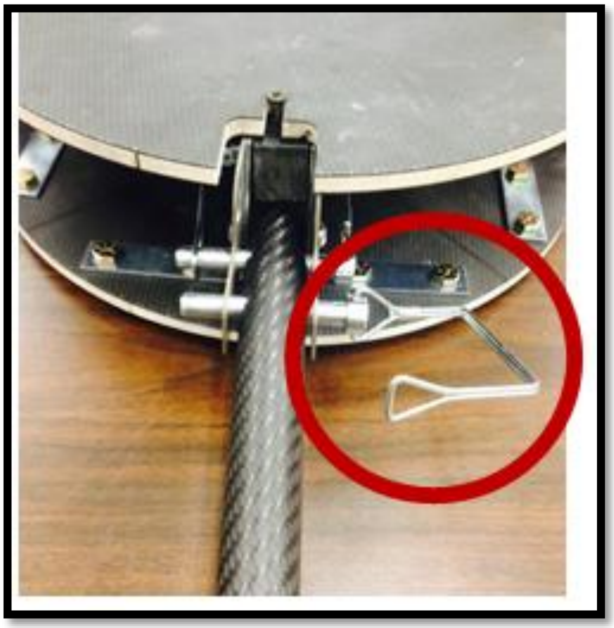


Figure 60. Position Arm Horizotally

Step 5- Next, the safety mechanism is reconnected as shown in Figure 61.

Figure 61. Lock Arm into Horizontal Position

Step 6- Finally, this is repeated for the remaining three arms. Figure 62 shows the rotorcraft with all four arms locked into the horizontal position.

Figure 62. Rotorcraft Deploy Position

Once the rotorcraft is ready to be deployed, the RC controller will both turn on and control the movements of the rotorcraft.

7.2 Performance Measures

Testing of the prototype was not performed in this phase for three main reasons. These reasons are listed below in order of most to least impact on testing.

The first of these reasons is the delayed assembly, as described in section 2.2.4. As of March 31st, the frame of the rotorcraft was fully assembled. The frame includes the baseplates, arms, and hinges. The other rotorcraft components, such as the motor and batteries, are the responsibility of the Electrical and Computer Engineering project members due to the necessity of wiring and soldering connections. These other components are to be attached to the frame and are not currently attached. It is impossible to test the prototype before it is fully assembled.

The second of these reasons is a lack of safety protocol. There are 18 senior design projects in the Department of Electrical and Computer Engineering and another one of these projects is also concerned with designing and building a rotorcraft. During this team's testing, a safety incident occurred. As a result, all rotorcraft teams must follow strict safety requirements prior to testing. These requirements are a hardship for this team at present, which presents a further delay to testing.

The third of these reasons is the lack of a testing facility. The team was advised that the rotorcraft could not be tested outside on Florida State University property because of FAA guidelines. To test the rotorcraft, the team must either find an indoor location with a very high ceiling or a large enough clearing in a residential area. The team is currently searching for a suitable testing location.

When the rotorcraft can be tested, the flight will be tested to ensure it can at least hover above the ground. If possible, the team will conduct this test with a payload at or below the thirty pounds described in section 2.1.2.

8. Conclusion

This project is concerned with designing and manufacturing a rotorcraft that is usable and useful in military applications. The project team is addressing this problem by designing a rotorcraft that can lift a payload of thirty pounds, fits in a military backpack, is relatively inexpensive to build, and is easy to assemble and use in the field. The project team is also building a prototype of this designed rotorcraft to prove that the design can be physically built and used.

In order to provide the necessary lift and thrust forces to lift a payload of thirty pounds, the team decided on a coaxial octocopter design. This means that there are eight motors and propellers on four arms, or two motors and propellers per arm. There is more room in between arms with four arms instead of the typical eight arms and thus larger propellers can be used in this configuration. This allows for improved lift and thrust forces as compared to the traditional radial configuration. The frame of this rotorcraft has been successfully built.

To prove the usefulness of the design, the team performed several analyses. These include the eCalc analysis discussed in section 4.3, the ergonomic analysis discussed in section 5.1, the stress analysis discussed in section 5.2, and the electrical hardware analysis discussed in section 5.3. The eCalc analysis helped the team to decide on a combination of components based on the estimated flight parameters the tool analyzes. The ergonomic analysis showed that removing the rotorcraft from the backpack was ergonomically sound. This means that the entire operation of carrying the rotorcraft and setting up the rotorcraft is safe for the user based on the assumption that the rotorcraft does not exceed the current acceptable maximum weight limit for a member of the United States Air Force. Also, the stress analysis showed that the rotorcraft would not undergo permanent deformation under the thirty pound load during operation. The electrical hardware analysis established the circuit design being used for the motors as well as the circuit design being used for the IMU sensor and microcontroller.

Additionally, the team ordered and received all the parts necessary for building the rotorcraft prototype. This includes successfully manufactured the two carbon fiber base plates for the rotorcraft using the VARTM process of composite manufacturing. More information on the manufacture of the plates can be found in section 6.1.

Due to FAA restrictions and safety concerns, the team is unable to test the flight of the rotorcraft at this point in time.

The next steps in this project are to establish safety protocols for testing and find a testing location where the team can safely operate the rotorcraft and ensure it at a minimum hovers. There is much room for design improvement as the basis for future projects, including both areas where the team failed to fully meet objectives and areas that were determined to be outside of this project's scope.

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Appendix A – Force equilibrium calculations

Force Equilibrium for Design #1:

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

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

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

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

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

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

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

Force Equilibrium for Design #2:

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

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

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

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

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

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

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

Force Equilibrium for Design #3:

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

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

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

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

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

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

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

Appendix B – Jack Simulation Results

Timing Report

Task Totals

Figure	Task	Duration (seconds)
Jack	Get_hermes	3.15
Jack	Put_hermes	4.92

Action Summaries

Figure	Task	Action	Duration (seconds)	Code
Jack	Get_hermes	Walk	1	W3FT
Jack	Get_hermes	Turn_Body	0	TBC1
Jack	Get_hermes	Bend_And_Reach	2.08	B + R23.196A(b)
Jack	Get_hermes	Grasp	0.07	G1A(b)
Jack	Put_hermes	Arise_From_Bend	1.15	AB
Jack	Put_hermes	Walk	1.44	W4FT
Jack	Put_hermes	Turn_Body	0	TBC1
Jack	Put_hermes	Bend_And_Reach	2.26	B + R28.096A(b)
Jack	Put_hermes	Release	0.07	RL1(b)

- Static Strength Prediction
- Data available upon request.
- Lower Back Analysis
- Data available beginning on next page.

Color formatting indicates status as a low, medium, or high-risk activity. Low risk activities are highlighted in green, medium risk activities are highlighted in yellow, and high risk activities are highlighted in red. The criteria levels are as follows:

Compression Forces *AP Shear Forces*

Low	< 3400 N	< 750 N
Medium	Between 3400 and 6400 N	Between 750 and 1000 N
High	> 6400 N	> 1000 N

Appendix C – Jack Simulation Results

Action			L4/L5 Forces (N)		Action			L4/L5 Forces (N)		Action			L4/L5 Forces (N)	
Time (seconds)	*Task*	*Action*	*Compression*	*AP Shear*	*Time (seconds)*	*Task*	*Action*	*Compression*	*AP Shear*	*Time (seconds)*	*Task*	*Action*	*Compression*	*AP Shear*
0	Get_hermes	Walk	482.136	14.891	2.7	Get_hermes	Bend And Reach	2303.218	751.158	5.4	Put_hermes	Walk	666.642	55.958
0.033	Get_hermes	Walk	482.133	14.89	2.733	Get_hermes	Bend And Reach	2296.382	753.282	5.433	Put_hermes	Walk	667.973	56.43
0.067	Get_hermes	Walk	469.874	0.936	2.767	Get_hermes	Bend And Reach	2287.705	754.706	5.467	Put_hermes	Walk	645.206	47.686
0.1	Get_hermes	Walk	438.469	-3.511	2.8	Get_hermes	Bend And Reach	2281.073	756.078	5.5	Put_hermes	Walk	631.819	37.104
0.133	Get_hermes	Walk	433.22	-5.304	2.833	Get_hermes	Bend And Reach	2274.931	757.148	5.533	Put_hermes	Walk	621.07	36.865
0.167	Get_hermes	Walk	444.13	-2.484	2.867	Get_hermes	Bend And Reach	2269.515	757.96	5.567	Put_hermes	Walk	603.56	26.192
0.2	Get_hermes	Walk	424.403	-2.985	2.9	Get_hermes	Bend And Reach	2263.168	758.246	5.6	Put_hermes	Walk	591.285	30.84
0.233	Get_hermes	Walk	423.861	3.295	2.933	Get_hermes	Bend And Reach	2259.806	758.648	5.633	Put_hermes	Walk	597.616	33.698
0.267	Get_hermes	Walk	417.585	-0.075	2.967	Get_hermes	Bend And Reach	2257.711	758.882	5.667	Put_hermes	Walk	612.216	37.984
0.3	Get_hermes	Walk	419.495	0.719	3	Get_hermes	Bend And Reach	2257.711	758.882	5.7	Put_hermes	Walk	614.225	38.68
0.333	Get_hermes	Walk	426.567	4.644	3.033	Get_hermes	Bend And Reach	2256.994	758.959	5.733	Put_hermes	Walk	620.137	40.734
0.367	Get_hermes	Walk	431.732	9.631	3.067	Get_hermes	Bend And Reach	2256.994	758.959	5.767	Put_hermes	Bend And Reach	629.859	44.11
0.4	Get_hermes	Walk	431.491	11.185	3.1	Get_hermes	Grasp	2256.994	758.959	5.8	Put_hermes	Bend And Reach	643.262	48.765
0.433	Get_hermes	Walk	450.721	4.56	3.133	Get_hermes	Grasp	2256.994	758.959	5.833	Put_hermes	Bend And Reach	660.228	54.659
0.467	Get_hermes	Walk	474.523	11.429	3.167	Put_hermes	Arise From Bend	2256.995	758.958	5.867	Put_hermes	Bend And Reach	680.631	61.751
0.5	Get_hermes	Walk	489.015	16.346	3.2	Put_hermes	Arise From Bend	2282.606	761.77	5.9	Put_hermes	Bend And Reach	704.347	69.999
0.533	Get_hermes	Walk	513.015	22.668	3.233	Put_hermes	Arise From Bend	2296.16	762.342	5.933	Put_hermes	Bend And Reach	731.247	79.362
0.567	Get_hermes	Walk	540.395	28.995	3.267	Put_hermes	Arise From Bend	2304.166	761.964	5.967	Put_hermes	Bend And Reach	761.195	89.798
0.6	Get_hermes	Walk	551.259	32.624	3.3	Put_hermes	Arise From Bend	2309.685	761.147	6	Put_hermes	Bend And Reach	794.045	101.259

Action			L4/L5 Forces (N)	
Time (seconds)	*Task*	*Action*	*Compression*	*AP Shear*
0	Get_hermes	Walk	482.136	14.891
0.033	Get_hermes	Walk	482.133	14.89
0.067	Get_hermes	Walk	469.874	0.936
0.1	Get_hermes	Walk	438.469	-3.511
0.133	Get_hermes	Walk	433.22	-5.304
0.167	Get_hermes	Walk	444.13	-2.484
0.2	Get_hermes	Walk	424.403	-2.985
0.233	Get_hermes	Walk	423.861	3.295
0.267	Get_hermes	Walk	417.585	-0.075
0.3	Get_hermes	Walk	419.495	0.719
0.333	Get_hermes	Walk	426.567	4.644
0.367	Get_hermes	Walk	431.732	9.631
0.4	Get_hermes	Walk	431.491	11.185
0.433	Get_hermes	Walk	450.721	4.56
0.467	Get_hermes	Walk	474.523	11.429
0.5	Get_hermes	Walk	489.015	16.346
0.533	Get_hermes	Walk	513.015	22.668
0.567	Get_hermes	Walk	540.395	28.995
0.6	Get_hermes	Walk	551.259	32.624
0.633	Get_hermes	Walk	550.877	33.39
0.667	Get_hermes	Walk	513.235	23.636
0.7	Get_hermes	Walk	483.478	16.042
0.733	Get_hermes	Walk	461.349	8.462
0.767	Get_hermes	Walk	415.604	-3.885
0.8	Get_hermes	Walk	421.38	4.074
0.833	Get_hermes	Walk	417.585	3.54
0.867	Get_hermes	Walk	426.595	1.713
2.7	Get_hermes	Bend And Reach	2303.218	751.158
2.733	Get_hermes	Bend And Reach	2296.382	753.282
2.767	Get_hermes	Bend And Reach	2287.705	754.706
2.8	Get_hermes	Bend And Reach	2281.073	756.078
2.833	Get_hermes	Bend And Reach	2274.931	757.148
2.867	Get_hermes	Bend And Reach	2269.515	757.96
2.9	Get_hermes	Bend And Reach	2263.168	758.246
2.933	Get_hermes	Bend And Reach	2259.806	758.648
2.967	Get_hermes	Bend And Reach	2257.711	758.882
3	Get_hermes	Bend And Reach	2257.711	758.882
3.033	Get_hermes	Bend And Reach	2256.994	758.959
3.067	Get_hermes	Bend And Reach	2256.994	758.959
3.1	Get_hermes	Grasp	2256.994	758.959
3.133	Get_hermes	Grasp	2256.994	758.959
3.167	Put_hermes	Arise From Bend	2256.995	758.958
3.2	Put_hermes	Arise From Bend	2282.606	761.77
3.233	Put_hermes	Arise From Bend	2296.16	762.342
3.267	Put_hermes	Arise From Bend	2304.166	761.964
3.3	Put_hermes	Arise From Bend	2309.685	761.147
3.333	Put_hermes	Arise From Bend	2316.204	760.462
3.367	Put_hermes	Arise From Bend	2321.946	759.617
3.4	Put_hermes	Arise From Bend	2329.488	757.188
3.433	Put_hermes	Arise From Bend	2335.494	749.627
3.467	Put_hermes	Arise From Bend	2325.57	734.007
3.5	Put_hermes	Arise From Bend	2299.127	714.505
3.533	Put_hermes	Arise From Bend	2256.72	691.238
3.567	Put_hermes	Arise From Bend	2198.076	664.188
5.4	Put_hermes	Walk	666.642	55.958
5.433	Put_hermes	Walk	667.973	56.43
5.467	Put_hermes	Walk	645.206	47.686
5.5	Put_hermes	Walk	631.819	37.104
5.533	Put_hermes	Walk	621.07	36.865
5.567	Put_hermes	Walk	603.56	26.192
5.6	Put_hermes	Walk	591.285	30.84
5.633	Put_hermes	Walk	597.616	33.698
5.667	Put_hermes	Walk	612.216	37.984
5.7	Put_hermes	Walk	614.225	38.68
5.733	Put_hermes	Walk	620.137	40.734
5.767	Put_hermes	Bend And Reach	629.859	44.11
5.8	Put_hermes	Bend And Reach	643.262	48.765
5.833	Put_hermes	Bend And Reach	660.228	54.659
5.867	Put_hermes	Bend And Reach	680.631	61.751
5.9	Put_hermes	Bend And Reach	704.347	69.999
5.933	Put_hermes	Bend And Reach	731.247	79.362
5.967	Put_hermes	Bend And Reach	761.195	89.798
6	Put_hermes	Bend And Reach	794.045	101.259
6.033	Put_hermes	Bend And Reach	829.637	113.699
6.067	Put_hermes	Bend And Reach	867.811	127.068
6.1	Put_hermes	Bend And Reach	908.384	141.312
6.133	Put_hermes	Bend And Reach	951.168	156.376
6.167	Put_hermes	Bend And Reach	995.955	172.202
6.2	Put_hermes	Bend And Reach	1042.535	188.727
6.233	Put_hermes	Bend And Reach	1090.679	205.889
6.267	Put_hermes	Bend And Reach	1140.149	223.618