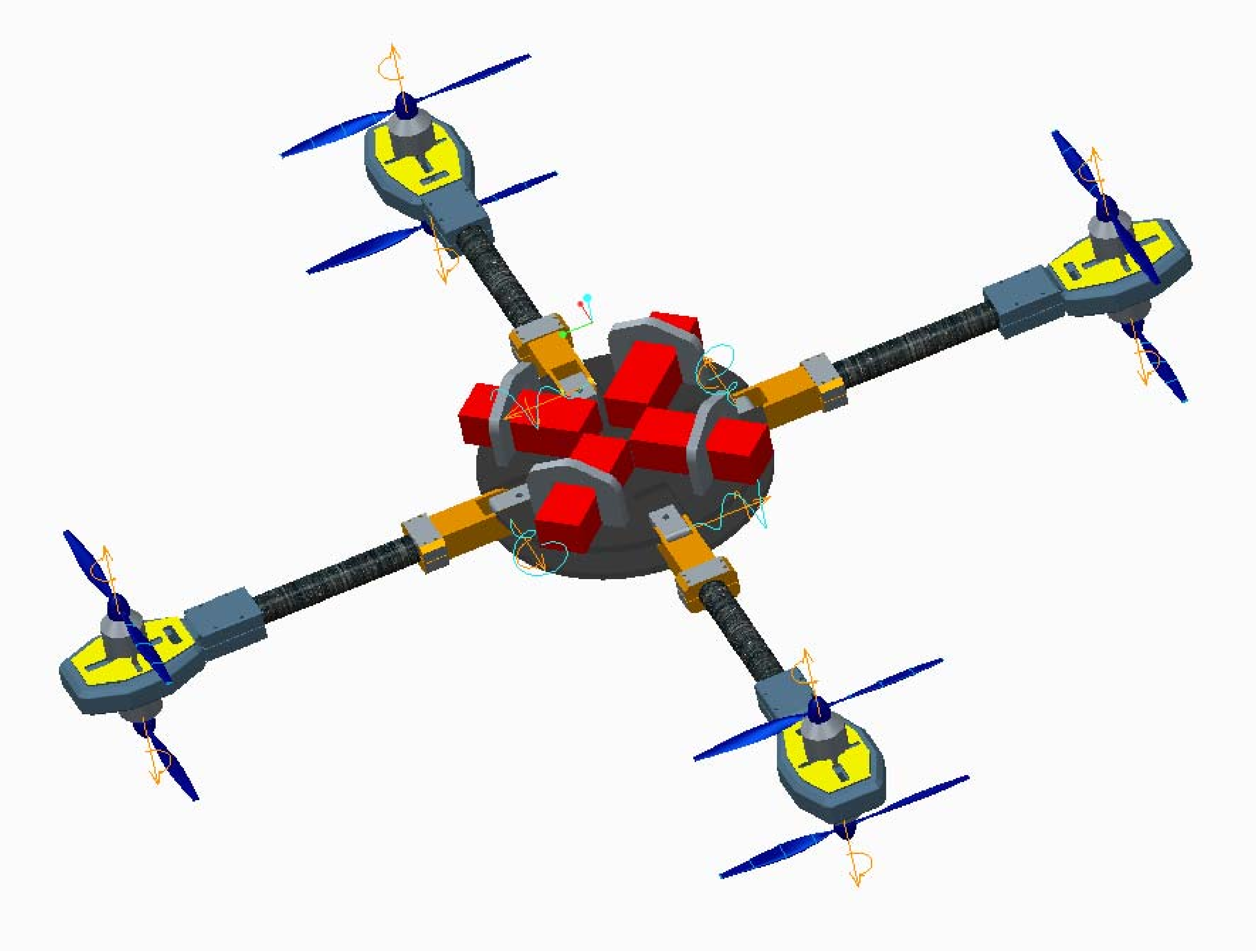
Design and Manufacture of a Rotorcraft

Analyze Phase Report



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Abstract

This paper represents an overview of the third of five phases in this project. This phase is known as the Analyze phase, in which both the current progress of the project and the upcoming calculations and steps that need to be taken to complete the project are analyzed. This report will also review the previous progress made by the team in the Define and Measure phases.

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.

With the final design of the rotorcraft selected in the Measure phase, software was utilized to analyze key components of the design. The Siemens Jack software was utilized in an ergonomic analysis to ensure no fatigue for a soldier while removing the rotorcraft from the backpack, eCalc was utilized to ensure part compatibility and rotorcraft performance, and Creo Parametric 2.0 allowed the team to design the craft to fit into the backpack and perform a stress analysis on the body of the craft.

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

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

Major design considerations and potential problems include the rotor number and configuration, the raw materials, folding/transport ability, and specifications of the electrical controls that will influence the overall performance of the device. In order to be useful to the Air Force, the sponsoring organization for this project, the vehicle must meet several requirements. More information on these requirements can be on Section 3. The most common application for these needs would likely be delivering explosive devices to enemy territory.

This report presents an overview of the Define and Measure reports and an in-depth examination of the work the team accomplished during the Analyze phase. The Jack Siemens software was utilized in this phase to simulate a soldier carrying and preparing the rotorcraft for deployment, calculate the time it takes to perform the task, and make sure the soldier will not suffer any physical strain when performing the task. The eCalc tool implemented on the Measure phase was implemented again to find out an optimal solution and compatibility between mechanical and electrical components. Also, Creo parametric 2.0 was employed to perform stress analyses on the rotorcraft design and simulate how it would fit on the backpack. Finally, an electrical hardware analysis was performed to find out the power required to operate the rotorcraft.

2. Project Charter

2.1 Overview

2.1.1 Background and History

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

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

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

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

As seen in Figure 1, a quad rotor uses four rotor blades [3]. A quad rotor is a useful example to show how these rotorcrafts perform because of its simplicity. Ω_2 and Ω_4 rotate in the clockwise direction, while Ω_3 and Ω_4 rotate in the counter-clockwise direction. This allows the rotorcraft to fly because it creates a balance for the drag created by each spinning rotor pair. Additionally, varying the number of rotations per minute for each rotor blade individually allows the user to control the lift and torque forces.

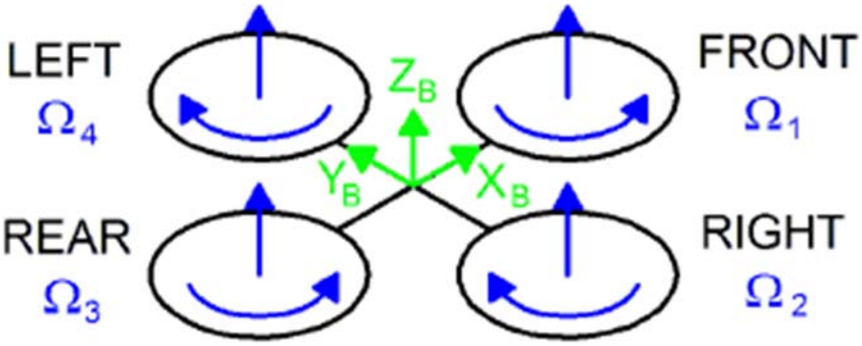


Figure 1. Quad rotor [3]

2.1.2 Objectives and Expected Benefits

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

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

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

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

2.1.3 Business Case

Current rotorcrafts on the market prioritize either payload capacity or rotorcraft size. However, there are applications where both payload capacity and minimization of rotorcraft size are desired, such as equipment delivery in the military or perhaps more martial and violent deliveries. 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 will initiate a market for rotorcraft that carries large loads while being small.

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

Weaknesses lie in 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. • Our advisors and resources (primarily Dr. Okoli, Dr. Dickens, Margaret, Emily, and Cameron) are reliable in their communication and availability to the team.	• It is more difficult to maintain order in a group of 8 students, which is one of the largest groups this year. • Finding published literature for rotorcraft carrying high payloads at a small size is difficult, as normally researchers and hobbyists prioritize one over the other. This leads to a higher need for synthesis of several vehicles instead of one or two that suit our needs. • Enforcement of internal deadlines is difficult with eight members, but it is not impossible.
OPPORTUNITIES	**THREATS**
• War or other military action in areas known for volatile terrain might lead to a spike in demand for unmanned aerial vehicles instead of unmanned terrain vehicles.	• Another military body or another funded group also developing a rotorcraft similar to the one described in this report might devalue the results of our project.

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

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

Table 2. SIPOC Analysis Chart

Suppliers	Input	Process	Output	Customers
College of Engineering departments (Industrial and Manufacturing, Electrical and Computer, and Mechanical)	Group member's knowledge and training in design and manufacturing	Design a rotorcraft that meets the customer's requirements and the manufacturing processes required to create the rotorcraft	A rotorcraft that can fit in a military backpack (23x14.5x15), can carry a payload of at least 30 pounds, is made with commercial off the shelf components, has a range of approximately 1 mile, and is easy to maintain and use in the field, along with the manufacturing processes and data required to produce this rotorcraft.	The Department of Industrial and Manufacturing Engineering at FAMU/FSU
Online retailers	Rotorcraft components: rotors, propellers, battery, IMU sensors, microcontroller, RC transmitter	Build a prototype rotorcraft		Military bodies
HPMI	Materials for the frame for the rotorcraft			

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

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 also are the contact between the team and the sponsor.

The team aims to work together in creating a positive, productive, and professional learning environment. This environment is established through mutual trust and respect, integrity and ethics, and open communication among all members. The team aims to work together in a timely yet careful manner to ensure that the project is completed properly and on time. Figure 2 illustrates the roles delegated to each team member for the Analyze phase and to whom each team member reports.

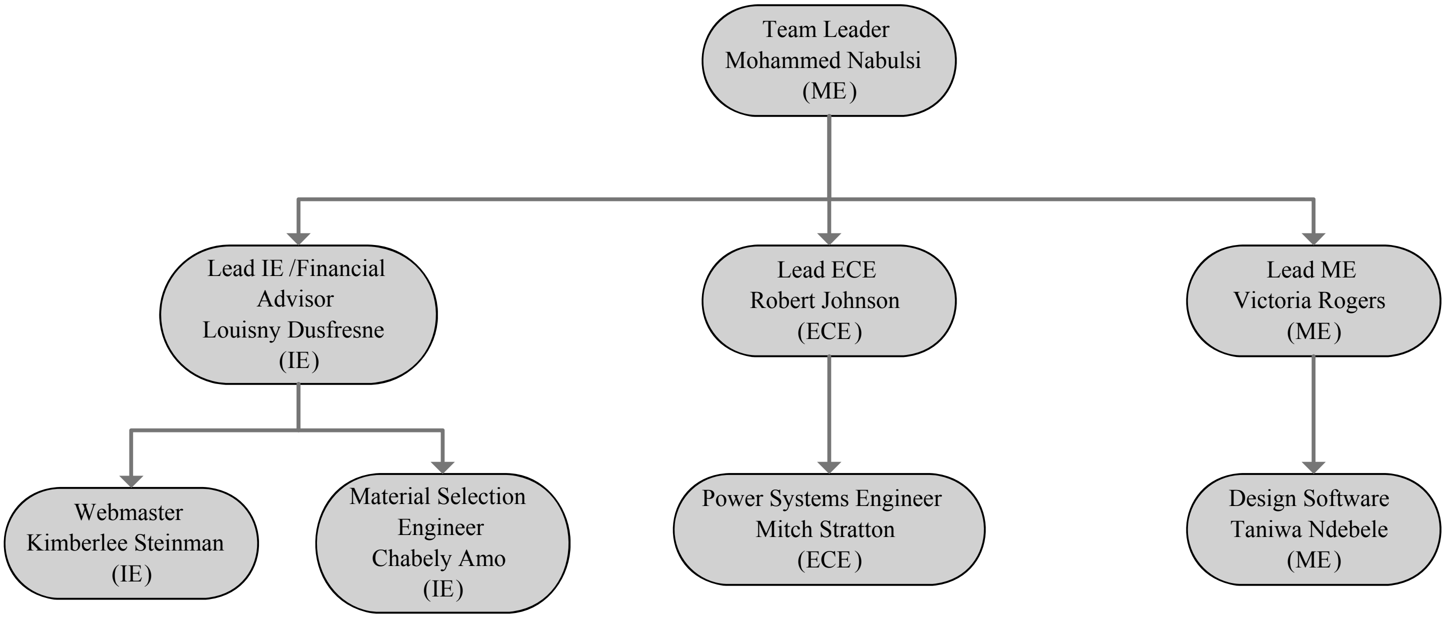


Figure 2. Organizational Chart of Team

- The Analyze phase Team Leader is responsible for setting reasonable goals and managing project completion. The Team Leader assures that workload is distributed evenly between the team members. The Team Leader also sets meeting agendas and keeps the communication flowing between team members, faculty members, and the sponsor.
- The Mechanical Engineering Lead is responsible for managing mechanical engineering members of team and scheduling meetings with the mechanical engineering advisor. The Mechanical Engineering Lead maintains constant contact with the Electrical and Computer Engineering Lead to ensure compatibility between mechanical and electrical components of the project and is in charge of maintaining the documents created by the Software Designer.

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

2.2 Approach

2.2.1 Scope

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

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

Table 3. Design Comparisons

Design	Lift Payload of 50 lbs.	Fit in the Military Backpack	Estimated Weight (Lbs.)	Cost ($)
Design #1	No	Yes	32	3841
Design #2	Yes	No	47	7451
Design #3	Conditionally	Yes	38	2630

In this Analyze phase, the team concentrated on performing an ergonomic analysis to prove the rotorcraft's weight and size is safe for the soldier to carry, implementing the eCalc tool to yield a deeper analysis on the design chosen, performing simulations to ensure the rotorcraft fits on the military backpack, and executing power analyses. Further, to accomplish objectives three and four, the milestones assigned to the Design and Verify phases are defined below in section 2.2.4.

2.2.2 Assumptions & Constraints

Along the execution of this project the team have made some assumptions that cannot be proven by the team members but are useful for the design of the same. These assumptions are the following:

- Mechanical Assumptions:
    1. The outside wind velocity will not cause the rotorcraft to exceed its maximum tilt
    2. The eCalc utilized in component selection is accurate within 10% as guaranteed on the website
    3. The stress analysis done is Creo Parametric 2.0 is accurate and no permanent deformation of the craft will occur under a load up to fifty pounds
    4. The net torque of the craft under steady state equilibrium conditions is equal to zero
    5. The carbon fiber composite created by the team has the same properties as found online
- Electrical Assumptions
    1. The microcontroller and sensor will be adequately protected from the weather by being inside the baseplates
    2. The wires and connections will stay intact while the craft is being moved in the backpack as well as in flight.
    3. The batteries do not have to be removed or recharged after use
    4. The batteries will discharge at full capacity the entire flight time
    5. The current will remain constant through the entire flight time
    6. All soldering will remain in usable condition throughout the entire usage of the rotorcraft
- Quality Control Assumptions:
    1. The quality control standards that each vendor utilizes are adequate and thus every component ordered for this project meets the requirements for the project
    2. Each motor is manufactured to be identical
    3. No inspection of purchased parts beyond rudimentary visual inspection is required by the team

4. Parts manufactured by the project team (that is, the discs of the frame and the cut arms) are created without defects.

- Testing Assumptions:
    1. The weight of the payload used in testing is accurately known and within the project parameters.
- Ergonomic Assumptions:
    1. The ergonomic software Jack generates accurate and reliable results
    2. The ground on which the user is working is relatively stable and flat
    3. The user does not travel very far when placing the rotorcraft on the ground
    4. The rotorcraft is symmetrical and thus the orientation of the rotorcraft does not matter as long as it is placed upright on the ground (that is, with the folded arms pointed up).
    5. The soldier user is in a group or squad of two or more soldiers total and is not responsible for carrying ammunition or weaponry other than the rotorcraft

2.2.3 Deliverables

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

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

2.2.4 Milestones and Schedule

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

- **Analyze phase:**
    - Industrial Engineers:

        - Perform ergonomic simulation using Siemens Jack software to ensure the safe operation of the rotorcraft and identify any region of the soldier's body that might get affected when operating the rotorcraft

    - Mechanical Engineers:
        - Analyze component characteristics using the e-calc 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:**
        - Protocol for the operation of the rotorcraft
        - Build the rotorcraft and provide assembly instructions
- **Verify Phase:**
        - Compare actual apparatus performance with simulations performed in previous phases
- **Business Plan:**
        - Finalize the project and establish a business case.

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

The full Gantt chart for the spring semester, including the Analyze, Design, and Verify phases, can be found in Appendix A. As the report submission for the Measure phase, the part orders had nor been completed. In this phase, the orders have been placed and the team is waiting for all the parts to arrive. As of now, the plan is to assemble the rotorcraft by the end of the design phase. The milestones mentioned above are due at the end of the phase they are listed under – that's is, Analyze phase deliverables are to be completed by the end of the Analyze phase, Design phase milestones are to be completed by the end of the Design phase, and so on.

2.2.5 Budget

The budget provided by the sponsor for this project is $2,500. After doing research on the components necessary for this project, two bills of materials were compiled and can be seen in Tables 4 and 5. Table 4 shows the components that were ordered by the department of Industrial and Manufacturing Engineering and Table 5 shows all the components required to build the rotorcraft. The team compiled two different bills of materials because some components, such as the materials required to perform the vacuum assisted resin transfer process (VARTM) and the batteries, will be provided by sources outside the Department of Industrial and Manufacturing Engineering. The materials required to perform the VARTM process (release fabric, flow medium, vacuum bag, mastic sealant, plumbing system, pump, and curing agent), will be provided by the High Performance Materials Institute (HPMI). Because the batteries required for the efficient maneuverability of the rotorcraft exceed the budget stated, the team spoke to the Department of Mechanical Engineering and the Department of Electrical and Computer Engineering. These departments were asked to sponsor the four batteries required. Each department agreed to purchase two batteries, resulting on a total cost of $1539 for the four batteries that is not accounted for in the costs of this project to the Department of Industrial and Manufacturing Engineering.

Even though some components will be sponsored by other entities, the bill of material shown in Table 4 exceeds the stated budget by $100. After justifying the team's proposal for using design #3 on the measure phase, the sponsor agreed to extend the budget to cover this overage. Thus, the total cost that will be sponsored by the department of Industrial and Manufacturing Engineering to build the rotorcraft is $2,600. However, the total cost for building the rotorcraft without donated components will be $4,396.

Table 4. Department of Industrial and Manufacturing Engineering Bill of Material

Part Name	Quantity	Unit Cost	Cost
RimFire 1.60	8	$179.99	$1,439
eRC 85A Brushless Programmable Opto ESC	8	$59.99	$479
19x12 APC Electric Prop	8	$13.20	$128
Arduino Leonardo ATmega32u4 with headers	1	$24.95	$24
With 2:1 Ratio Slow Epoxy Hardener (32 oz.)	1	$41.95	$41
PVA Release Film (1 Gal)	1	$24.75	$24
High-Strength Carbon Fiber Tube, 1.313" OD, 1.188" ID, .063" Wall Thick (6ft)	2	$230.59	$461
		Total Cost	$2,600

Table 5. Rotorcraft Bill of Material

Part Name	Quantity	Unit Cost	Cost
RimFire 1.60	8	$179.99	$1,439
eRC 85A Brushless Programmable Opto ESC	8	$59.99	$479
5000mAh 9-Cell/9S 33.3V G8 Performance Pro 45C LiPo,	4	$384.99	$1,539
19x12 APC Electric Prop	8	$13.20	$12
Arduino Leonardo ATmega32u4 with headers	1	$24.95	$24
Adafruit 10-DOF IMU Breakout - L3GD20H + LSM303 + BMP180	1	$29.95	$29
5.7oz Twill Carbon Fiber Fabric 3k (6ft)	5	$35.50	$177
With 2:1 Ratio Slow Epoxy Hardener (32 oz.)	1	$41.95	$41
PVA Release Film (1 Gal)	1	$24.75	$24
High-Strength Carbon Fiber Tube, 1.313" OD, 1.188" ID, .063" Wall Thick (6ft)	2	$230.59	$461
Yellow Sealant Tape ½" wide; 1⁄8" thick; 25 feet per roll	1	$7.95	$7
3/8 in. x .170 in. x 25 ft. Polyethylene Tubing	1	$4.99	$4
Stretchlon 200 Bagging Film (1 yd. roll)	2	$4.95	$9
Nylon Release Peel Ply (1 yd. roll)	2	$12.95	$25

3. Defining Customer & Technical Requirements

3.1 Meeting Critical Customer Requirements

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

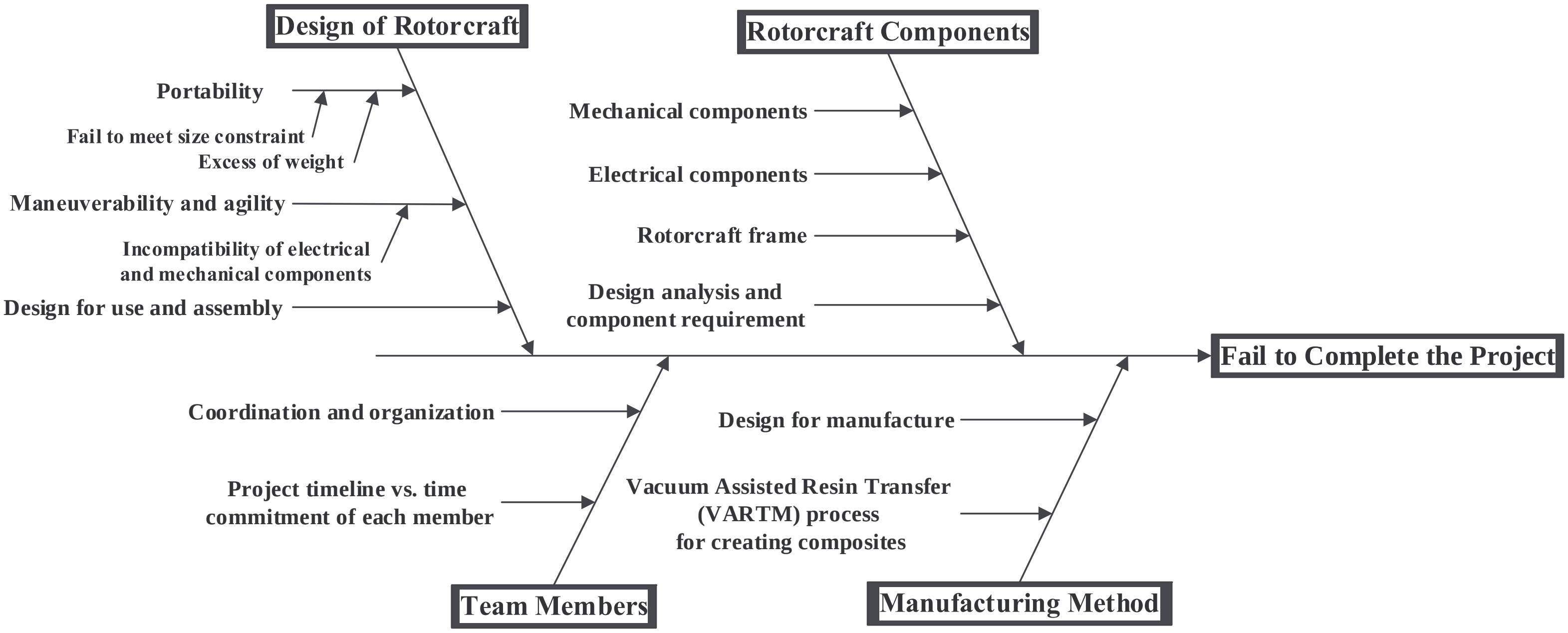


Figure 3. Fishbone Diagram

Design of rotorcraft

This category refers to problems caused within the actual design of the rotorcraft. In order to be useful to the project sponsor, the rotorcraft must be portable, meaning it has to meet the given size constraint of fitting in a military backpack and dose not exceed the appropriate weight limit for a soldier to carry. Additionally, the electrical and mechanical components must be compatible with each other to ensure the rotorcraft’s maneuverability and agility during flight. Failing to consider these aspects during the design phase will result in a failed project, as the designed rotorcraft will not meet the customer requirements.

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

Components

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

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

Team members

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

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

Manufacturing method

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

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

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

3.2 Critical Customer Requirements (CCR)

3.2.1 Voice of the Customer Tree

The Voice of the Customer tree is a diagram used to capture the customer requirements in depth. The customer requirements for the rotorcraft were determined after several discussions between the stakeholders and the team, taking into consideration the cause and effect diagram (Fishbone diagram) created by the team and shown in Section 3.1. Figure 4 illustrates the rotorcraft customer requirements and the approaches to achieve the design and manufacture of the rotorcraft. There are eight critical requirements the design of the rotorcraft must meet. These requirements are:

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

The rotorcraft must fit in a military backpack, which is 23 inches in length by 15 inches in width by 14.5 inches in height. Foldable arms will help to achieve this requirement and make it possible to fold and unfold the arms when necessary. These arms fold at a hinge located at one end of the arm. Mechanical and electrical components sizes will be taken into consideration at the components selection stage, and a simulation of the rotorcraft with all the components on it will be performed to ensure they all fit together and met the size constraint.

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

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

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

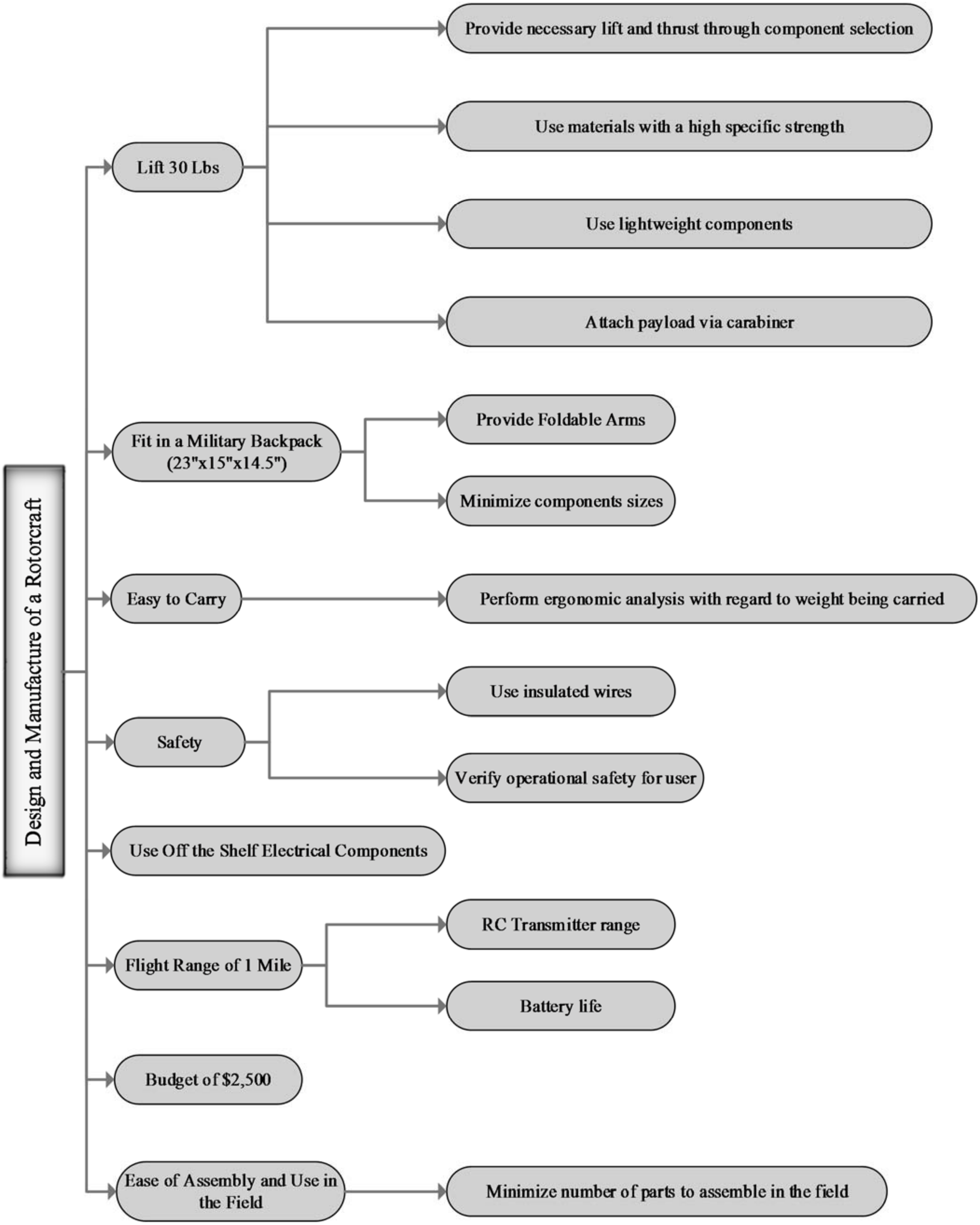


Figure 4. Voice of the Customer Tree

3.2.2 House of Quality Matrix

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

Relationship Matrix

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

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

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

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

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

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

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

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

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

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

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

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

Correlations among Technical Requirements

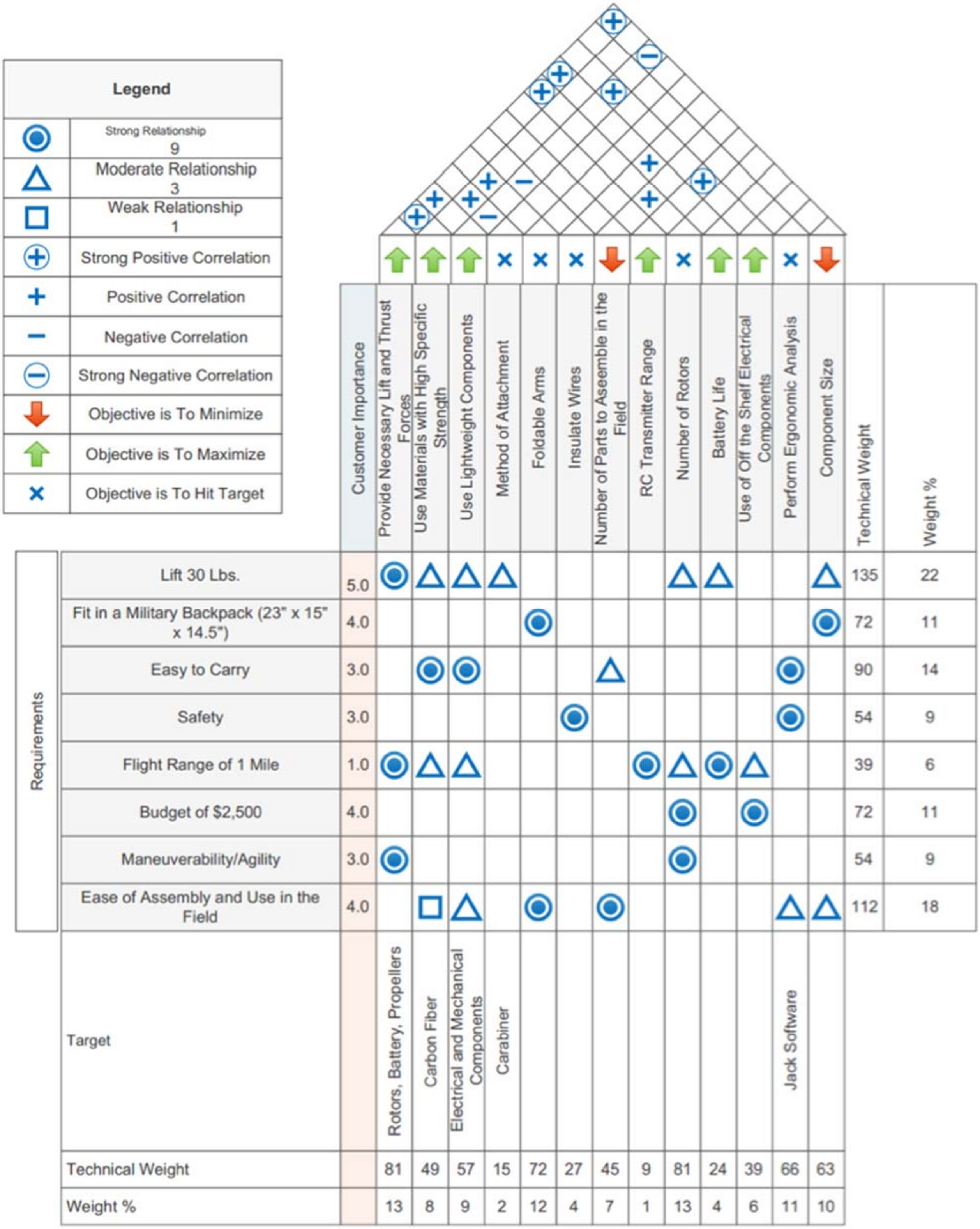
As can be seen in the roof of the House of Quality, there are twelve different correlations among the technical requirements. The reasons for these correlations are as follows, with the correlated technical requirements highlighted in bold text:

1. **Provide necessary lift and thrust forces** and **Use materials with high specific strength**: Materials with a high specific strength have a high strength relative to their weight. Using materials with a high specific strength reduces the weight of the craft without sacrificing component strength, which reduces the lift and thrust forces that must be provided.
2. **Provide necessary lift and thrust forces** and **Use lightweight components**: As in correlation 1, using lightweight components reduces the weight of the craft and thus reduces the lift and thrust forces that must be provided.
3. **Provide necessary lift and thrust forces** and **Number of rotors**: Increasing the number of rotors decreases the lift and thrust that must be provided by each rotor, and thus the number of rotors is positively correlated with the total lift and thrust forces that can be provided.
4. **Provide necessary lift and thrust forces** and **Battery life**: The power supplied by the battery and the time over which this power is supplied affects the rotorcraft's ability to provide lift and thrust forces. If the battery is dead, the rotorcraft no longer works and is no longer providing lifts and thrust forces.
5. **Provide necessary lift and thrust forces** and **Component size:** The bigger the component size the more likely it will be able to provide more lift and thrust. A big battery will have more capacity than a small one, therefore, component size and provide necessary lift and thrust forces have strong positive correlation.
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.
11. **Use lightweight components** and **Component size:** The total weight of the rotorcraft depends on the overall weight of its components. The bigger the components sizes, the less lightweight the rotorcraft is.
12. **Insulate Wires** and **Battery life**: Insulating the wires extends the battery life, as there is less loss to the environment.
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 transmitter range** and **Use of off the Shelf Electrical Components**: The RC transmitter range depends heavily on the ranges available in commercial off the shelf transmitters.

Technical Requirements Objectives and Targets

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



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 5. House of Quality

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.

4. Analyses Performed

4.1 General Design and Assembly

The configuration of the Octo-copter design is "coaxial" meaning there are two identical counter-rotating motors using the same prop on each arm. This is similar to the X8 configuration in Figure 6. With the configuration of the craft determined the ideal setup of the rotorcraft must be chosen. The setup of a rotorcraft essentially it boils down to number of booms, and single or coaxial engine mounting. The choice of frame will affect many aspects of the multi copter, 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 6 shows the radial and coaxial configuration for an Octo-copter [4]

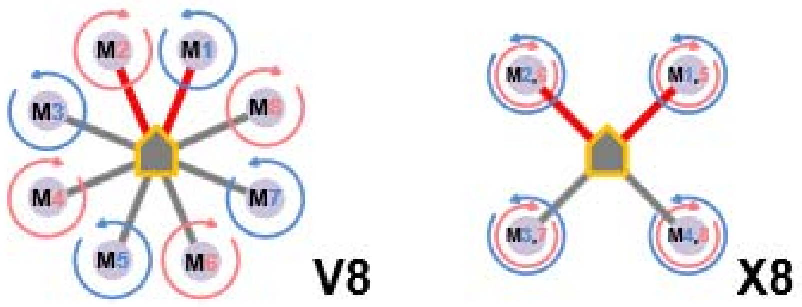


Figure 6. Multi Copter Configuration

Taking a look at the different configurations, the key component to keep in mind is the number of booms, which in most cases equals the number of motors. Coaxial versions, such as the X8 in Figure 6, have two engines mounted co-axially on the ends of each boom. One motor is on the top of the boom and the other is on the bottom, with one tractor and one pusher propeller to maintain a downwards thrust vector. The vast majority of designs will opt for non-coaxial setups, as the coaxial rotorcrafts have a few drawbacks. These drawbacks include poor efficiency and a tendency to overshoot on the yaw, in one direction. However, coaxial rotorcrafts excel in lifting power and stability. The reason for the high lifting power of the coaxial craft is that a lower number of booms results in more room for propellers and components in comparison to a non-coaxial design of the same size. Larger propellers and strong components allow for more thrust and lifting capacity. Another positive attribute of the coaxial frame is ease of transport because of the lower number of booms involved.

Due to the size constraint of the backpack, the rotorcraft will be collapsible. When the rotorcraft is not in use, the arms will be folded up and will look similar to a table that has been placed upside-down on its tabletop. 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 7. 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.

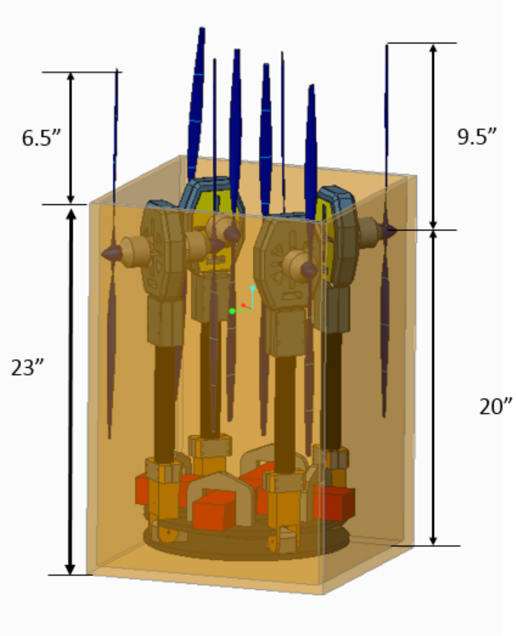


Figure 7. Rotorcraft Displayed in the Backpack

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° in relation to its functioning position so that all the components are able to fit into the backpack. If this were not the case, the shafts from the motor will be pressing and poking the side casing of the backpack. This may damage the backpack or the shafts themselves.

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

When the rotorcraft is being prepared for flight, the arms will fold out and down from a hinge joint as can be seen in Figure 8. The top plate will twist and lock in place to ensure that the arms will not pop out of position when in flight due to rough weather conditions or obstacles. The hinge will also have its own lock mechanism. The mounting motor arms will be rotated 90°

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. Analysis will be performed on this design to ensure it works safely and efficiently in the coming sections.

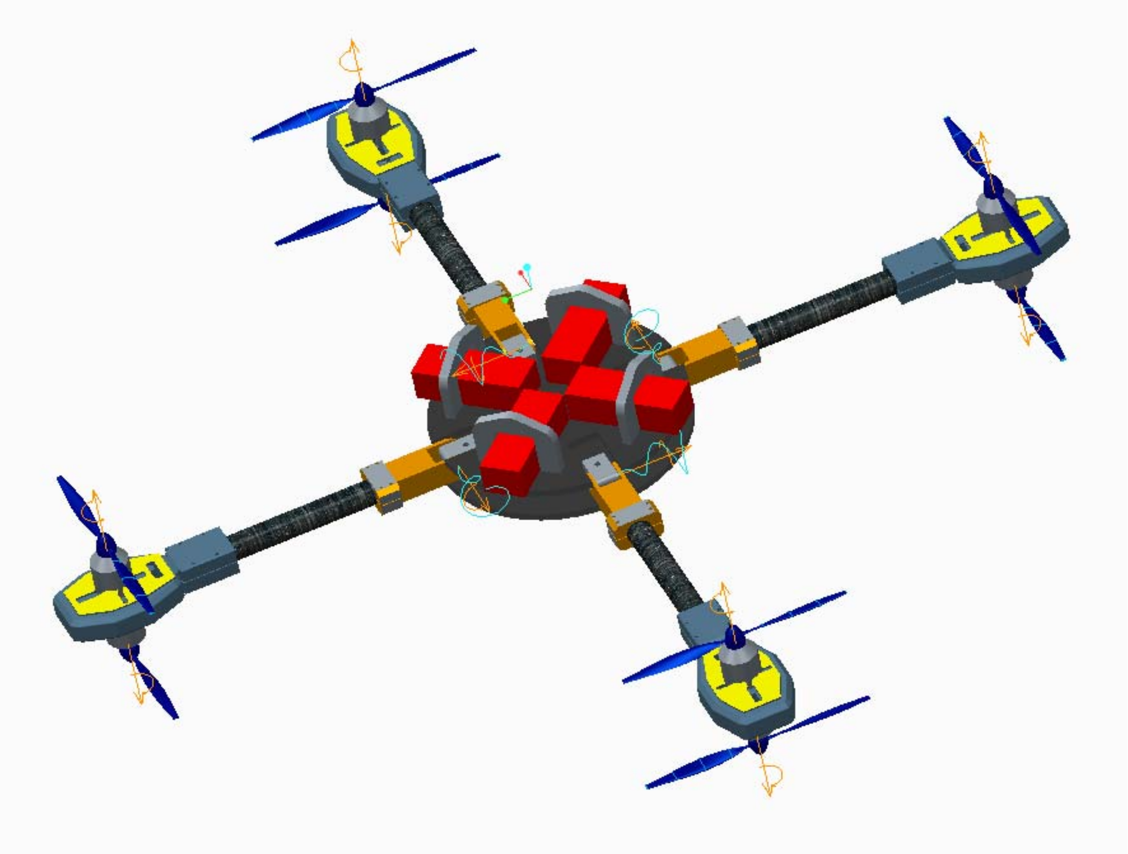


Figure 8. Rotorcraft Before Take-Off

4.2 Ergonomic Analysis

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 9. 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.

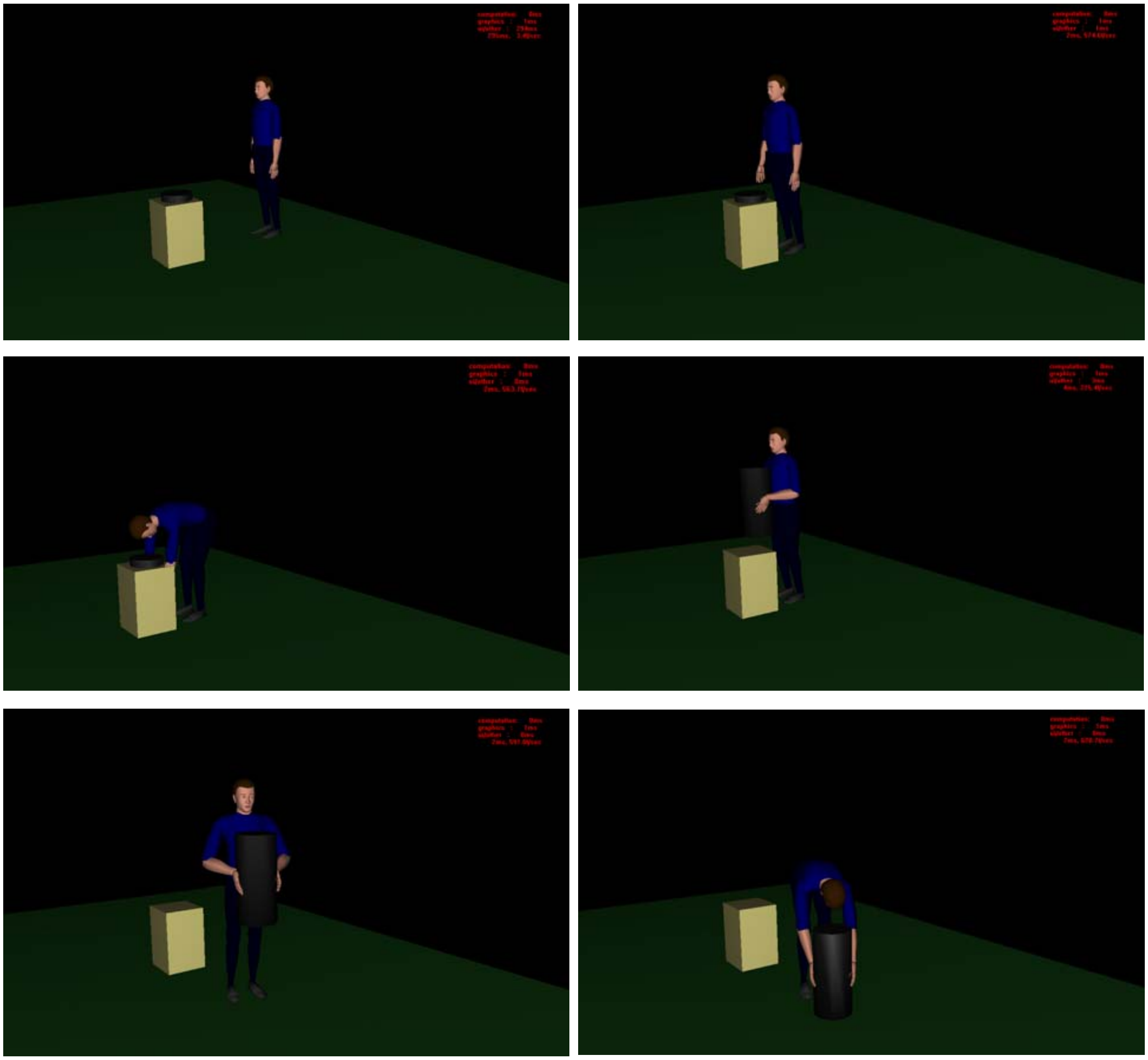


Figure 9. Screenshots of Six Key Points of the Jack Simulation

The key points of the screenshots in Figure 9 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.

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"[5].

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 [6]. 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.

4.3 Mechanical Components Analysis

In the third phase of the six-sigma process, the statistical study of a problem begins. The focal point of this phase is to identify and analyze the root causes of the problem. In order to achieve this, different methods of measuring the capability of the rotorcraft are set forth. First, the team utilized eCalc, a web-based quality service, to calculate, evaluate, and design electric motor driven systems for RC (remote controlled) models [7]. eCalc allows the team to measure expected flight time, motor efficiency, motor throttle, maximum tilt of the rotorcraft, and the maximum speed of the rotorcraft. It should be noted that eCalc analysis was performed again due to the fact that different components were chosen for the final design. The reason for the change in components is that some components, including the battery, motor, and propellers, were sold out when it was time to purchase the parts. eCalc was used to test the new components, which will be discussed in the coming paragraphs.

Figure 10 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. 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 [8]. With this in mind, the battery cells will be oriented in series to maximize the battery pack voltage and must be composed of cells with an appropriate electric charge. The battery pack must be composed of several individual cells oriented in a desired configuration to allow for easy installation and removal. The batteries which possess both a higher current capacity, electric charge, typically have higher weight and lower voltage.

General
Motor Cooling: medium
# of Rotors: 2 coax (BETA-Test)
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: 45 C cont. 225 C max
Weight: 139 g 4.9 oz

Controller
Type: max 80A
cont. Curent: 80 A
max. Curent: 80 A
Resistance: 0.0035 Ohm
Weight: 105 g 3.7 oz

Motor
Manufacturer - Type (Kv): ElectriFly RimFire 1.60² (242)
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: APC Electric E - 0°
Diameter: 19 inch
Pitch: 12 inch
Blades: 2
PConst: 1.08
Gear Ratio: 1 : 1

Remarks:

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

Battery	
Load:	28.77 C
Voltage:	30.71 V
Rated Voltage:	33.30 V
Flight Time:	2.1 min
Mixed Flight Time:	2.7 min
Hover Flight Time:	2.9 min
Weight:	1251 g 44.1 oz

Motor @ Optimum Efficiency	
Current:	44.91 A
Voltage:	31.53 V
Revolutions*:	7163 rpm
electric Power:	1415.8 W
mech. Power:	1327.1 W
Efficiency:	93.7 %

Motor @ Maximum	
Current:	71.93 A
Voltage:	30.46 V
Revolutions*:	6770 rpm
electric Power:	2190.8 W
mech. Power:	2034.9 W
Efficiency:	92.9 %
est. Temperature:	72 °C 162 °F

Motor @ Hover	
Current:	43.92 A
Voltage:	31.57 V
Throttle (linear):	81 %
electric Power:	1386.3 W
mech. Power:	1300.0 W
Efficiency:	93.8 %
est. Temperature:	51 °C 124 °F
specific Thrust:	3.28 g/W 0.12 oz/W

Total Drive	
Drive Weight:	3004 g 106 oz
Current @ Hover:	87.83 A
P(in) @ Hover:	2924.9 W
P(out) @ Hover:	2599.9 W
Efficiency @ Hover:	88.9 %
Current @ max:	143.85 A
P(in) @ max:	4790.3 W
P(out) @ max:	4069.9 W
Efficiency @ max:	85.0 %

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

Figure 10. eCalc with 50 pound payload

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, etc.…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.)

$$13.6\ kg + 22.7kg = 36.3\ kg \qquad \text{Eq. (3)}$$

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.).

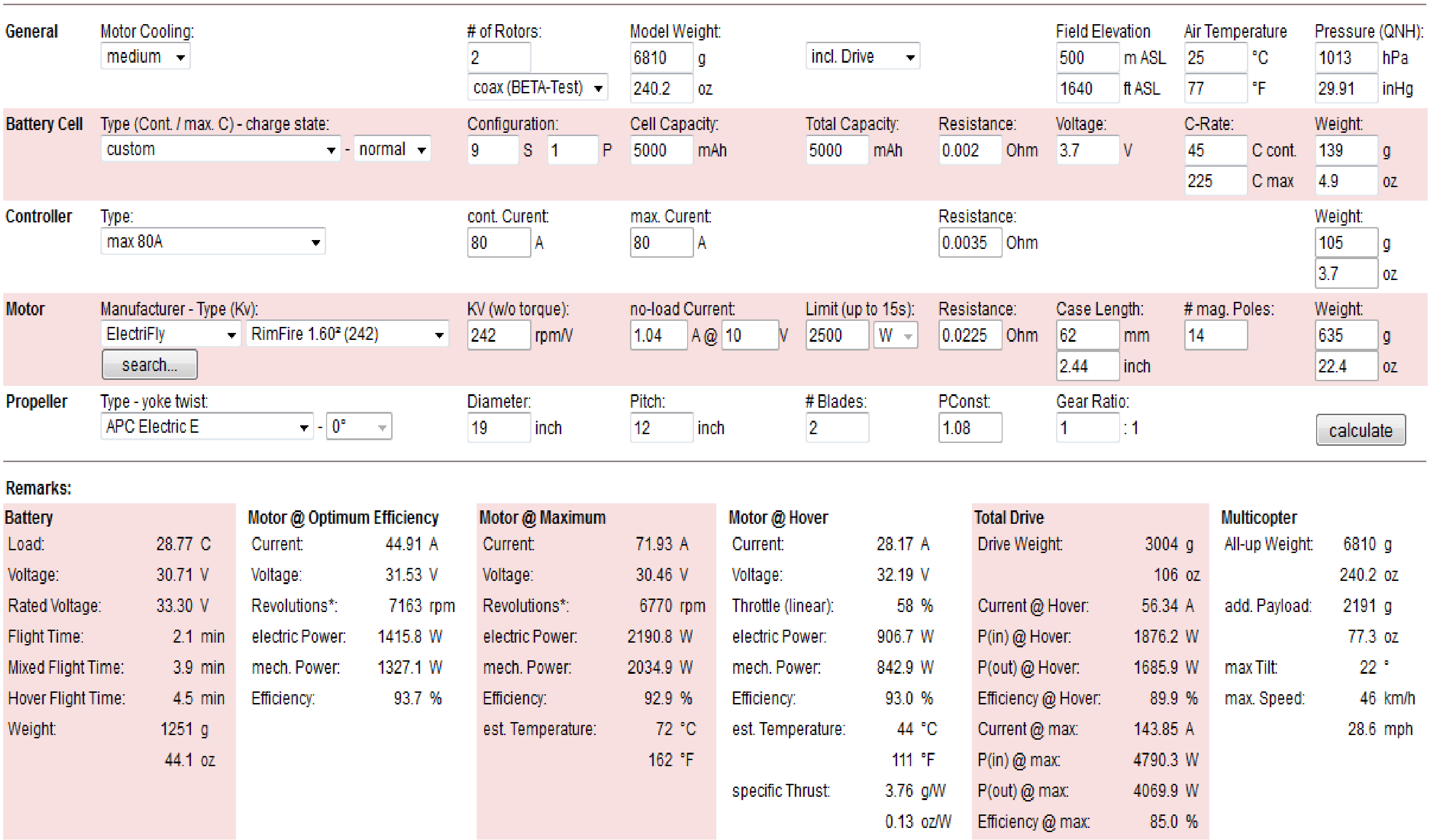
$$\frac{36.3\ kg\ (total\ weight)}{8\ rotors} = 4.54 \frac{kg}{rotor} \qquad \text{Eq. (4)}$$

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.).

$$4.54 \quad \frac{kg}{rotor} \times 2\ rotors = 9.08\ kg \qquad \text{Eq. (5)}$$

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, 100 Amp ESC controller, ElectriFly RimFire, and APC Electric 19x12 inch 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 81%.

By using these components and attempting to lift a payload of 11.3 kg (30 lbs.), much more favorable results are produced and that's why the project scope was changed as stated earlier in the report. As seen in Figure 11, the design would be able to carry this payload with a throttle of only 58%. 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 54 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 30 seconds.



General
Motor Cooling: medium
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Configuration: 9 S 1 P
Cell Capacity: 5000 mAh
Total Capacity: 5000 mAh
Resistance: 0.002 Ohm
Voltage: 3.7 V
C-Rate: 45 C cont. 225 C max
Weight: 139 g 4.9 oz

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cont. Curent: 80 A
max. Curent: 80 A
Resistance: 0.0035 Ohm
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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
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Weight: 635 g 22.4 oz

Propeller
Type - yoke twist: APC Electric E - 0°
Diameter: 19 inch
Pitch: 12 inch
Blades: 2
PConst: 1.08
Gear Ratio: 1 : 1

Remarks:

Battery	
Load:	28.77 C
Voltage:	30.71 V
Rated Voltage:	33.30 V
Flight Time:	2.1 min
Mixed Flight Time:	3.9 min
Hover Flight Time:	4.5 min
Weight:	1251 g 44.1 oz

Motor @ Optimum Efficiency	
Current:	44.91 A
Voltage:	31.53 V
Revolutions*:	7163 rpm
electric Power:	1415.8 W
mech. Power:	1327.1 W
Efficiency:	93.7 %

Motor @ Maximum	
Current:	71.93 A
Voltage:	30.46 V
Revolutions*:	6770 rpm
electric Power:	2190.8 W
mech. Power:	2034.9 W
Efficiency:	92.9 %
est. Temperature:	72 °C 162 °F

Motor @ Hover	
Current:	28.17 A
Voltage:	32.19 V
Throttle (linear):	58 %
electric Power:	906.7 W
mech. Power:	842.9 W
Efficiency:	93.0 %
est. Temperature:	44 °C 111 °F
specific Thrust:	3.76 g/W 0.13 oz/W

Total Drive	
Drive Weight:	3004 g 106 oz
Current @ Hover:	56.34 A
P(in) @ Hover:	1876.2 W
P(out) @ Hover:	1685.9 W
Efficiency @ Hover:	89.9 %
Current @ max:	143.85 A
P(in) @ max:	4790.3 W
P(out) @ max:	4069.9 W
Efficiency @ max:	85.0 %

Multicopter	
All-up Weight:	6810 g 240.2 oz
add. Payload:	2191 g 77.3 oz
max Tilt:	22 °
max. Speed:	46 km/h 28.6 mph

Figure 11. eCalc with 30 lbs. Payload

eCalc also allows the team to measure the maximum tilt and the maximum speed of the Octocopter. As can be seen in Figure 11 the maximum tilt for the final design is 22 degrees, and the maximum speed is 28.5 mph (miles per hour). 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’s best to keep each wire pair as short as possible and use the thickest wire gauge appropriate for each application.

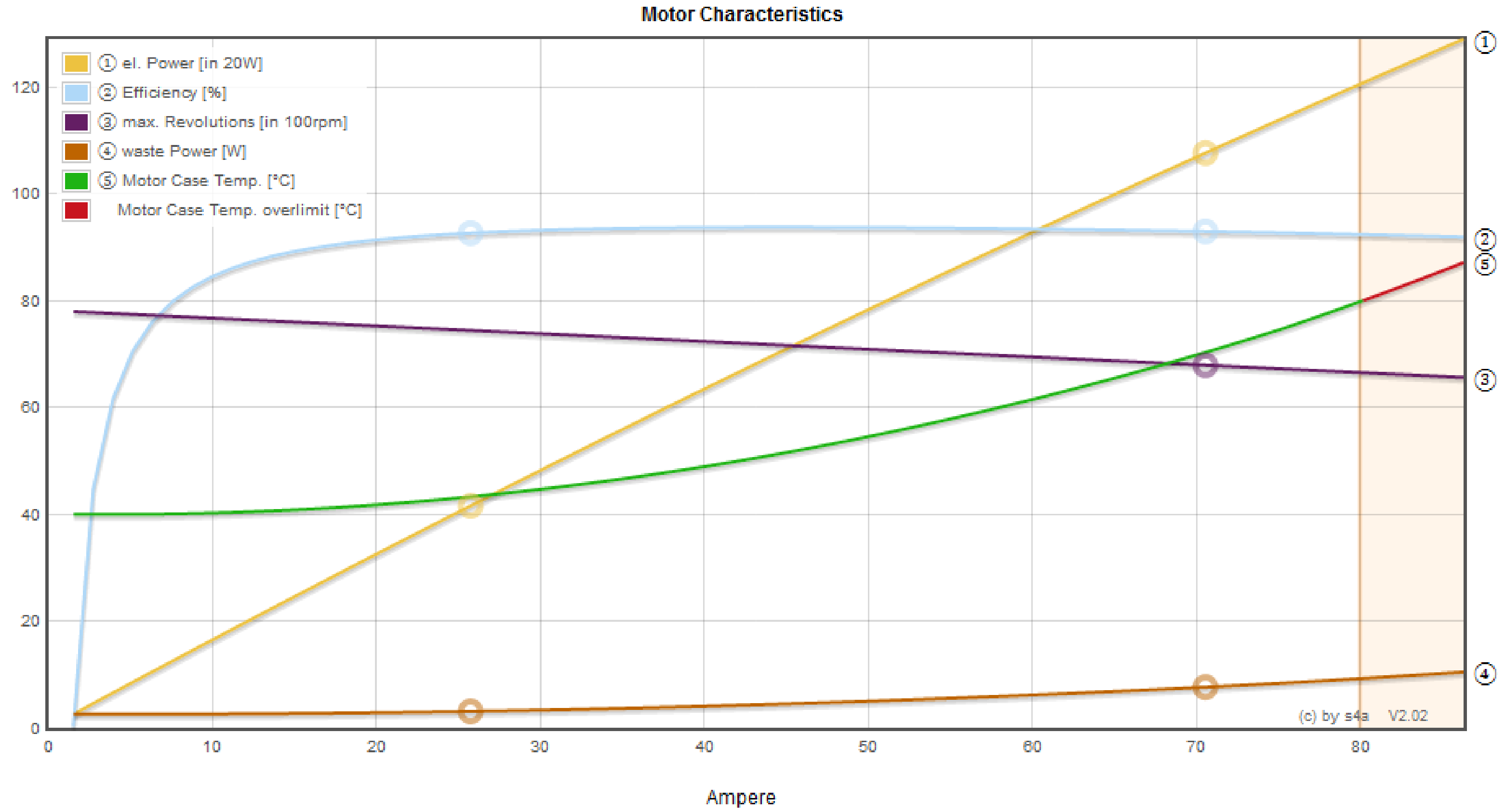

Figure 12. Motor Characteristics

Looking at the right hand side of Figure 12, 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 $78 \times 20Watts = 1560Watts$. 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. 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 [9]. 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) which plots the motor case temperature in degree Celsius. Looking at 50 Amperes, the motor case temperature is only 55℃. As can also be seen in Figure 12, the estimated motor case temperature will turn red as soon as it goes over 80℃. This is important to note because higher motor case temperature can result in permanent damage to the motor.

Through Figure 12, 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.

4.4 Stress Analysis

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 13.

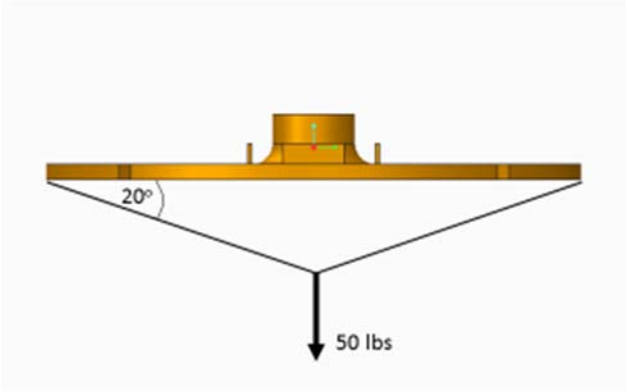

Figure 13. Payload Attachment Design

A new 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 14 from two different views.

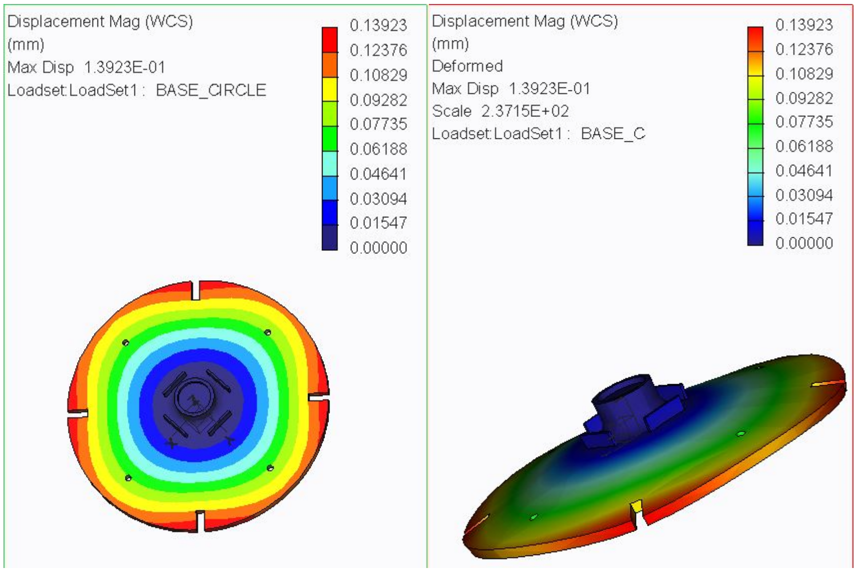

Figure 14. Baseplate Deformation Analysis

In Figure 14, 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 15 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 15, 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.

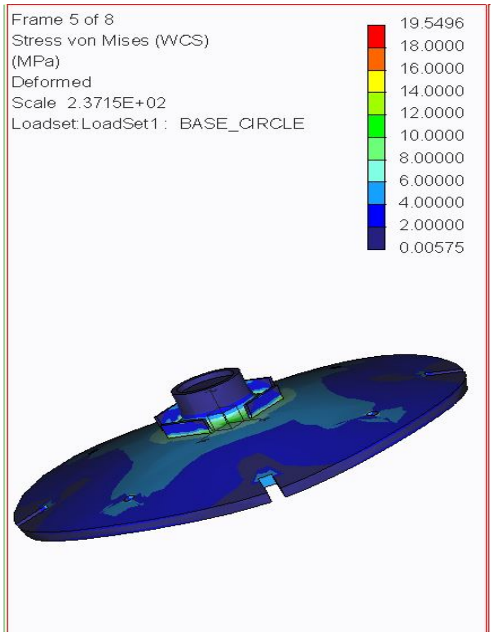

Figure 15. Baseplate Stress Von Mises Analysis

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 16 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.

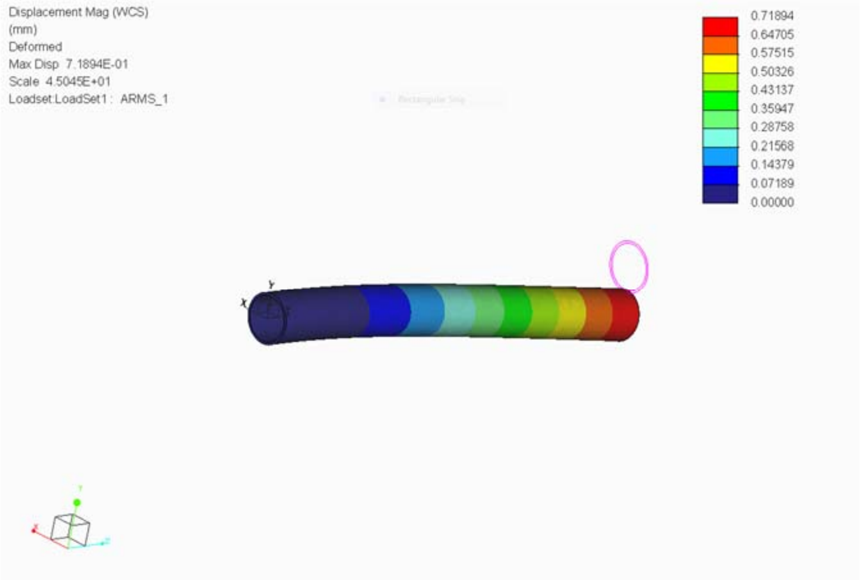

Figure 16. SideView of Creo Parametric 2.0 Stress Analysis

4.5 Electrical Hardware Analysis

The importance of the hardware analysis is ensuring that the components of the rotorcraft don’t 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 17 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.

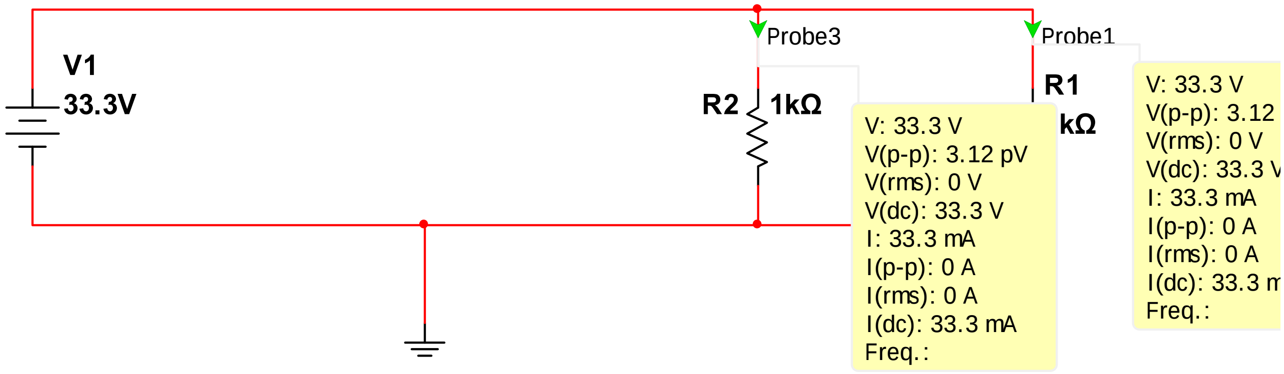

Figure 17. Power Circuit

Other electronics hardware that needs to be considered is the power of the microcontroller and the IMU sensors, which will be powered by 9V batteries. Both of these components, however, have maximum voltages of 5V. The IMU sensors have built in voltage regulators, which allows for direct connection between the battery and the sensors [10]. In order for microcontroller to be powered safely, the team can either utilize a voltage regulator or resistors in the circuit. The resistor method is also called voltage division because voltage is divided evenly between two or more resistors with this method. Using voltage division, V1 is defined as the 9V battery and V2 is defined as the output into the microprocessor. The equation for voltage division is shown in Equation 6. In order for 4.5V to be delivered to the microcontroller, R1 and R2 must be equal. This has the effect of dividing the voltage in half because Equation 6 then reduces to Equation 7. Figure 18 shows an example of the circuit that can be used.

$$V2 = \frac{V1\ x\ R2}{R1+R2} \qquad \text{Eq. (6)}$$

$$V2 = \frac{V1\ x\ R2}{2R2} \qquad \text{Eq. (7)}$$

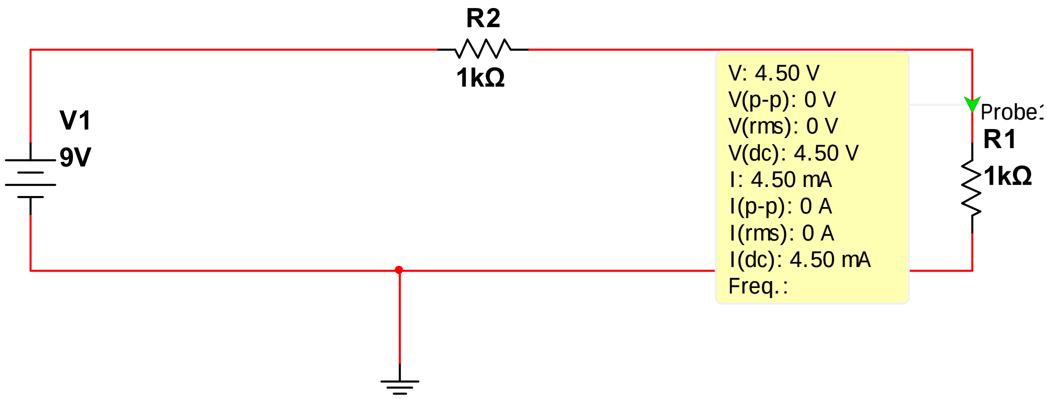

Figure 18. Circuit for Microcontroller and IMU

5. Conclusion

The objectives for this project are as follows:

1. Design a rotorcraft that can:
    - Fit in a military backpack (23x14.5x15)
    - Can carry a payload of at least 30 pounds
    - Made with COTS components (off the shelf)
    - Has a range of approximately 1 mile
    - Easy to maintain and use in the field
2. Design the manufacturing processes to be used in creating the rotorcraft described in Goal
3. Build a prototype of the rotorcraft described in Goal 1.

Within the Analyze phase, multiple software tools were utilized to analyze various parts of the overall project. In order to perform an ergonomic simulation of a soldier removing the rotorcraft from the backpack, Siemens Jack software was used. This was done to ensure that no portion of the soldier's body is negatively affected in removing the craft from the bag. The results of this analysis are that no task should cause difficulty or fatigue as the soldier is expected to be at or above the 50th percentile of the male population and no task was expected to be difficult for 82.72% of the population. Additionally the results showed that the entire task of removing the rotorcraft from the backpack is currently expected to take 8.02 seconds

Also within the Analyze phase, the eCalc tool was used to ensure rotorcraft performance and part compatibility. From eCalc the final components were selected and are as follows: Thunder 5,000 mAh (mille Ampere Hour) 9S Lipo battery, ESC controller, ElectriFly RimFire, and APC Electric 19x12 inch propeller. Additionally eCalc allowed the team to measure the expected flight time, the maximum tilt, the efficiency of the motor at it maximum rating, the efficiency of the motor at hover, the wasted power in the motor, and the motor case temperature. These results help to ensure that the parts for the rotorcraft will all be compatible and help the team better understand how the rotorcraft will behave, before it is constructed.

The final software utilized in this phase was Creo Parametric 2.0. Creo Parametric 2.0 was used to design the rotorcraft and ensure that the craft could fit into the backpack. Additionally a stress analysis was performed in Creo Parametric 2.0 to ensure that the baseplate and arms of the craft would not deform under the 30 lbs. load. The results for this simulation confirmed that under the load neither the arms nor baseplate would experience any permanent deformation.

Though no software was utilized, a power analysis was performed. The importance of this analysis is ensuring that the components of the rotorcraft do not overheat or burn out. The analysis showed that the propellers, battery, and motors are all compatible from an electrical standpoint, verifying eCalc's results. Additionally, both the microcontroller and the IMU sensors should not have issues with burning out so long as resistors are used to allow for voltage division for the microcontroller.

The next step for this project is to continue calling vendors to ensure that all the ordered components are delivered as soon as possible. In the next design phase the protocol for the operation of the rotorcraft will be determined and the rotorcraft will be built.

6. References

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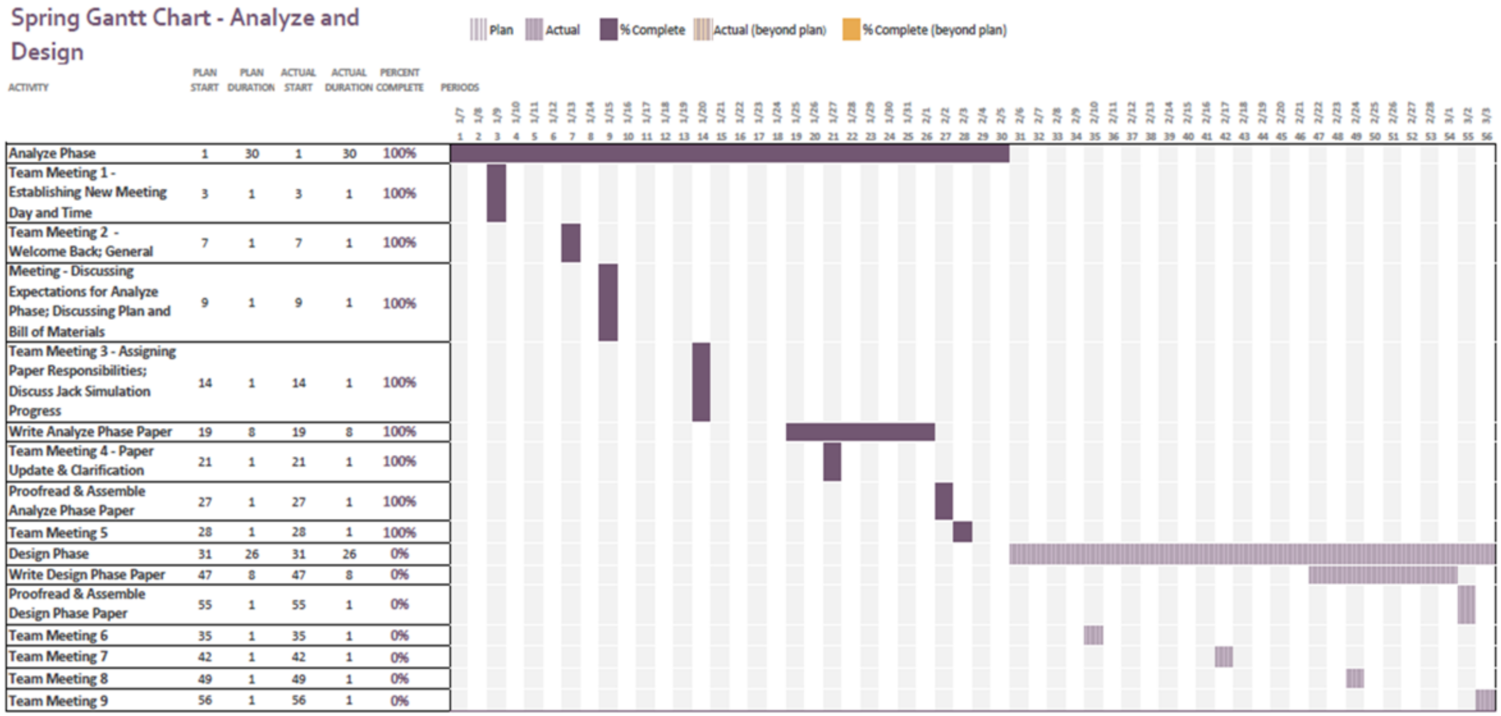
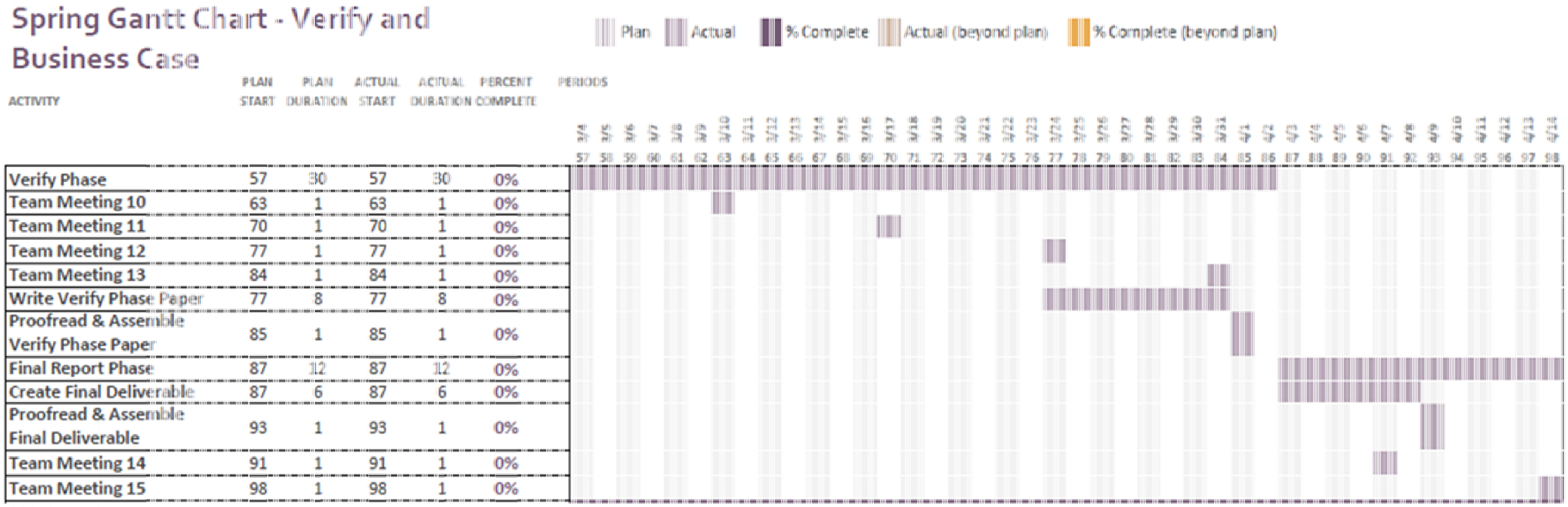
Appendix A – Gantt chart for Spring Semester



Spring Gantt Chart - Analyze and Design

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Analyze Phase	1	30	1	30	100%
Team Meeting 1 - Establishing New Meeting Day and Time	3	1	3	1	100%
Team Meeting 2 - Welcome Back; General	7	1	7	1	100%
Meeting - Discussing Expectations for Analyze Phase; Discussing Plan and Bill of Materials	9	1	9	1	100%
Team Meeting 3 - Assigning Paper Responsibilities; Discuss Jack Simulation Progress	14	1	14	1	100%
Write Analyze Phase Paper	19	8	19	8	100%
Team Meeting 4 - Paper Update & Clarification	21	1	21	1	100%
Proofread & Assemble Analyze Phase Paper	27	1	27	1	100%
Team Meeting 5	28	1	28	1	100%
Design Phase	31	26	31	26	0%
Write Design Phase Paper	47	8	47	8	0%
Proofread & Assemble Design Phase Paper	55	1	55	1	0%
Team Meeting 6	35	1	35	1	0%
Team Meeting 7	42	1	42	1	0%
Team Meeting 8	49	1	49	1	0%
Team Meeting 9	56	1	56	1	0%



Spring Gantt Chart - Verify and Business Case

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Verify Phase	57	30	57	30	0%
Team Meeting 10	63	1	63	1	0%
Team Meeting 11	70	1	70	1	0%
Team Meeting 12	77	1	77	1	0%
Team Meeting 13	84	1	84	1	0%
Write Verify Phase Paper	77	8	77	8	0%
Proofread & Assemble Verify Phase Paper	85	1	85	1	0%
Final Report Phase	87	12	87	12	0%
Create Final Deliverable	87	6	87	6	0%
Proofread & Assemble Final Deliverable	93	1	93	1	0%
Team Meeting 14	91	1	91	1	0%
Team Meeting 15	98	1	98	1	0%

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

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
0.633	Get_hermes	Walk	550.877	33.39	3.333	Put_hermes	Arise From Bend	2316.204	760.462	6.033	Put_hermes	Bend And Reach	829.637	113.699
0.667	Get_hermes	Walk	513.235	23.636	3.367	Put_hermes	Arise From Bend	2321.946	759.617	6.067	Put_hermes	Bend And Reach	867.811	127.068
0.7	Get_hermes	Walk	483.478	16.042	3.4	Put_hermes	Arise From Bend	2329.488	757.188	6.1	Put_hermes	Bend And Reach	908.384	141.312
0.733	Get_hermes	Walk	461.349	8.462	3.433	Put_hermes	Arise From Bend	2335.494	749.627	6.133	Put_hermes	Bend And Reach	951.168	156.376
0.767	Get_hermes	Walk	415.604	-3.885	3.467	Put_hermes	Arise From Bend	2325.57	734.007	6.167	Put_hermes	Bend And Reach	995.955	172.202
0.8	Get_hermes	Walk	421.38	4.074	3.5	Put_hermes	Arise From Bend	2299.127	714.505	6.2	Put_hermes	Bend And Reach	1042.535	188.727
0.833	Get_hermes	Walk	417.585	3.54	3.533	Put_hermes	Arise From Bend	2256.72	691.238	6.233	Put_hermes	Bend And Reach	1090.679	205.889
0.867	Get_hermes	Walk	426.595	1.713	3.567	Put_hermes	Arise From Bend	2198.076	664.188	6.267	Put_hermes	Bend And Reach	1140.149	223.618
0.9	Get_hermes	Walk	464.537	10.168	3.6	Put_hermes	Arise From Bend	2105.27	624.05	6.3	Put_hermes	Bend And Reach	1195.233	242.605
0.933	Get_hermes	Walk	489.426	16.185	3.633	Put_hermes	Arise From Bend	1981.01	567.518	6.333	Put_hermes	Bend And Reach	1251.078	262.022
0.967	Get_hermes	Walk	489.484	16.195	3.667	Put_hermes	Arise From Bend	1765.061	492.623	6.367	Put_hermes	Bend And Reach	1307.683	281.818
1	Get_hermes	Walk	492.08	17.052	3.7	Put_hermes	Arise From	1579.827	421.166	6.4	Put_hermes	Bend And	1364.758	301.913

							Bend					Reach		
1.033	Get_hermes	Bend And Reach	499.76	19.587	3.733	Put_hermes	Arise From Bend	1388.453	347.27	6.433	Put_hermes	Bend And Reach	1422.028	322.229
1.067	Get_hermes	Bend And Reach	512.342	23.741	3.767	Put_hermes	Arise From Bend	1210.368	280.76	6.467	Put_hermes	Bend And Reach	1479.203	342.683
1.1	Get_hermes	Bend And Reach	529.651	29.46	3.8	Put_hermes	Arise From Bend	1117.71	248.492	6.5	Put_hermes	Bend And Reach	1536.001	363.195
1.133	Get_hermes	Bend And Reach	551.506	36.687	3.833	Put_hermes	Arise From Bend	1026.197	216.376	6.533	Put_hermes	Bend And Reach	1592.152	383.685
1.167	Get_hermes	Bend And Reach	577.722	45.365	3.867	Put_hermes	Arise From Bend	963.795	192.809	6.567	Put_hermes	Bend And Reach	1649.059	404.349
1.2	Get_hermes	Bend And Reach	608.103	55.436	3.9	Put_hermes	Arise From Bend	910.004	170.73	6.6	Put_hermes	Bend And Reach	1703.091	424.556
1.233	Get_hermes	Bend And Reach	642.45	66.841	3.933	Put_hermes	Arise From Bend	865.724	152.316	6.633	Put_hermes	Bend And Reach	1757.246	444.761
1.267	Get_hermes	Bend And Reach	680.482	79.503	3.967	Put_hermes	Arise From Bend	867.021	152.546	6.667	Put_hermes	Bend And Reach	1809.652	464.625
1.3	Get_hermes	Bend And Reach	722.202	93.401	4	Put_hermes	Arise From Bend	867.574	152.644	6.7	Put_hermes	Bend And Reach	1860.113	484.086
1.333	Get_hermes	Bend And Reach	767.159	108.428	4.033	Put_hermes	Arise From Bend	867.914	152.704	6.733	Put_hermes	Bend And Reach	1908.454	503.085
1.367	Get_hermes	Bend And Reach	815.179	124.526	4.067	Put_hermes	Arise From Bend	868.195	152.754	6.767	Put_hermes	Bend And Reach	1954.52	521.57
1.4	Get_hermes	Bend And Reach	866.01	141.623	4.1	Put_hermes	Arise From Bend	868.459	152.801	6.8	Put_hermes	Bend And Reach	1999.312	539.668
1.433	Get_hermes	Bend And Reach	919.381	159.644	4.133	Put_hermes	Arise From Bend	868.719	152.847	6.833	Put_hermes	Bend And Reach	2041.451	557.141
1.467	Get_hermes	Bend And Reach	975.009	178.507	4.167	Put_hermes	Arise From Bend	868.977	152.893	6.867	Put_hermes	Bend And Reach	2080.868	573.96
1.5	Get_hermes	Bend And Reach	1032.592	198.128	4.2	Put_hermes	Arise From Bend	869.235	152.939	6.9	Put_hermes	Bend And Reach	2113.34	589.482
1.533	Get_hermes	Bend And Reach	1091.82	218.422	4.233	Put_hermes	Arise From Bend	869.492	152.985	6.933	Put_hermes	Bend And Reach	2142.419	604.135
1.567	Get_hermes	Bend And Reach	1152.372	239.296	4.267	Put_hermes	Arise From Bend	707.014	56.417	6.967	Put_hermes	Bend And Reach	2168.676	618.042
1.6	Get_hermes	Bend And Reach	1218.566	261.447	4.3	Put_hermes	Arise From Bend	671.71	56.671	7	Put_hermes	Bend And Reach	2192.115	631.186
1.633	Get_hermes	Bend And Reach	1285.439	284.005	4.333	Put_hermes	Walk	665.214	55.309	7.033	Put_hermes	Bend And Reach	2212.773	643.557
1.667	Get_hermes	Bend And Reach	1352.884	306.9	4.367	Put_hermes	Walk	665.244	55.7	7.067	Put_hermes	Bend And Reach	2229.484	654.953
1.7	Get_hermes	Bend And Reach	1420.505	330.023	4.4	Put_hermes	Walk	659.951	54.103	7.1	Put_hermes	Bend And Reach	2244.733	665.763
1.733	Get_hermes	Bend And Reach	1487.911	353.264	4.433	Put_hermes	Walk	636.355	46.591	7.133	Put_hermes	Bend And Reach	2257.454	675.803
1.767	Get_hermes	Bend And Reach	1554.718	376.519	4.467	Put_hermes	Walk	615.992	39.985	7.167	Put_hermes	Bend And Reach	2267.782	685.089
1.8	Get_hermes	Bend And Reach	1620.54	399.679	4.5	Put_hermes	Walk	594.439	32.238	7.2	Put_hermes	Bend And Reach	2274.357	693.395
1.833	Get_hermes	Bend And Reach	1685.012	422.643	4.533	Put_hermes	Walk	616.351	40.771	7.233	Put_hermes	Bend And Reach	2280.294	701.218
1.867	Get_hermes	Bend And Reach	1747.776	445.307	4.567	Put_hermes	Walk	648.745	51.939	7.267	Put_hermes	Bend And Reach	2284.328	708.351
1.9	Get_hermes	Bend And Reach	1810.2	467.858	4.6	Put_hermes	Walk	665.543	56.731	7.3	Put_hermes	Bend And Reach	2284.891	714.542
1.933	Get_hermes	Bend And Reach	1868.518	489.628	4.633	Put_hermes	Walk	669.916	56.674	7.333	Put_hermes	Bend And Reach	2285.602	720.372

1.967	Get_hermes	Bend And Reach	1924.199	510.824	4.667	Put_hermes	Walk	643.716	47.483	7.367	Put_hermes	Bend And Reach	2286.597	725.842
2	Get_hermes	Bend And Reach	1976.99	531.367	4.7	Put_hermes	Walk	631.538	37.544	7.4	Put_hermes	Bend And Reach	2286.56	730.767
2.033	Get_hermes	Bend And Reach	2026.672	551.184	4.733	Put_hermes	Walk	618.75	33.418	7.433	Put_hermes	Bend And Reach	2287.269	735.412
2.067	Get_hermes	Bend And Reach	2074.451	570.438	4.767	Put_hermes	Walk	611.674	30.021	7.467	Put_hermes	Bend And Reach	2285.639	739.34
2.1	Get_hermes	Bend And Reach	2118.651	588.824	4.8	Put_hermes	Walk	616.743	29.95	7.5	Put_hermes	Bend And Reach	2285.077	743.052
2.133	Get_hermes	Bend And Reach	2157.954	606.098	4.833	Put_hermes	Walk	633.283	28.571	7.533	Put_hermes	Bend And Reach	2282.527	746.116
2.167	Get_hermes	Bend And Reach	2195.962	622.824	4.867	Put_hermes	Walk	637.99	41.521	7.567	Put_hermes	Bend And Reach	2281.317	749.019
2.2	Get_hermes	Bend And Reach	2223.759	637.536	4.9	Put_hermes	Walk	640.769	46.184	7.6	Put_hermes	Bend And Reach	2278.437	751.338
2.233	Get_hermes	Bend And Reach	2248.623	651.363	4.933	Put_hermes	Walk	653.964	51.399	7.633	Put_hermes	Bend And Reach	2275.595	753.326
2.267	Get_hermes	Bend And Reach	2269.829	664.187	4.967	Put_hermes	Walk	667.658	56.148	7.667	Put_hermes	Bend And Reach	2274.445	755.225
2.3	Get_hermes	Bend And Reach	2287.467	676.009	5	Put_hermes	Walk	662.423	54.372	7.7	Put_hermes	Bend And Reach	2272.181	756.678
2.333	Get_hermes	Bend And Reach	2303.022	687.059	5.033	Put_hermes	Walk	648.652	49.573	7.733	Put_hermes	Bend And Reach	2271.544	758.005
2.367	Get_hermes	Bend And Reach	2313.989	696.916	5.067	Put_hermes	Walk	638.885	44.949	7.767	Put_hermes	Bend And Reach	2269.962	758.917
2.4	Get_hermes	Bend And Reach	2321.859	705.817	5.1	Put_hermes	Walk	633.616	39.775	7.8	Put_hermes	Bend And Reach	2268.792	759.568
2.433	Get_hermes	Bend And Reach	2328.342	714.04	5.133	Put_hermes	Walk	623.45	30.527	7.833	Put_hermes	Bend And Reach	2267.899	759.898
2.467	Get_hermes	Bend And Reach	2330.716	721.135	5.167	Put_hermes	Walk	622.446	36.049	7.867	Put_hermes	Bend And Reach	2267.652	760.029
2.5	Get_hermes	Bend And Reach	2332.277	727.644	5.2	Put_hermes	Walk	614.099	29.987	7.9	Put_hermes	Bend And Reach	2267.694	760.036
2.533	Get_hermes	Bend And Reach	2330.165	733.1	5.233	Put_hermes	Walk	621.888	35.178	7.933	Put_hermes	Bend And Reach	2267.694	760.036
2.567	Get_hermes	Bend And Reach	2327.865	738.081	5.267	Put_hermes	Walk	627.302	36.617	7.967	Put_hermes	Bend And Reach	2267.694	760.036
2.6	Get_hermes	Bend And Reach	2322.394	742.103	5.3	Put_hermes	Walk	638.148	39.596	8	Put_hermes	Bend And Reach	2267.694	760.036
2.633	Get_hermes	Bend And Reach	2317.389	745.769	5.333	Put_hermes	Walk	640.818	45.727	8.033	Put_hermes	Release	2267.694	760.036
2.667	Get_hermes	Bend And Reach	2309.74	748.578	5.367	Put_hermes	Walk	651.749	50.756	8.067	Put_hermes	Release	2267.694	760.036