FAMU-FSU COLLEGE OF ENGINEERING

Development of a Semi-Autonomous Oil Palm Fruit Harvesting Device

IME Group 10: Control Phase

A report submitted to Dr. Okenwa Okoli
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This report is the fifth of five progress reports. It defines the opportunities and constraints of this project, following the Six Sigma methodology of “Define, Measure, Analyze, Improve, Control” (DMAIC). The team’s approach, deliverables that the team will provide at the termination of the project, detailed descriptions of the customer requirements and previous design concepts, an analysis of the team’s selected design, the optimization of the selected design, and a description of the completed prototype are provided.

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Abstract

In this report, the development and construction of an electromechanical system to harvest oil palm fruit are discussed. An analysis of the global oil market illustrated that approximately one third of all oils produced is made from oil palm fruit. Since oil palms yield approximately 3.7 metric tons of palm oil per planted hectare per year and are the most efficient oil-producing crop, there is a large demand for palm oil. The current oil palm fruit harvesting method consists of a worker ascending a tree that is approximately 12 meters tall, manually cutting the fruit bunch, and then descending the tree. Dr. Okenwa Okoli, Chair of the Department of Industrial and Manufacturing Engineering at the College of Engineering of Florida Agricultural and Mechanical University and Florida State University, believes that the current harvesting method is dangerous and inefficient. He has sponsored this project with the intent of replacing the current climbing process by developing a portable and simple electromechanical device that improves workers' safety and productivity. Dr. Okoli's design requirements and the timeline for the entire project are discussed extensively in this report. $2,500 was allocated for the development of the device, while a target selling price of $2,000 was established to ensure that the device can be sold in developing countries.

This report also discusses the team's selected design. The design consists of a semi-circular track that is attached to a telescoping pole. The track and pole are transported from tree to tree by pulling a cart. The telescoping poles concept was adopted and improved from the Class of 2015's design, which had portability issues. Finite element analyses were then conducted on the components of the design to determine if it could achieve design requirements. The selected design was then optimized by conducting a lifting assessment. Finally, the prototype was assembled and its performance was measured.

1. Introduction

The oil palm can easily be called the greatest oil-producing crop in the world. Capable of producing up to approximately 3.7 metric tons of palm oil annually per hectare of oil palm trees planted, it is the ideal plant to meet the global food market's demand for cooking oil [1]. It is not surprising, then, that it is responsible for 36% of all oil produced globally, while only encompassing 5% of the farm land used for oil [1]. Therefore, even a slight modification to the oil palm harvesting process could greatly increase production capacity.

Currently, the process by which oil palm fruits are harvested involves a worker ascending a tree and manually cutting each fruit bunch [2]. Since the trees are grown in developing countries whose workers are paid very low wages, this process is fairly inexpensive [3]. However, there are many disadvantages to this manual process. Laborers experience poor working conditions, such as climbing a maximum of 12 meters by wrapping their arms around the oil palm tree's trunk. These conditions result in workers being diagnosed with various musculoskeletal disorders [2]. Additionally, the process of ascending oil palms is slow and exhausting, necessitating a large work force. For example, a 2,600-hectare oil palm plantation requires 333 workers. Therefore, one worker is theoretically responsible for walking approximately 8 hectares per day. Roughly one metric ton per worker is expected to be harvested each day [4].

The project's sponsor, Dr. Okenwa Okoli, chair of the Department of Industrial and Manufacturing Engineering (IME) at the College of Engineering of Florida Agricultural and Mechanical University and Florida State University (FAMU-FSU) College of Engineering, believes that the current process for harvesting oil palm fruit can be improved. Since the multibillion dollar palm oil industry [5] depends on such an inefficient harvesting method, developing a device to improve current harvesting methods would increase oil palm fruit production capacity and result in millions of dollars of increased revenue and savings for companies involved in the industry.

The team's task is to develop an electromechanical device that can safely and easily harvest ripe oil palm fruit in a way that is less expensive and more productive than hiring a person to do it. Since this device is intended to replace the work of one person, the sponsor has specified that it must require no more than one operator. Furthermore, this electromechanical device must be able to operate in the equatorial tropical regions where oil palm trees are planted [2]. Finally, since the farmers that grow oil palm trees generally live in developing countries [1], it is essential that the selling price of the final design be low enough to make it marketable.

Two different approaches to designing a harvesting device have been attempted in past years. The Class of 2012's design involved a tree-climbing robot that would gradually climb up to the top of the tree and cut fruit [6]. However, once the prototype was built, it was too heavy to transport from tree to tree and Dr. Jonathan Clark strongly advised the project's team not to program it to climb the tree because it would endanger individuals on the ground. The project was not assigned to the Class of 2013 [7]. The Class of 2014 designed a system that utilized telescoping polyvinyl chloride (PVC) poles that were transported on a cart; the poles extended a saw upward to cut oil palm fruit bunches [8]. The Class of 2015's design replaced the PVC poles with aluminum [9]. Upon completion, the design was too heavy to be pushed through the rough terrain of an oil palm fruit plantation, too unstable to ensure the safety of the operators, and too difficult to assemble, because the poles were too long.

The approach for the development of the team's prototype design was divided into a top cutting mechanism and base support system. The top cutting mechanism involves a structure that encircles the trunk of the tree and cuts the oil palm fruit bunch while being controlled from the ground. The base support system holds the weight of the whole mechanism using a series of interconnected poles to push the cutting tool upward. However, in the Analyze Phase, it was determined that in order to make a functional poling system, the amount of material required would be too heavy to be transported by hand. Therefore, a new design was selected that uses the poling system from the Class of 2015's design and makes it more transportable, in addition to adding the team's new ring design to improve the cutting mechanism. The selected design consists of telescoping poles that are mounted to a wheelbarrow platform. The platform is moved utilizing handles extending from it.

In the Improve Phase, the team examined the selected design to determine if it could be optimized. A lifting assessment was conducted to assess whether an operator would be able to lift the prototype throughout their entire shift; the results of this analysis allowed the cart's handles to be shortened. A mounting system for the pole was then analyzed and it was found that the pole would be able to withstand typical loads during operation by using 16 ½" bolts and eight steel L-brackets. By using nuts and bolts instead of welding, the poles will be able to be modular and easily detachable for servicing. Additionally, the prototype's controller was assembled and tested. Next, the cart electronics and cutting mechanism were also assembled and tested. Finally, new batteries for the cutting mechanism were selected and purchased.

In this phase, the optimized prototype was constructed. An assembly guide was written that details how the cart and cutting mechanism should be constructed. Furthermore, detailed operating instructions were written for the prototype. Then, the prototype's functionality was shown to meet the sponsor's requirements. In this report, the requirements for developing an electromechanical oil palm fruit harvesting device are defined. First, background research of the palm oil industry and an analysis of the market potential of an oil palm fruit harvester are presented. Next, the technical requirements necessary to complete the customer's needs are determined. Furthermore, the entire project's schedule is outlined and several rudimentary design concepts are discussed. The selected design presented utilizes aspects of these design concepts. Renderings are then shown that were made using Creo Parametric software that allowed finite element analyses to be conducted. The results of these analyses of the components' displacements and stresses under internal and external loads are then presented. The electronic components for the cutter were also tested in this phase and the results are presented. Finally, the bill of materials needed for the prototype is provided. Next, the optimization of the selected design is discussed. The assembly and operating instructions for the prototype are also provided. Finally, the prototype is evaluated to determine if it meets the sponsor's specifications.

2. Project Charter

2.1 Project Overview

2.1.1 Objectives and Expected Benefits

The objective of this project is to design a mechanism and build a prototype of a device that can harvest oil palm fruit semi-autonomously by utilizing only one operator. The mechanism must be able to reach the top of the palm tree, allow the operator to determine which bunches of fruit are ripe, and cut the ripe bunches. This project prohibits the device's operator from being physically lifted to the top of the oil palm tree and cutting the oil palm fruit. However, a worker is permitted to operate the device from the ground. The detailed requirements obtained from the team's meetings with Dr. Okoli are described in Table 1.

Table 1: Project Sponsor's Requirements

Requirement	Description
1. Low Cost	The device must be able to be sold at a retail price of no more than $2,000. The device must also only require minimal maintenance to assist in minimizing the cost of ownership.
2. Portable	The device must be able to maneuver from oil palm to oil palm in rough terrain. For a freestanding design, this means the prototype must be lightweight.
3. Efficient	The device must be able to harvest oil palm fruit faster than human workers are able to harvest them. In addition, the harvesting time should be no greater than 20 minutes. Furthermore, the device is to be operated by no more than one worker.
4. Easy to Use	The device must be operable by current oil palm fruit harvesters. This means that the prototype must have simple controls that require only a short training period.
5. Durable	The device must be able to withstand tropical conditions, as well as be able to effectively traverse through rough terrain. Furthermore, the device must be able to withstand any impacts from the oil palm trees it might encounter.
6. Safe	The device must minimize the risk of injury or death to the operator or bystanders when it is being used. This means that any cutting mechanisms attached to the device must be secured physically, without the use of adhesives.
7. Environmentally Friendly	The device cannot cause any damage to the oil palm trees when it is harvesting fruit.

There are many ways meeting the objectives described in Table 1 would benefit society. Developing a low-cost harvesting device would allow plantation owners to be able to justify the expenditure in the long run, while making the device portable, efficient, and safe would allow a worker to harvest oil palm fruit in a much more effective manner than the current methods used [2]. Making the device is easy to use will allow the current harvesters to be able to operate it, while ensuring the device does not damage the tree will allow oil palm fruits to be harvested again in the future. Furthermore, the most tangible benefit of a successful prototype is the improved safety of the oil palm harvesters who currently climb trees as high as 12 meters to cut oil palm fruit bunches [2].

2.1.2 Business Case

There are four oils that account for 99% of annual global oil production by mass. These oils and their respective compositions are depicted in Figure 1 [1].

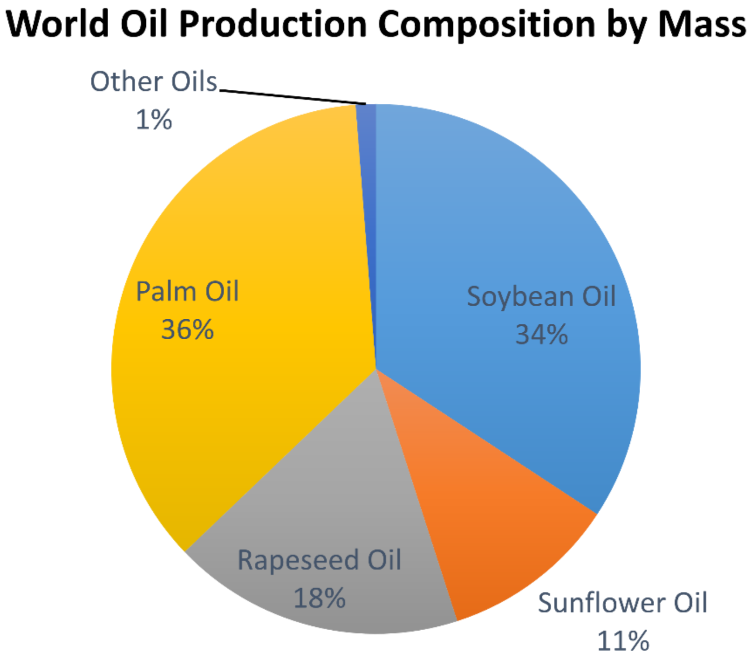


Figure 1: Composition of World Oil Production by Mass [1]

Figure 1 illustrates that palm oil is the most produced oil each year. Currently, the palm oil industry is valued at $44 billion [5] and is projected to increase by more than 65% by 2020 [10]. Additionally, 50% of consumer products that are used daily contain palm oil [11].

Oil palm fruit also yield a much larger quantity of oil than soybeans, rapeseeds, and sunflowers. The yearly average yield of each crop in metric tons per hectare planted is depicted in Figure 2 [1].

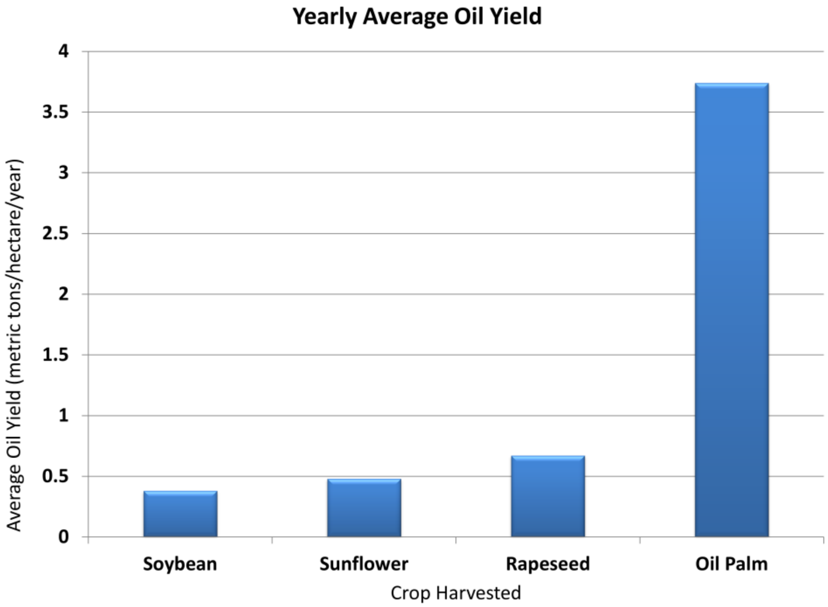


Figure 2: Average Oil Yield in metric tons per hectare of the Top Four Oil Sources [1]

In addition to oil palm fruit being used to produce 36% of the world's oil (Figure 1), the fruits also produce approximately seven times more oil than rapeseeds, the crop with the second highest yield per hectare (Figure 2). The composition of oil crops by area is depicted in Figure 3 [1].

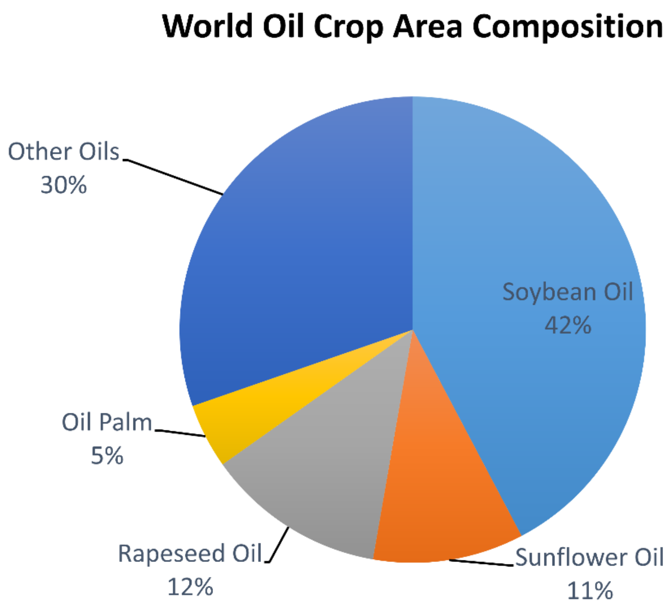


Figure 3: Composition of World Oil Crop Area [1]

In addition to oil palm fruit having the most efficient yield of any crop, Figure 3 illustrates that the fruit comprise the smallest area among all planted oil producing crops. Oil palm trees' relatively small crop area, coupled with oil palm fruit's high oil yield, helps explain why oil palm fruit are the most popular source of oil. However, oil palm fruit are currently harvested in a hazardous and inefficient manner. Laborers must climb oil palm trees that are 12 meters high, identify if the fruit are ripe, cut the proper ripe fruit bunch, and then descend the tree, all while avoiding the many protrusions of the oil palm tree's trunk and not damaging the remaining fruit bunches [2].

It is evident that oil palm fruit are important to worldwide oil production; however, current harvesting techniques can be improved. From a business standpoint, there is a $44 billion market [5] that currently has no competition or innovation in improving oil palm harvesting techniques. As the world's population continues to increase, demand for palm oil, used in 50% of consumer goods [11], will also increase. There will be increased pressure to harvest only crops that have high oil yields to ensure that customers from many countries can afford to purchase them. Thus, there will be a great demand for efficient sources of oil, such as palm oil. Currently, the target consumers of an oil palm fruit harvesting mechanism are oil palm plantation owners and workers in Indonesia and Malaysia, because these two countries produce 85% of the world's palm oil [12]. In addition, plantation owners or workers in any country that wish to increase harvesting efficiency are also considered target consumers. These customers' needs were analyzed and a Threat and Opportunities matrix intended to address these needs was developed and is shown in Table 2. The threats are displayed in red and opportunities are displayed in green. More information regarding short-term threats and opportunities is given in , while further descriptions of long-term ones are given in Table 4.

Table 2: Threats and Opportunities Matrix

	Threats	Opportunities
Short Term (Less than 6 Months)	No feasible design developed	Conceive an innovative design
	More unskilled laborers hired to harvest oil palm fruit	Decrease the number of harvesters needed
	Prototype could damage oil palm trees	Develop a device that does not harm oil palm trees
	Prototype could harvest unripe fruit	Develop a device that can discern ripe oil palm fruit
Long Term (More than 6 Months)	Harvesters will continue to be endangered	Harvesters will have a safer work environment
	Palm oil prices will continue to increase	Decrease palm oil prices by increasing harvesting efficiency
	Harvesting methods do not change	Ability to revolutionize the oil palm harvesting industry
	Oil palm fruit harvesting efficiency research decreases	Oil palm fruit harvesting efficiency research increases

Table 3: Descriptions of Short-Term Threats and Opportunities

Threat	Threat Description	Opportunity	Opportunity Description
No feasible design developed.	This means that the project will not be able to be completed, because a prototype cannot be improved if it does not exist.	Conceive an innovative design.	This means that an original design could be developed that will be able to harvest oil palm fruit without a worker climbing the tree.
More unskilled laborers hired to harvest oil palm fruit.	Palm tree plantation owners will have to continue searching for unskilled laborers willing to endanger themselves and ascend oil palm trees to harvest oil palm fruit.	Decrease the number of harvesters needed.	A harvesting device would decrease the amount of harvesters that are needed to climb and cut oil palm fruit, because the device will be able to harvest more fruit than a human can.
Prototype could damage oil palm trees.	If the prototype is not designed correctly, it may result in fatal damage to the tree that would prevent fruits from being harvested in the future.	Develop a device that does not harm oil palm trees.	A device must be developed that does not harm the oil palm tree and cause it to stop producing fruit.
Prototype could harvest unripe fruit.	If the prototype does not have a way of detecting whether fruit is ripe, unripe fruit may be harvested accidentally.	Develop a device that can discern ripe oil palm fruit.	Any prototype constructed must have a way for the user to discern if an oil palm fruit bunch is ripe before harvesting it.

Table 4: Descriptions of Long-Term Threats and Opportunities

Threat	Threat Description	Opportunity	Opportunity Description
Harvesters will continue to be endangered.	Workers will continue to risk their lives climbing trees that are 12 meters tall.	Harvesters will have a safer work environment.	A harvesting device will allow workers to remain on the ground when harvesting oil palm fruit.
Palm oil prices will continue to increase.	As labor costs inevitably increase over time, the cost of palm oil to consumers will increase.	Decrease palm oil prices by increasing harvesting efficiency.	A harvesting device will allow workers to harvest fruit more efficiently and help lower labor costs, which will prevent the consumer from paying higher palm oil prices.
Harvesting methods do not change.	Current harvesting methods will not change and oil palm fruit will continue to be harvested in an inefficient manner.	Ability to revolutionize the oil palm harvesting industry.	A proof-of-concept prototype would allow the oil palm industry to realize that the harvesting process’s efficiency can be improved.
Oil palm frit harvesting efficiency research decreases.	Harvesting efficiency research might decrease if a successful prototype is not constructed.	Oil palm fruit harvesting efficiency research increases.	Research into ways to improve a constructed prototype might increase.

2.1.3 Project Stakeholders and Team Organization

The project’s sponsor is Dr. Okenwa Okoli, who is the Chair of the IME deparment at the FAMU-FSU College of Engineering. The IME department is providing the funding for this project. Dr. Okoli informs the team of any prototype’s functional requirements and is the project’s main stakeholder. The team has weekly meetings with Dr. Okoli to discuss the project’s progress. Since this project also involves the Department of Mechanical Engineering (ME) and the Department of Electrical and Computer Engineering (ECE), Dr. Nikhil Gupta and Dr. Jerris Hooker, supervisors of each department’s respective senior design courses, are also project stakeholders. Furthermore, Ms. Margaret Scheiner and Mr. Ryan Adams, the IME senior design Teaching Assistants, are also stakeholders in this project. The FAMU-FSU College of

Engineering, IME, ME, and ECE departments are also stakeholders in this project. Finally, the team is also a stakeholder in this project, in order to ensure the project is completed.

The team's hierarchy is depicted in Figure 4. A discipline leader is one that is responsible for that discipline's segment of the entire project. The team reports to Dr. Okoli, the project's sponsor. Patrick Howard was elected the team's current Phase Leader and Material Analyst, because he has experience with automobiles and is currently taking a graduate technical elective on vehicle design. The team required an ME Phase Leader, because the actual phase requires managing the technical aspects of the project. Gabriel Diez was elected as the ME Lead, as well as the historian who is responsible for taking and maintaining audio recordings of each team meeting. Matthew Gerstenblitt was elected as the IME Lead, because he has experience working in research and development, as well as project management skills. Matthew was also elected the team's parliamentarian for team contract purposes. Maria Vetencourt was elected as the Business Analyst, because she is also a business management major and has experience analyzing the business applications of technical projects. Enrique Gonzalez was elected the team's Safety Inspector, because he has experience working in machine shop management, as well as supervising manufacturing and job shop production lines. Enrique is aware of the risks involved in machining parts and constructing prototypes.. Alberto was elected as the ECE Lead, because he has extensive leadership experience in managing individuals. Alberto is also the team's Secretary, who is responsible for taking and uploading the group's meeting minutes to the Blog and File Exchange on Blackboard. Finally, Derek was elected as the group's webmaster, because he is a computer engineering major with HTML, CSS, and JavaScript experience.

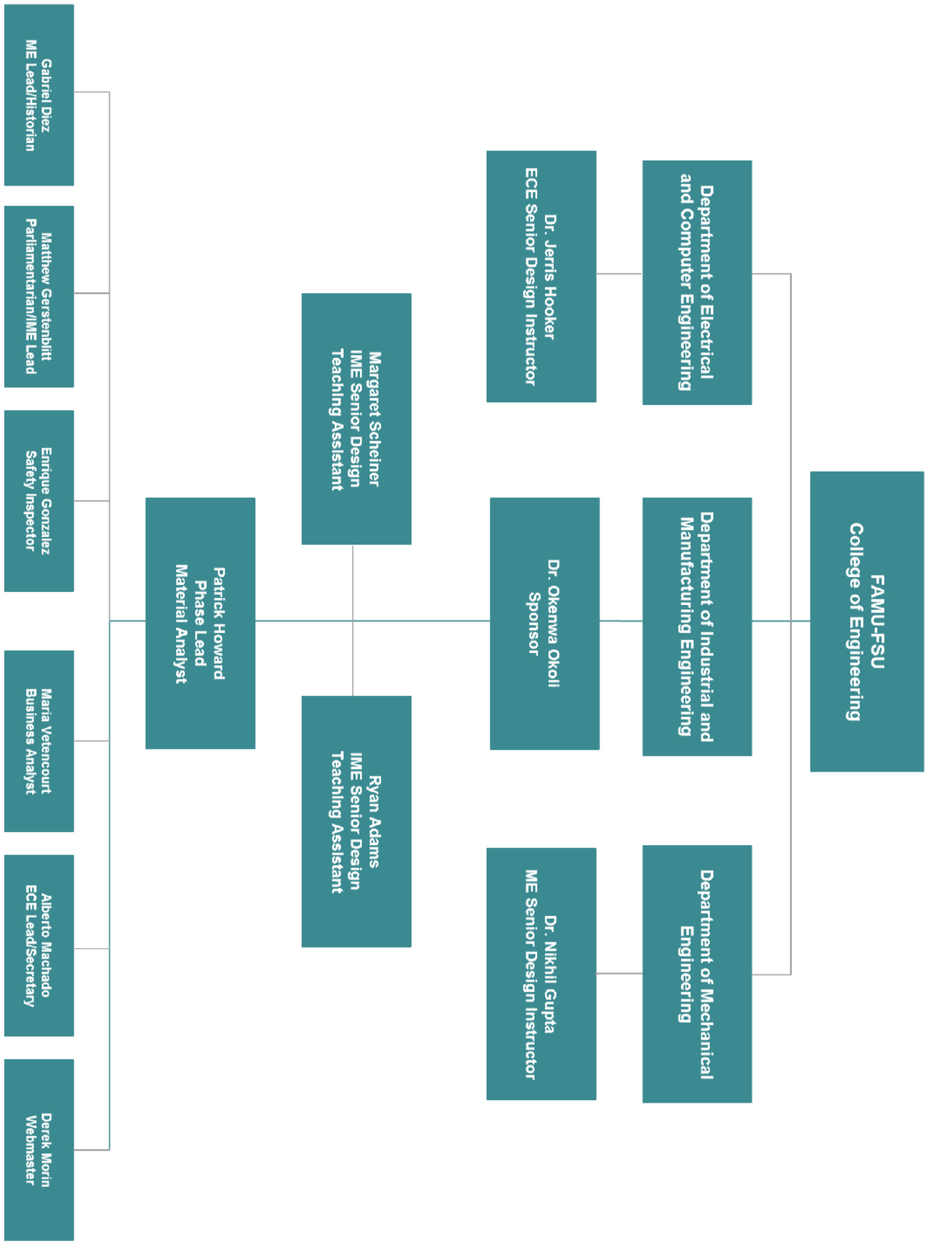


Figure 4: Team Organization Diagram

2.2 Approach

2.2.1 Scope

The scope of this project focuses mainly on developing an electromechanical device to harvest oil palm fruit. In order to construct such a device, the group will research oil palm trees and fruit, as well as current oil palm fruit harvesting methods. Once this research is completed, the team will brainstorm electromechanical design ideas that are consistent with the sponsor's requirements discussed in Section 3.1. Once a design is selected that meets all of the sponsor's criteria, the group will design a prototype utilizing PTC Creo Parametric software and analyze its functionality. Based on the results of the team's analysis, the prototype will be optimized to harvest fruit in the shortest possible amount of time. Finally, documentation will be created that will instruct workers how to operate the device. However, there are several items that are outside the scope of this project. The team is not required to market the product to potential buyers, but only design a device that could be sold by the sponsor. Furthermore, optimizing the production of the designed device is also outside the scope of this project. Finally, the team is not required to obtain feedback from harvesters using the device, because the team will be unable to transport the device to any potential users.

Since the Class of 2015's team was not able to meet Dr. Okoli's requirements successfully, most of the prototype's components were discarded. Only assorted small parts remain from the device. Since the team is still able to access the Class of 2015's reports and documentation, their failures should be able to be avoided in this project.

After referencing the Class of 2012's report [6], the Class of 2014's report [13], and the Class of 2015's report [9], the team learned that there are two design approaches to improve the oil palm fruit harvesting process. The first is a ground-based system that extends from the ground to the top of the tree and cuts the fruit bunches. This has the benefit of being simpler and more feasible to design and build, as well as being less expensive to sell. (It is possible that a different design approach may be conceived when discussing improvements to this design.) The second approach involves designing a system that uses the tree for support and autonomously climbs it to reach the fruit. While this would probably be lighter, easier to operate, and transport, it is more complicated and may not be feasible to finish within the time and budget constraints provided.

This year's goals will consist of one of two approaches. The first approach consists of designing and building a subsystem for the Class of 2015's prototype and developing a design for the finished prototype for following years to complete. Some examples of this approach include a robotic arm with a cutter and a tree climbing subsystem. The second approach consists of completing a proof-of-concept prototype to demonstrate that the design concept is feasible, with an improvement plan for succeeding years. Regardless of the approach selected, the team will still have a prototype constructed and delivered by the end of the Control Phase.

The scope of this project has been defined through meetings with the sponsor, and the team will continue to have weekly meetings with the sponsor throughout the entire project. Dr. Okoli will notify the team if the scope of the project needs to be changed based on the team's feedback and progress.

2.2.2 Assumptions and Constraints

Since oil palm trees require a tropical rainforest climate to grow [11] and there are no oil palm trees in Tallahassee, Florida, there are many assumptions that must be made regarding the trees. These assumptions inevitably constrain how any harvesting mechanism can be designed. These constraints provide the project with the direction and necessary standards that must be met before it can be considered completed. Based on conversations with the project's sponsor and the Class of 2015's documentation [9], a series of assumptions and their corresponding constraints for the project are listed in Table 5 [2], [14], [15].

Table 5: Project Assumptions and Constraints [2], [14], [15]

Assumptions	**Constraints**
Oil palm trees grow 12 meters high [14].	The mechanism must be capable of reaching a height of 12 meters.
Oil palm plantations have very rough ground and very soft soil.	The device must be lightweight and maneuverable.
Trees are planted approximately 9 meters apart over vast hectares of land [15].	The design must be easily portable.
Oil palm trees are grown in a tropical rainforest climate that is prone to high heat and heavy rainfall [2].	The mechanism must be heat and water resistant.
Oil palm trees are grown in very poor regions of the world.	The device must be inexpensive and have a maximum selling price of $2,000.
Users of any device are unlikely to have experience with sophisticated electromechanical systems.	The prototype must be easy to use.
Any design must lower the cost of harvesting oil palm fruit.	The number of users must be minimized. Two users are allowed to move the device from a truck to the ground, but only one user is allowed to operate and move the machine on the ground of the plantation.
Oil palm fruit weigh 18–30 kilograms [2].	Any design must be able to be operated from a safe distance.

2.2.3 Deliverables

Table 6 lists all items the team will deliver by the end of this project and accounts for the ECE, IME, and ME departments' requirements.

Table 6: Project Deliverables

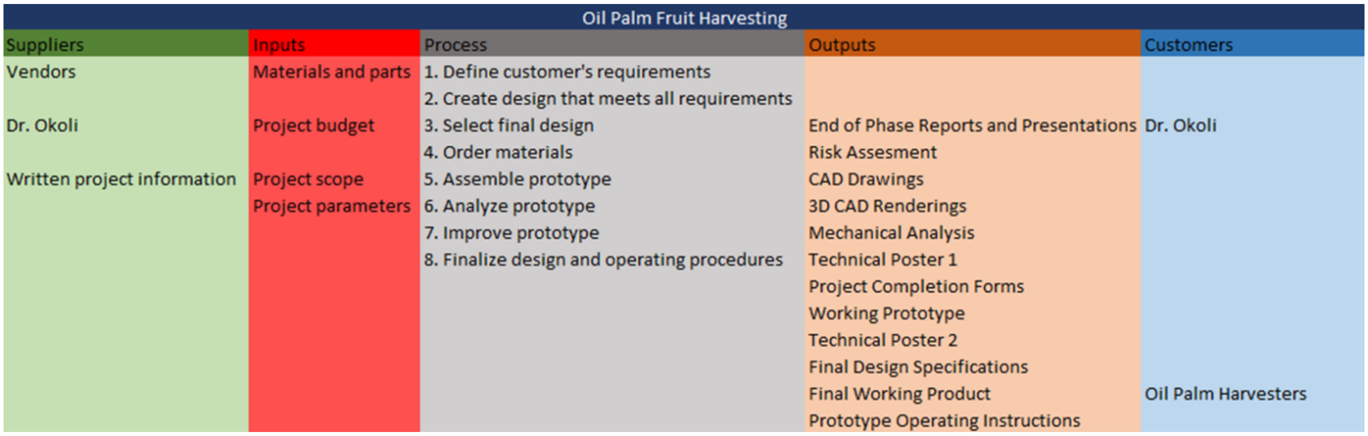
Deliverable	**Due Date**
Define Phase	
Define Phase Gate Review Report	October 20, 2015
Define Phase Gate Review Presentation	October 20, 2015
Risk Assessment	October 20, 2015
Define Phase Peer Evaluation Forms	October 20, 2015
Measure Phase	
Technical Poster 1 Draft	November 24, 2015
Initial 3D CAD* Renderings	December 1, 2015
Initial Bill of Materials	December 1, 2015
Initial Mechanical Analysis	December 1, 2015
Measure Phase Gate Review Report	December 1, 2015
Measure Phase Gate Review Presentation	December 1, 2015
Measure Phase Peer Evaluation Forms	December 1, 2015
Final Technical Poster 1	December 3, 2015
Project Completion Form	December 4, 2015
Analyze Phase	
Analyze Phase Gate Review Report	January 29, 2016
Analyze Phase Gate Review Presentation	January 29, 2016
Analyze Phase Peer Evaluation Forms	January 29, 2016
Final 3D CAD Renderings	January 29, 2016
Final Mechanical Analysis	January 29, 2016
Final Bill of Materials	January 29, 2016
Improve Phase	
Improve Phase Gate Review Presentation	February 26, 2016
Improve Phase Peer Evaluation Forms	February 26, 2016
Control Phase	
Control Phase Gate Review Report	March 31, 2016
Final Design Specifications	March 31, 2016
Prototype Operating Instructions	March 31, 2016
Working Prototype	March 31, 2016
Control Phase Peer Evaluation Forms	March 31, 2016
Post-Control Phase	
Business Analysis Report	April 12, 2016
Business Analysis Presentation	April 12, 2016
Business Analysis Peer Evaluation Forms	April 12, 2016
Technical Poster 2	April 12, 2016
CD of All Deliverables	April 19, 2016
Project Completion Form	April 19, 2015
Completed Team Website	April 19, 2015

*CAD refers to computer-aided design software, such as AutoCAD.

The term “initial” refers to the design outlined by the Measure Phase, which is a preliminary model that is intended to meet all baseline performance requirements. The term “final” applies to the Analyze Phase design.

2.2.4 SIPOC Diagram

To help visualize the project's process, a Supplier-Inputs-Process-Outputs-Customers (SIPOC) diagram was created and is depicted in Figure 5.



Oil Palm Fruit Harvesting

Suppliers	Inputs	Process	Outputs	Customers
Vendors	Materials and parts	1. Define customer's requirements		
		2. Create design that meets all requirements		
Dr. Okoli	Project budget	3. Select final design	End of Phase Reports and Presentations	Dr. Okoli
		4. Order materials	Risk Assesment	
Written project information	Project scope	5. Assemble prototype	CAD Drawings	
	Project parameters	6. Analyze prototype	3D CAD Renderings	
		7. Improve prototype	Mechanical Analysis	
		8. Finalize design and operating procedures	Technical Poster 1	
			Project Completion Forms	
			Working Prototype	
			Technical Poster 2	
			Final Design Specifications	
			Final Working Product	Oil Palm Harvesters
			Prototype Operating Instructions	

Figure 5: SIPOC Diagram

The SIPOC diagram depicted in Figure 5 displays the suppliers, inputs, process, outputs, and customers for the oil palm fruit harvesting device. The suppliers providing resources for the project are the team's sponsor, Dr. Okoli, vendors from which the team will obtain parts to build the prototype, and all written information regarding the project provided to the team. Dr. Okoli provides the project budget to obtain all needed items to complete the project, such as the parts needed to build a working prototype. Any parts needed will be ordered from a vendor and then assembled by the team. Thus, the project's inputs include materials and parts, the project's budget, the project's scope, and the project's parameters. The process column in Figure 5 lists the high-level steps necessary for completing the project. Outputs for this project depicted in Figure 5 include, but are not limited to, each phase's respective report, presentation and peer evaluation forms, as well as the final prototype's operating instructions. Computer-aided designs are also used to perform a mechanical analysis on all parts that will be used. Finally, the customers that will benefit at the conclusion of this project include the sponsor, Dr. Okoli, as well as oil palm plantation owners and workers. The plantation owners will be able to increase the output of their oil palm crops, while the harvesters will benefit from a safer and more efficient workplace.

3. Defining Customer and Technical Requirements

3.1 Customer Requirements

According to the sponsor, the purpose of this project is to improve the method by which palm fruits are harvested. Currently, this involves a laborer climbing a 12-meter tree and cutting each fruit manually [2]. Dr. Okoli wishes to improve the productivity and safety of this process by using an electromechanical device. The customer's requirements were converted into a diagram and are depicted in Figure 6. Descriptions of each requirement are given in Table 7.

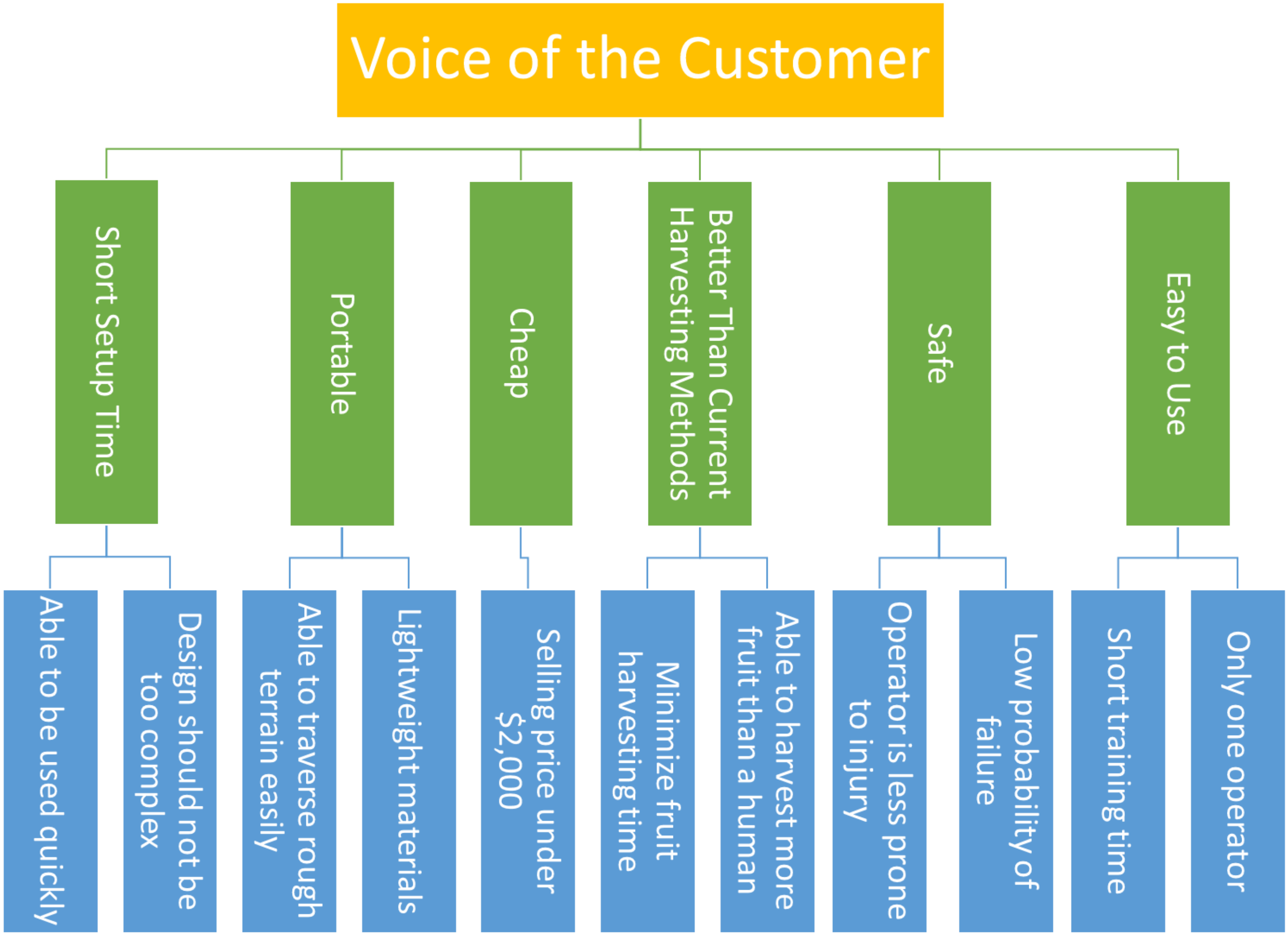


Figure 6: Voice of the Customer Diagram

Table 7: Descriptions of Customer Requirements

Customer Requirement	Description
Easy To Use	The device should be able to be used by current oil palm fruit workers that have limited skills [2]. Since each tree is currently harvested by only one worker, any machine that requires two operators would immediately double the cost of production, by doubling the labor costs per tree. Therefore, any design that requires more than one person to operate it is not acceptable to our sponsor.
Safe	Since the current process is dangerous [2], worker safety must be improved. This includes ensuring the design is safe and that the operator does not risk injury from the device.
Better Than Current Harvesting Methods	Since the purpose of this project is to improve a process that is currently performed by humans, it is critical that the device be superior to a human worker. This includes factors such as fatigue. A well-designed prototype is only limited by its power source. Therefore, the machine must be able to reach the top of the tree faster and harvest more fruit than a human can in the same amount of time.
Low Cost	Since the regions where the device is expected to be used are generally very poor, the sponsor specified that the final machine cannot have a sale price of more than $2,000.
Lightweight/Portable	Since oil palm plantations occupy vast stretches of land [2], portability is extremely important. Otherwise, the time to go from tree to tree would increase, causing a decrease in productivity. One simple way to increase portability would be to make the design as lightweight as possible.
Short Setup Time	Since a human worker can immediately grab onto the tree and start climbing, the time for the design to be ready to operate must be minimized. Otherwise, it cannot be considered a superior alternative to current harvesting methods.

3.2 Technical Requirements

The technical requirements needed to meet the customer's requirements are described in Table 8. In order to complete a design that meets the goal of improving this process, the technical requirements from Table 8 were inputted into the house of quality discussed in Section 3.5.

Table 8: Descriptions of Technical Requirements

Technical Requirement	Description
System Weight	Minimizing the weight would make the device more portable and would make any forces acting on it cause less severe damage. From an efficiency standpoint, a lightweight design would theoretically use less material.
Modular	A modular design would improve the device's portability and make it easier to ship. Furthermore, it would lower the maintenance costs and selling price of the design.
Strength of Materials	Since the machine will be encountering heavy fruit bunches at heights of up to 12 meters, the strength of its materials must be high in order for it to survive any accidents that may occur.
Energy Capacity	Whether the energy source of the machine is stored chemically with gasoline or electrically with a battery, it must be able to last for an entire day of harvesting.
Shielded Electronics	Since the electronics are highly vulnerable to both water and impact, it is crucial that any design protects them from both of these factors.

Fruit Visibility	Oil palm fruit ripen at different rates [2]. Therefore, not all oil palm fruit bunches may be ready to be harvested at the same time. A human climber can easily determine which fruit bunches must be cut and which bunches should remain. The oil palm fruit harvesting machine must be able to either determine which fruit bunches are ready to be cut or allow a human operator to make the decision from the ground.
Electromechanical Components	While electromechanical components may make the achievable goal easier by means of programmed intelligence and endurance, they add a level of delicacy and expense to the design.
Setup Time	Since a human climber can immediately grab onto the tree and start climbing, the time for the design to be ready to operate must be minimized. Otherwise, it cannot be considered to be a superior alternative to the current harvesting methods.
Autonomy	More autonomy would require less human input and would decrease the amount of skill necessary to operate the system. Theoretically, a completely autonomous system would eliminate the need for workers to monitor the device. However, that assertion is currently outside the scope of this project.
User Control System	As the control the user has over the system increases, the number of individuals necessary to operate the system decreases. Therefore, the number of controls should reflect the goal of requiring only one operator.
Harvesting Time	The time for the machine to arrive at a tree and harvest a fruit bunch must be less than that of a human, in order to improve productivity.
Training Time	It would be ideal for this design to require as little training as possible, to allow individuals with minimal skill to be able to operate it. Additionally, training a worker takes time and costs money and should therefore be avoided as much as possible.

3.3 Current Harvesting Process

The process being improved is oil palm fruit harvesting. The purpose of studying this process is to improve the poor methods currently used. When workers first arrive at the plantation, they receive their tree climbing and cutting tools. Oil palm fruit harvesters then walk through oil palm plantations looking for a ripe fruit bunch. A typical worker walks 3–4 hectares per day [2]. These bunches are identified if a tree has loose fruit on the ground or any fruit bunches visible have a red or brown color to them. After the worker cuts a fruit bunch, it must be moved to a designated collection point on the plantation. Cutting fruit from trees less than 6.1 meters tall is not an issue, because there are cutting tools that exist for performing this task [2]. However, cutting fruit from trees that are 6.1 meters to 12 meters high presents a problem. If the fruit bunches are not visible from the ground, a worker may climb a tree and find that no fruit bunches are ready to be harvested. Even if a worker does climb the tree successfully, the worker has a high risk of injury when ascending and descending the tree [2]. For this process to function properly, there must be unskilled laborers willing to climb oil palms. The current harvesting process for trees that are 6.1 meters to 12 meters tall (hereinafter referred to as “tall trees”) is depicted in Figure 7 [2]. The goal of this project is to allow workers to determine if fruit bunches are ready to be harvested and allow workers to use an electromechanical device to harvest the fruit, from the ground.

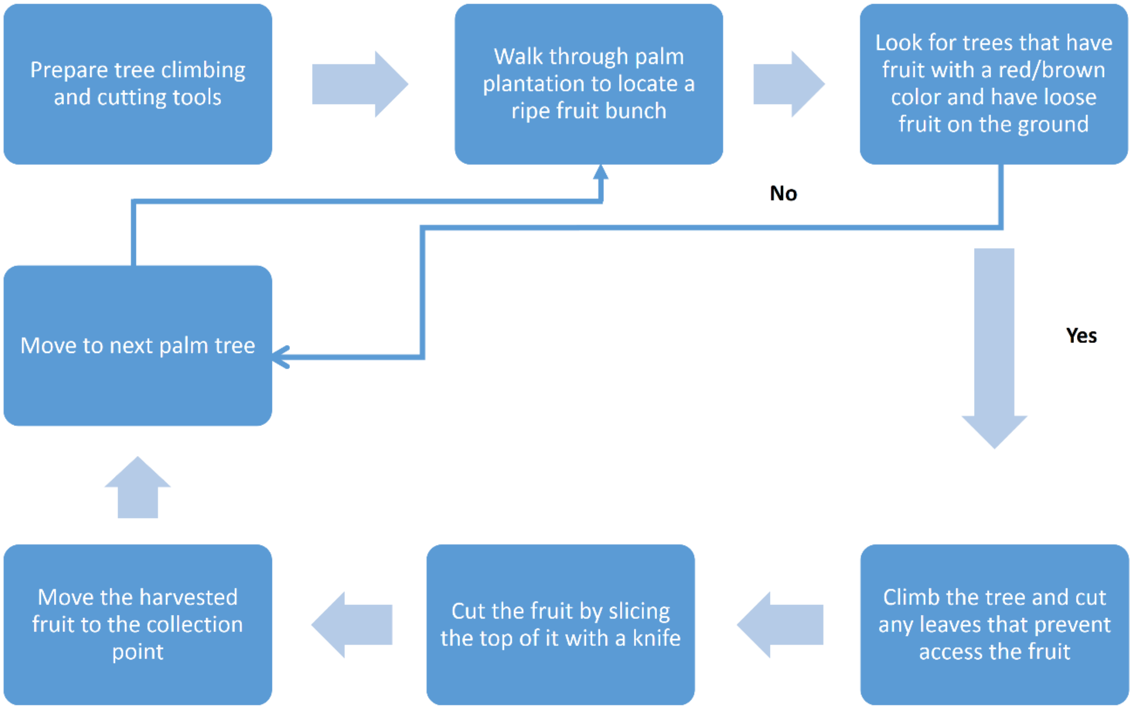


Figure 7: Current Oil Palm Fruit Harvesting Method for Tall Trees [2]

The process depicted in Figure 7 works properly when workers are able to identify a tree that has ripe fruit bunches from the ground, ascend the tree, cut the fruit, descend the tree, and then move the fruit to the designated collection point. However, there is a major flaw with this process. A worker could climb tall trees for an entire day and not find any ripe fruit bunches to be cut. This is inefficient and puts the worker in unnecessary danger. Allowing workers to determine if oil palm fruits are ripe and then harvest them from the ground would significantly improve the process. An Ishikawa diagram of the issues with the current harvesting process is depicted in Figure 8.

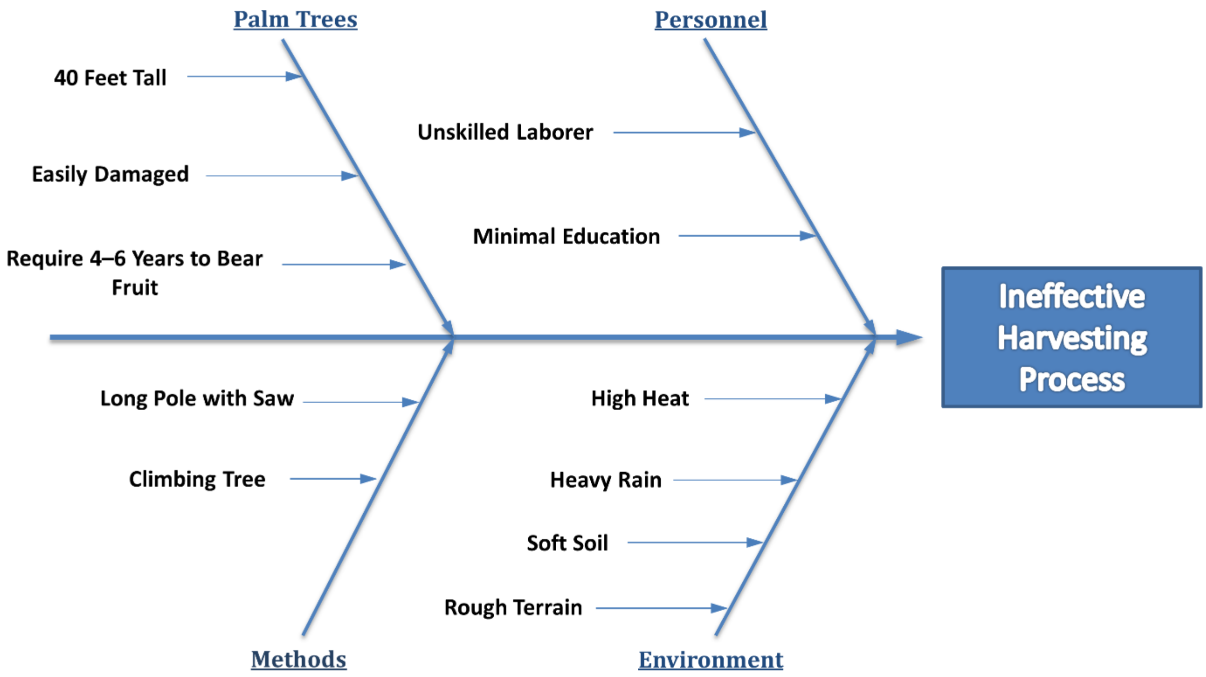


Figure 8: Ishikawa Diagram of the Palm Harvesting Process [2]

Figure 8 helps direct the project by highlighting important aspects of the current harvesting methods. These trees can easily be damaged, grow to a maximum of approximately 12 meters, and require four to six years to bear fruit. Therefore, any system must be able to reach 12 meters and not cause harm to the trees. Since the personnel operating any assembled device will be used to manually ascending and descending oil palm trees, the device must be easy to use. Analyzing current methods enables the team to see the advantages and disadvantages associated with these methods. Finally, understanding the climate of oil palm tree plantations allows the team to ensure any finalized design will have a long life cycle.

3.4 Need for an Electromechanical Harvesting Device

The current oil palm fruit harvesting process involves a worker climbing a tree and manually cutting ripe fruit bunches. In addition to the dangers associated with climbing 12 meters numerous times per day, it is exhausting work that limits the number of trees a worker can climb [2]. Since no devices currently exist to assist workers harvesting oil palm fruit from tall trees, the team's solution is to create an electromechanical system that would eliminate the risk a worker faces when harvesting fruit bunches. Also, the device would be able to ascend the height of the tree with speed and ease, thus increasing the number of oil palm fruits that one worker could harvest. With a greater number of oil palm fruit harvested, oil palm plantation owners would be able to increase their profits, and laborers would experience a safer and more efficient work environment.

3.5 House of Quality

A house of quality was created to assist with this project and is depicted in Figure 9. The house of quality is important because it allows the customer's requirements to be converted into technical requirements and helps determine the team's prioritization of tasks [16]. The team's house of quality was constructed after meeting with the project's sponsor and then brainstorming any technical requirements that may be needed for future designs.

Customer requirements (also known as the demanded qualities) are listed on the left side of Figure 9 and were discussed in Section 3.1. These functional requirements for the final prototype were divided into the following categories: Easy to Use, Performance, and Cost. In order to meet these customer requirements, the team devised several quality characteristics (also known as technical requirements) that are related to the customer's demands. These technical requirements were divided into the categories Design and Operation, shown in Figure 9 and were discussed in Section 3.2. The Customer Importance column assigns a quantitative value to each of the customer's demands. A score of "1.0" denotes that it is the least important, while a score of "9.0" denotes that it is the most important; these rankings were determined based on the team's meetings with the sponsor. More than one of the customer's demands can receive the same ranking. The Organizational Difficulty row in Figure 9 utilizes the same numerical scale, but denotes the difficulty of the team accomplishing each of the technical requirements.

3.5.1 Relationships

The cells in the center of Figure 9 represent correlations among customer requirements (each row) and technical requirements (each column). Each cell may have a “weak,” “medium,” “strong,” or no relationship between its respective customer and technical requirement. Explanations of the correlations of each customer requirement to technical requirements are given in Table 9, Table 10, Table 11, Table 12, Table 13, Table 14, Table 15, and Table 16.

Table 9: Explanation of "One Operator" Relationships

Technical Requirement	Strength of Relationship	Explanation
System Weight	Strong	A lightweight system would allow one individual to operate it.
Modular	Medium	A modular design would allow one operator to assemble the system.
Electromechanical Components	Weak	Fewer electromechanical components would allow one operator to utilize the system, because fewer controls would be needed.
Autonomy	Strong	A system that requires minimal user control would allow one operator to use it.
Number of User Controls	Strong	Fewer user controls would allow only one operator to utilize the system.

Table 10: Explanation of "Lightweight/Portable" Relationships

Technical Requirement	Strength of Relationship	Explanation
System Weight	Strong	A lighter system would allow any developed prototype to be portable.
Modular	Strong	A modular design would allow a prototype to be disassembled and easily transported.
Strength of Materials	Medium	Using stronger materials may increase the weight of the system.
Energy Capacity	Medium	Using a larger power source may increase the weight of the system.
Shielded Electronics	Weak	Ensuring the electronics are shielded from the environment may slightly increase the weight of the system.
Electromechanical Components	Strong	Adding more electromechanical components would add more weight to the system.
Setup Time	Medium	A portable system may require some assembly before use.
Number of User Controls	Weak	More controls may slightly increase the weight of the system.

Table 11: Explanation of "Better than Current Harvesting Methods" Relationships

Technical Requirement	Strength of Relationship	Explanation
Modular	Weak	A modular design may increase the safety of the workers, because they may not have to carry an open blade.
Energy Capacity	Strong	A machine does not experience fatigue like a human does.
Shielded Electronics	Weak	Any electronics would not be as susceptible to the environment as a human would be.
Fruit Visibility	Strong	The fruit must be visible to the operator on the ground.
Electromechanical Components	Medium	Electromechanical components do not experience fatigue like humans do.
Setup Time	String	The system should take at most as much time to setup as it currently takes a human to manually climb a tree.
Autonomy	Strong	A more autonomous system would decrease the amount of human interaction needed.
Number of User Controls	Weak	Fewer controls would help improve the current manual process.
Harvesting Time	Strong	Harvesting time should be no greater than the time it takes a human to cut a fruit bunch and descend the tree.
Training Time	Medium	The time it takes to train current operators to use any prototype should be minimized.

Table 12: Explanation of "Waterproof" Relationships

Technical Requirement	Strength of Relationship	Explanation
Shielded Electronics	Strong	Electronics must be shielded from the environment to be waterproof.
Fruit Visibility	Medium	Making the electromechanical components waterproof should not influence fruit visibility.
Electromechanical Components	Medium	Electromechanical components must be waterproof to ensure that they remain functional.
Autonomy	Weak	If the system is not waterproof, the components that allow the device to be autonomous may fail.
Training Time	Weak	Making components waterproof may require additional time to train operators how to maintain the device.

Table 13: Explanation of "Durable" Relationships

Technical Requirement	Strength of Relationship	Explanation
Modular	Weak	Assembling and disassembling the prototype may cause more wear over time.
Strength of Materials	Strong	A durable design must have the strongest materials possible, while also satisfying other customer requirements.
Energy Capacity	Weak	A larger energy capacity would allow the device to operate longer in the field.
Shielded Electronics	Strong	Electronics must be shielded from the environment to ensure that the system functions properly.
Electromechanical Components	Weak	Wear from electromechanical components may marginally decrease the durability of the system.
Autonomy	Weak	Autonomous systems are more complex and may be more likely to fail.
Number of User Controls	Weak	A greater number of user controls may result in more frequent component replacements.

Table 14: Explanation of "High Capacity Power Source" Relationships

Technical Requirement	Strength of Relationship	Explanation
System Weight	Strong	A larger capacity power source may require a heavier battery and increase the system's weight.
Energy Capacity	Strong	A high capacity power source would ensure a large energy capacity.
Autonomy	Weak	A more autonomous system may require a larger power source to operate.
Number of User Controls	Weak	More user controls may require a larger power source to operate.
Harvesting Time	Weak	A faster harvesting time may require a larger power source to operate.

Table 15: Explanation of "Below $2,000" Relationships

Technical Requirement	Strength of Relationship	Explanation
System Weight	Weak	A sale price of $2,000 may limit the type of materials that can be used and require less expensive, but heavier materials.
Modular	Strong	A modular design may use fewer large pieces and thus decrease the production cost.
Strength of Materials	Weak	Strong materials must be selected within the $2,000 sale price.
Shielded Electronics	Weak	The cost of shielding all electronics must have a minimal effect on the production cost of the prototype.
Fruit Visibility	Weak	A high-resolution camera to allow the operator to see the fruit bunches from the ground will be more expensive than a low-resolution one.
Electromechanical Components	Strong	The minimum amount of electromechanical components should be used to reduce costs.
Autonomy	Medium	$2,000 may limit the possible autonomy of the system to remain within the target production cost.
Number of User Controls	Medium	The minimum number of user controls should be used to reduce costs.

Table 16: Explanation of "Low Maintenance Expenses" Relationships

Technical Requirement	Strength of Relationship	Explanation
System Weight	Medium	Heavier materials may cause the system to experience more wear and require more frequent repairs.
Modular	Strong	A modular system allows pieces of the system to be replaced, instead of requiring the user to purchase an entirely new device.
Strength of Materials	Strong	Stronger materials may result in components being replaced less frequently.
Shielded Electronics	Strong	Electronics that are shielded from the environment would have a lower replacement frequency.
Electromechanical Components	Strong	Using reliable electromechanical components may decrease their replacement frequency.
Autonomy	Medium	A more autonomous system may be more likely to require more frequent servicing.
Number of User Controls	Medium	A fewer number of user controls may result in less frequent maintenance.

3.5.2 Correlations

The cells at the top of Figure 9 depict correlations between the Quality Characteristics/Technical Requirements. Each cell can have a strongly negative correlation, a moderately negative correlation, no correlation, a moderately positive correlation, or a strongly positive correlation. Explanations of the correlations for each technical requirement are provided in Table 17, Table 18, Table 19, Table 20, Table 21, Table 22, Table 23, Table 24, Table 25, Table 26, Table 27, and Table 28.

Table 17: Explanation of "System Weight" Correlations

Technical Requirement	Strength of Correlation	Explanation
Strength of Materials	Negative	Higher strength materials are generally heavier, which increases the system’s weight.
Energy Capacity	Negative	Higher capacity batteries are normally heavier than lower capacity ones.
Electromechanical Components	Positive	Decreasing the number of electrochemical components would decrease the system’s overall weight.
Setup Time	Positive	Decreasing the system weight would result in lighter parts that require less time to assemble.

Table 18: Explanation of "Modular" Correlations

Technical Requirement	Strength of Correlation	Explanation
Electromechanical Components	Positive	A modular design may require fewer electromechanically components to be used, so that it can be easily disassembled.
Setup Time	Positive	A modular system would be able to be assembled quickly.
Training Time	Negative	A modular system would allow the operator to learn how the system works by using it.

Table 19: Explanation of "Strength of Materials" Correlations

Technical Requirement	Strength of Correlation	Explanation
System Weight	Negative	Higher strength materials are generally heavier, which increases the system’s weight.

Table 20: Explanation of "Energy Capacity" Correlations

Technical Requirement	Strength of Correlation	Explanation
System Weight	Negative	Higher capacity batteries are normally heavier than lower capacity ones.

Table 21: Explanation of "Shielded Electronics" Correlations

Technical Requirement	Strength of Correlation	Explanation
Electromechanical Components	Positive	Using fewer electromechanical components would require less space to shield them from the environment.

Table 22: Explanation of "Fruit Visibility" Correlations

Technical Requirement	Strength of Correlation	Explanation
Harvesting Time	Strong Positive	A higher resolution camera would allow the user to accurately cut fruit bunches, thus reducing harvesting time.
Training Time	Negative	Poor fruit visibility will require more time to train an employee to use the system.

Table 23: Explanation of "Electromechanical Components" Correlations

Technical Requirement	Strength of Correlation	Explanation
System Weight	Positive	Fewer electrochemical components will decrease the system’s overall weight.
Modular	Positive	A modular design may require fewer electromechanically components to be used, so that it can be easily disassembled.
Shielded Electronics	Positive	Using fewer electromechanical components would require less space to shield them from the environment.
Setup Time	Positive	Fewer electromechanical components may decrease setup time.
Autonomy	Strong Positive	More electromechanical components may have to be used to make the system more autonomous.
Number of User Controls	Positive	Using more electromechanical components may require increasing the number of user controls.
Training Time	Negative	Increasing the number of electromechanical components may require a user to spend more time with the system to be able to use it.

Table 24: Explanation of "Setup Time" Correlations

Technical Requirement	Strength of Correlation	Explanation
System Weight	Positive	Decreasing the system weight would result in lighter parts that require less time to assemble.
Modular	Positive	A modular system would be able to be assembled quickly.
Electromechanical Components	Positive	Fewer electromechanical components may decrease setup time.
Training Time	Positive	Increasing the number of electromechanical components may require a user to spend more time with the system to be able to use it.

Table 25: Explanation of "Autonomy" Correlations

Technical Requirement	Strength of Correlation	Explanation
Electromechanical Components	Strong Positive	More electromechanical components may have to be used to make the system more autonomous.
Number of User Controls	Strong Negative	A more autonomous the system would require less user control.
Training Time	Strong Negative	A more autonomous the system, would require less time to train an individual to use it.

Table 26: Explanation of "Number of User Controls" Correlations

Technical Requirement	Strength of Correlation	Explanation
Electromechanical Components	Positive	Using more electromechanical components may require increasing the number of user controls.
Autonomy	Strong Negative	A more autonomous the system would require less user control.
Harvesting Time	Negative	A greater number of user controls may require the operator to spend more time harvesting fruit bunches.
Training Time	Strong Negative	A greater number of user controls may require the operators to spend more time learn how to use the device.

Table 27: Explanation of "Harvesting Time" Correlations

Technical Requirement	Strength of Correlation	Explanation
Fruit Visibility	Strong Positive	A higher resolution camera would allow the user to accurately cut fruit bunches, thus reducing harvesting time.
Number of User Controls	Negative	A greater number of user controls may require the operator to spend more time harvesting fruit bunches.

Table 28: Explanation of "Training Time" Correlations

Technical Requirement	Strength of Correlation	Explanation
Modular	Negative	A modular system would allow the operator to learn how the system works by using it.
Fruit Visibility	Negative	Poor fruit visibility will require more time to train an employee to use the system.
Electromechanical Components	Negative	Increasing the number of electromechanical components may require a user to spend more time with the system to be able to use it.
Setup Time	Positive	Increasing the number of electromechanical components may require a user to spend more time with the system to be able to use it.
Autonomy	Strong Negative	A more autonomous the system, would require less time to train an individual to use it.
Number of User Controls	Strong Negative	A greater number of user controls may require the operators to spend more time learn how to use the device.

3.5.3 Calculations

There are several values that were calculated from Figure 9. The Weighted Importance is calculated for each Quality Characteristics/Technical Requirements column by taking the relationship symbol value for each related customer requirement row and multiplying it by its corresponding customer importance value. These computed values are then summed. For example, the Weighted Importance of the "Training Time" technical requirement was calculated using the information from Table 29.

Table 29: Values Used to Compute the Weighted Importance of the "Training Time" Technical Requirement

Customer Requirement	Customer Importance Value	Relationship to Technical Requirement (Value)
Better than Current Harvesting Methods	8.0	Moderate (3.0)
Waterproof	9.0	Weak (1.0)

Calculating the Weighted Importance:

$$3(8) + 1(9) = 33.0$$

Using the information from Table 29, the Weighted Importance for the “Training Time” was calculated to be 33.0.

The Relative Importance for each Quality Characteristic/Technical Requirement is calculated by dividing the Weighted Importance of each Technical Requirement by the sum of all the Weighted Importance values and multiplying by 100%. For example, to calculate the Weighted Importance of the “Training Time” Technical Requirement:

Computing the sum of Weighted Importance values using the information from the house of quality in Figure 9:

Table 30: Weighted Importance Values of Each Technical Requirement

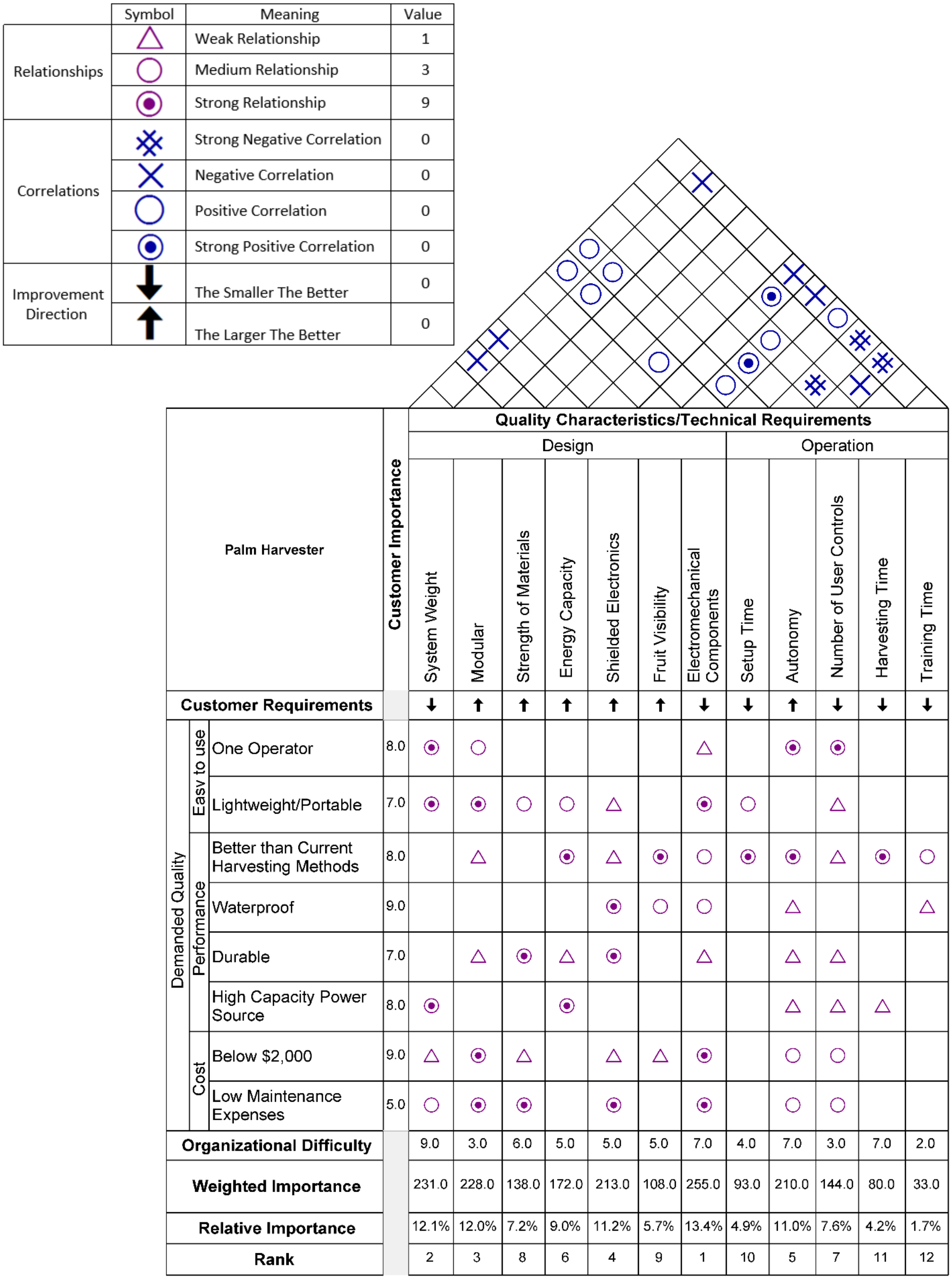
Quality Characteristic/Technical Requirement	Weighted Importance Value
System Weight	231.0
Modular	228.0
Strength of Materials	138.0
Energy Capacity	172.0
Shielded Electronics	213.0
Fruit Visibility	108.0
Electromechanical Components	255.0
Setup Time	210.0
Autonomy	210.0
Number of User Controls	144.0
Harvesting Time	80.0
Training Time	33.0
Sum	1905.0

Calculating the Relative Importance of the “Training Time” Technical Requirement using the information from Table 30:

$$Relative\ Importance_{"Training\ Time"} = \frac{Weighted\ Importance_{"Training\ Time"}}{\sum(Relative\ Importance)} \times 100\%$$

$$Relative\ Importance_{"Training\ Time"} = \frac{33.0}{1905.0} \times 100\% = 1.7\%$$

Finally, the rank denotes the order of importance for each of the requirements, based on the computed relative importance percentages. A value of “1” indicates the relatively most important requirement, while a value of “12” indicates the relatively least important requirement. From Figure 9, the most important requirement is the electromechanical components. Thus, the team will focus on the electromechanical components, to help ensure the customer’s requirements are met.



	Symbol	Meaning	Value
Relationships	△	Weak Relationship	1
	○	Medium Relationship	3
	◉	Strong Relationship	9
Correlations	⋇	Strong Negative Correlation	0
	✕	Negative Correlation	0
	○	Positive Correlation	0
	◉	Strong Positive Correlation	0
Improvement Direction	↓	The Smaller The Better	0
	↑	The Larger The Better	0

Palm Harvester			Customer Importance	Quality Characteristics/Technical Requirements											
				Design							Operation				
				System Weight	Modular	Strength of Materials	Energy Capacity	Shielded Electronics	Fruit Visibility	Electromechanical Components	Setup Time	Autonomy	Number of User Controls	Harvesting Time	Training Time
Customer Requirements				↓	↑	↑	↑	↑	↑	↓	↓	↑	↓	↓	↓
Demanded Quality	Easy to use	One Operator	8.0	◉	○					△		◉	◉		
		Lightweight/Portable	7.0	◉	◉	○	○	△		◉	○		△		
	Performance	Better than Current Harvesting Methods	8.0		△		◉	△	◉	○	◉	◉	△	◉	○
		Waterproof	9.0					◉	○	○		△			△
		Durable	7.0		△	◉	△	◉		△		△	△		
		High Capacity Power Source	8.0	◉			◉					△	△	△	
	Cost	Below $2,000	9.0	△	◉	△		△	△	◉		○	○		
		Low Maintenance Expenses	5.0	○	◉	◉		◉		◉		○	○		
Organizational Difficulty				9.0	3.0	6.0	5.0	5.0	5.0	7.0	4.0	7.0	3.0	7.0	2.0
Weighted Importance				231.0	228.0	138.0	172.0	213.0	108.0	255.0	93.0	210.0	144.0	80.0	33.0
Relative Importance				12.1%	12.0%	7.2%	9.0%	11.2%	5.7%	13.4%	4.9%	11.0%	7.6%	4.2%	1.7%
Rank				2	3	8	6	4	9	1	10	5	7	11	12

Figure 9: House of Quality

3.6 Work Breakdown Structure

A work breakdown structure (WBS) was created using the information from Table 6 and is depicted in Figure 10. The purpose of the WBS is to organize the team's work (by phase) into manageable sections.

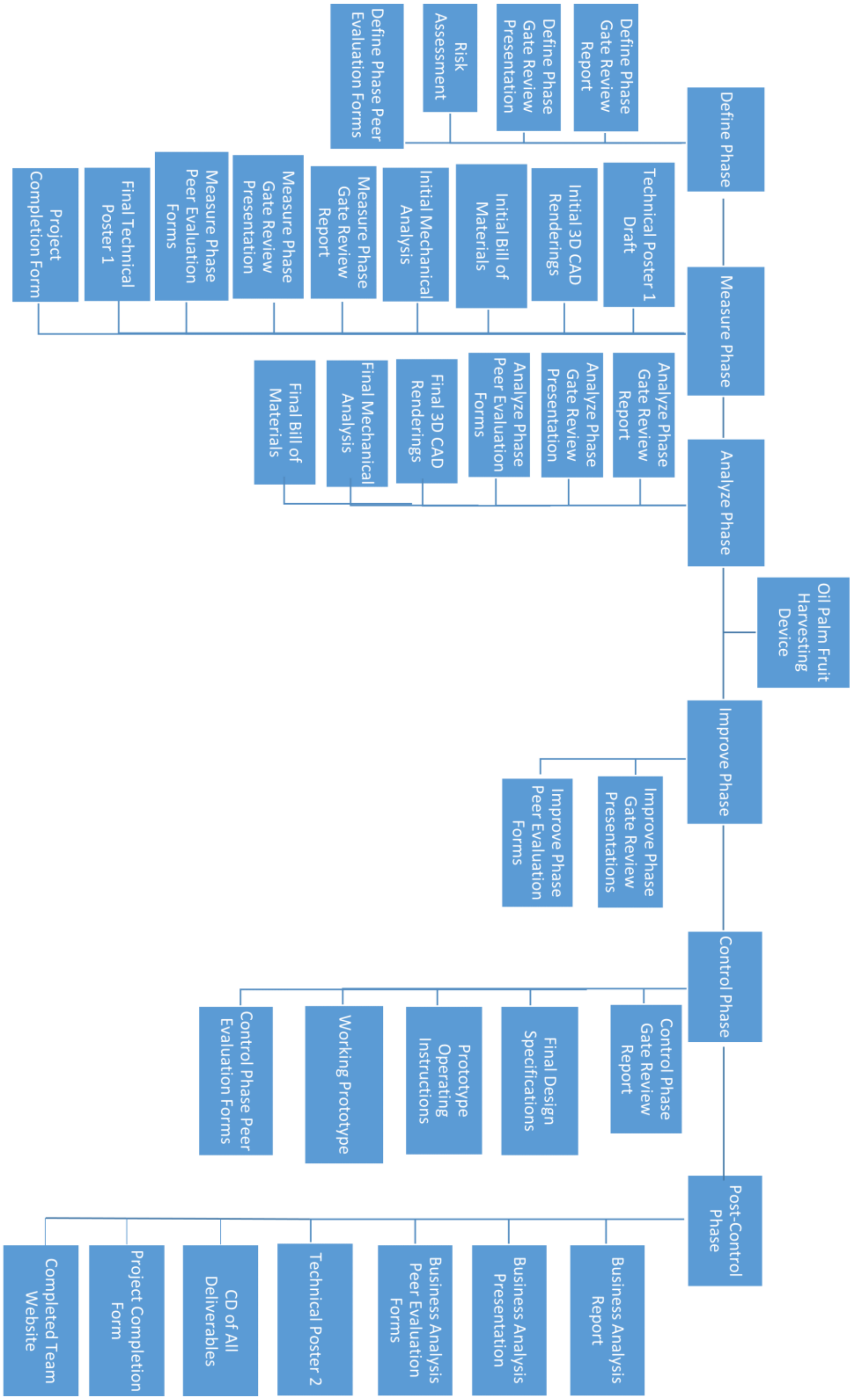


Figure 10: Work Breakdown Structure

3.7 Responsibility Assignment Matrix

A responsibility assignment matrix (RAM) was created from the deliverables described in Table 6 and is depicted in Table 31. The RAM describes which team members are responsible for each work package.

Table 31: Responsibility Assignment Matrix

Oil Palm Fruit Harvesting Device							
Task/Person	Matthew Gerstenblitt	Gabriel Diez	Patrick Howard	Enrique Gonzalez	Maria Vetencourt	Alberto Machado	Derek Morin
Define Phase Gate Review Report	R	I	A	C	C	A	I
Define Phase Gate Review Presentation	R	A	C	I	C	I	A
Risk Assessment	C	C	I	R	A	C	A
Define Phase Peer Evaluation Forms	R	R	R	R	R	R	R
Technical Poster 1 Draft	A	I	A	C	R	I	C
Initial 3D CAD Renderings	I	A	R	I	I	C	C
Initial Bill of Materials	I	A	I	R	I	C	C
Initial Mechanical Analysis	I	A	R	I	I	C	C
Measure Phase Gate Review Report	A	C	C	I	R	I	A
Measure Phase Gate Review Presentation	A	I	A	C	R	C	I
Measure Phase Peer Evaluation Forms	R	R	R	R	R	R	R
Final Technical Poster 1	A	A	A	R	C	C	I
Project Completion Form	R	I	C	A	I	A	C
Analyze Phase Gate Review Report	C	R	A	A	C	I	I
Analyze Phase Gate Review Presentation	A	A	I	I	C	R	C
Analyze Phase Peer Evaluation Forms	R	R	R	R	R	R	R
Final 3D CAD Renderings	I	R	A	I	I	C	C

Final Mechanical Analysis	I	R	A	I	I	C	C
Final Bill of Materials	I	A	R	I	I	C	C
Improve Phase Gate Review Presentation	I	C	R	I	C	A	A
Improve Phase Peer Evaluation Forms	R	R	R	R	R	R	R
Control Phase Gate Review Report	C	A	I	C	A	R	I
Final Design Specifications	A	C	R	I	A	C	I
Prototype Operations Instructions	I	R	C	I	A	A	C
Working Prototype	R	R	R	R	R	R	R
Control Phase Peer Evaluation Forms	R	R	R	R	R	R	R
Business Analysis Report	I	A	I	R	C	C	A
Business Analysis Presentation	A	A	I	C	R	I	C
Business Analysis Peer Evaluation Forms	R	R	R	R	R	R	R
Technical Poster 2	A	C	C	I	A	I	R
CD of All Deliverables	C	I	A	A	I	C	R
Project Completion Form	A	I	C	C	I	R	A
Completed Team Website	A	C	I	I	I	C	R

Code:	Represents:	This Person Is:
R	Responsible	Responsible, the one doing the work
A	Accountable	Accountable, the one expected to justify actions or decisions
C	Consult	To be consulted, one whose expertise may help the one completing the work
I	Inform	To be kept informed, one who does not fit into the preceding three categories

4. Selected Design

4.1 Design Ideas

4.1.1 Improving the Class of 2015's Design

The Class of 2015's design utilized telescoping poles comprised of Aluminum 6061 with a saw attached at the top of the pole and is depicted in Figure 11 [9].

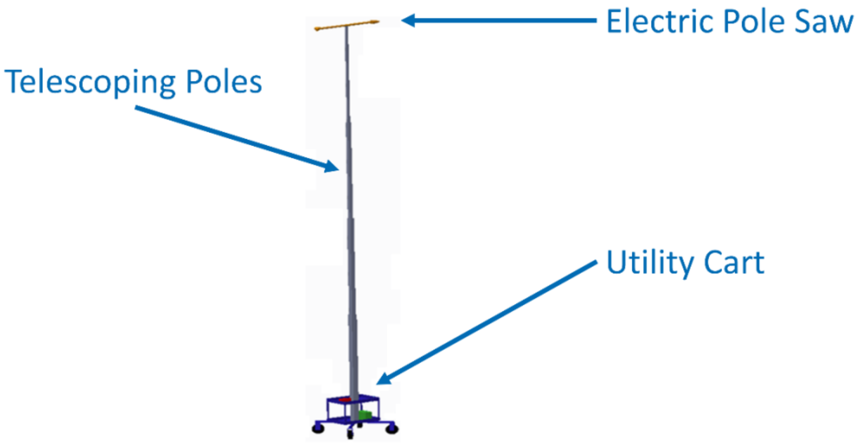


Figure 11: Class of 2015's Design [9]

The design depicted in Figure 11 consisted of a pole that was mounted on a manually operated cart with four rugged never-flat wheels protruding from the sides. An electric motor was used to drive a pulley mechanism to extend the pole approximately 12 meters upward. The saw was controlled from the ground by several ropes. While this design proved capable of extending to the required height to harvest the fruit bunches, there were several aspects that prevented it from being an ideal solution. The 12-meter telescoping pole had to be thick enough to resist bending forces. The poles were too heavy to be moved using a small cart and were not able to remain stable when they were extended. Finally, the saw was not securely attached to the poles and the chainsaw blade was dangerously left uncovered [9].

In order to improve this design, a new chassis to hold the pole would need to be designed. The chassis would need to be large enough to ensure the pole remains stable, while also being lightweight enough to be moved by one person. This support structure must also be capable of operating in rough terrain, which may require the construction of a suspension system. Furthermore, the saw located at the top of the pole must be covered when it is not in use, to decrease the risk of injury to the operator. This means that the rope system used to control the saw should be converted to an electronic system, because it is less likely to injure a worker using the device.

4.1.2 Extended Pole Pruner

The extended pole pruner concept utilizes an existing device from the landscaping industry—an extendable gas-powered pole saw. This current device is depicted in Figure 12 [17]. Currently, the device depicted in Figure 12 is used to trim palm trees that are a maximum of 5.2 meters tall from the ground.

Figure 12: Extendable Gas-Powered Saw [17]

Patrick Howard conceived the aforementioned design concept because he has used the device in the field. This design concept would modify the device's shaft to reach a height of 12 meters. However, since a worker on the ground would not be able to see the top of the pole, a high-definition video camera would be mounted at the top of the device. This camera would connect via Bluetooth to a tablet mounted on the device to allow the operator to see the top of the palm tree and determine which fruit bunches to cut. This design concept is depicted in Figure 13.

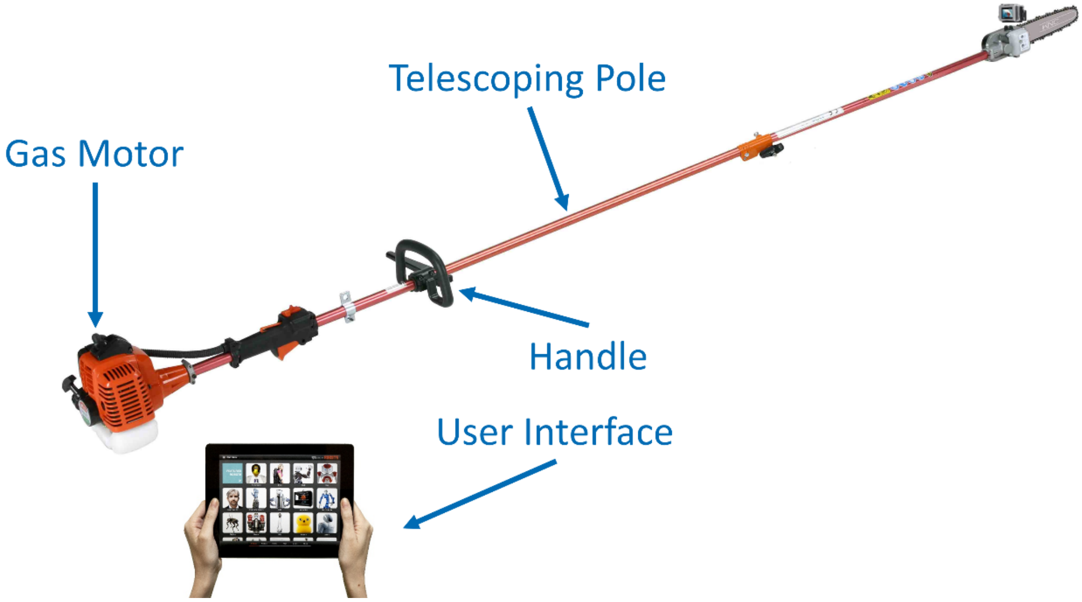


Figure 13: Modified Pole Pruner Framework

This design would meet all of the sponsor's requirements discussed in Section 3.1 and Section 3.5, except that it would be difficult to maneuver due to its 6.1-meter length [17]. However, the extended length of the pole saw would make it difficult for an operator to hold the device without it moving in undesired directions. Therefore, a telescoping tripod stand could be designed and built that would be able to be setup by one operator. This stand would help the user keep the device steady and act as a pivot point.

4.1.3 *Tree Crawler*

The tree clawer concept involves designing a mechanism that can ascend an oil palm tree, cut ripe fruit bunches, and then descend the tree safely. The mechanism consists of two claws, one at the top of the device and one at the bottom, which would wrap around the palm tree's trunk. A body will connect these two claws, which will be designed to retract and extend. The process by which this design would operate is depicted in Figure 14.

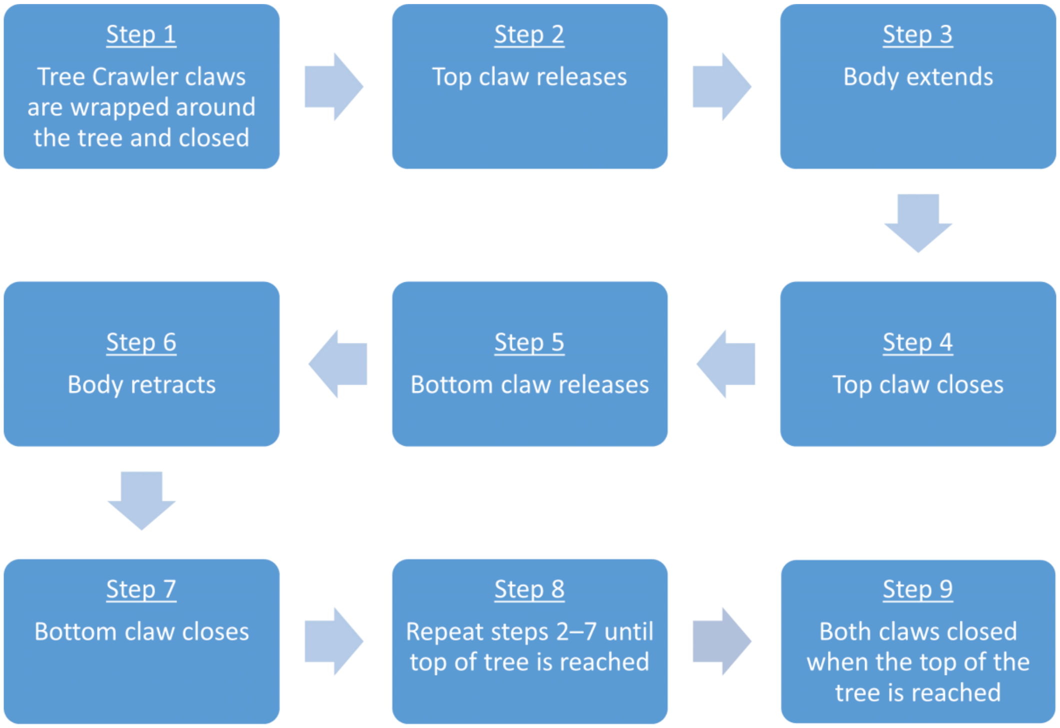


Figure 14: Tree Crawler Operation Process

As illustrated in Figure 14, both claws will need to close once the device has reached the top of the tree. To ensure the device stops at the proper location, the prototype will have a video camera that will be connected via Bluetooth to a display on the user's controller. This controller will allow the user to start and stop the device from ascending and descending the tree. Once the device is in the proper position at the top of the tree, the user will operate an extendable saw at the top of the device to cut ripe fruit bunches, using the video camera's output. Once all desired fruit bunches have been harvested, the user will instruct the robot to descend the tree. The process depicted in Figure 14 operates in reverse when the device descends the tree. Finally, the user will transport the device to the next tree and repeat the process illustrated in Figure 14.

This design would meet all of the sponsor's requirements discussed in Section 3.1 and Section 3.5, except it would be more difficult to use, because it would be a very complex system. However, this concept would require a large number of electromechanical components and an extensive amount of programming to operate efficiently. Adding more electromechanical components also increases the cost and weight of the device. Furthermore, as the number of components increases, the durability of the system decreases. The claw connectors would also have to withstand a large moment to support the weight of the machine and would also need to be resistant against the vibration that would occur when cutting fruit bunches.

4.1.4 Final Design Choice

The team selected a design that incorporates components from the aforementioned concepts. The design consists of four major components: the pole, the ring, the cutter, and the base. The cutter will stay on the ring and the ring will be attached around the tree at the base. The ring and cutter will then be lifted up using a series of poles that will attach to one another at the base. The base is intended to hold up the weight of the entire mechanism as the operator adds more poles to lift it up. It will also serve the purpose of adding stability to the overall structure.

4.2 The Pole

The poling used to raise and lower the system is critical to preventing the design from collapsing. The pole will experience several different forces, such as bending stress from the weight of the ring and the cutting mechanism hanging from the end of it, as well as a vertical column stress from the weight of the track and cutter mechanism. Due to the sheer volume associated with such a long pole, a lightweight material, in addition to a small cross-sectional area, is essential to maintain maneuverability. Two materials considered were aluminum 6061 and carbon fiber. Aluminum has a density of 2.7 grams per cubic centimeter [18], while carbon fiber epoxy composite has a density 1.6 grams per cubic centimeter [19]. Clearly, carbon fiber is lighter than aluminum; however, aluminum costs $1.46 per kilogram [20], whereas carbon fiber costs $22.05 per kilogram [21]. Since the design is intended to be a proof of concept, aluminum 6061 was selected as the pole’s material. The project’s sponsor specified that PVC was not allowed to be used for the poling, because it would not be durable enough for the conditions found on an oil palm planation. In the final system, however, the manufacturer would most likely use an engineering plastic due to its much lighter weight and superior stiffness.

The connectors are designed to slip over the ends of the pipe; a male connector is located on one side and a female connector on the other. These connectors will consist of a series of drilled holes with screws to mount to the ends of the poling. As the user lifts the system up the tree, the next pole would insert into to the previous one and turn approximately 90 degrees to lock in place. These connectors would be made from aluminum to support the weight of the system when it is attached to the base.

Another design feature is the straps at the top and bottom of the system. These straps wrap around the tree and are used to secure the design to the tree. This feature provides added stability for the cutting mechanism as it traverses 360 degrees around the track, which will increase the stability of the ring. These bands would be made from thin aluminum sheets that remain flexible to ensure they do not fracture. The bands will be opened and closed by a heavy-duty thin rope that has a high tensile strength. The rope will run through the inside diameter of the poles and tighten when the user pulls the strap toward the ground. The rope will then be tied at the base of the pole to secure the system. The final part of the pole design is a connector that is rigidly attached to the ring at the top of the extended pole. The connector will need to be rigidly attached to prevent any major deflection from the weight of the cutter mechanism. This connector will be machined from aluminum 6061 for strength and rigidity.

4.3 The Ring

The ring is designed to wrap around an oil palm tree’s trunk. The cutting mechanism will rotate around the trunk and will have a hinge and a lock that will allow the user to open it and wrap it around the base of the tree. The ring will then be lifted up the tree using the pole sections. Since weight and strength are critical for this design, the production model would ideally be made from a plastic material that has been engineered to have an acceptable strength-to-weight ratio. However, such a material would require an injection mold to be custom made to maintain the material’s strength properties, which would far exceed the given budget. Yet, such a mold would be cost effective for a final product, since the investment would eventually be recovered by the number of models sold. Therefore, as a proof of concept, this project will use aluminum instead of an engineering plastic, even though it will be heavier. The added weight from the aluminum, in addition to the weight of the cutter at a maximum distance of 1.5 meters from the pole, will cause the forces and moments to act upon the ring that must be considered. The shape of the ring will be a circular L-bracket with sides that measure 50.8 millimeters each and have an initial thickness of 6.35 millimeters. The ring is depicted in Figure 15 to scale.

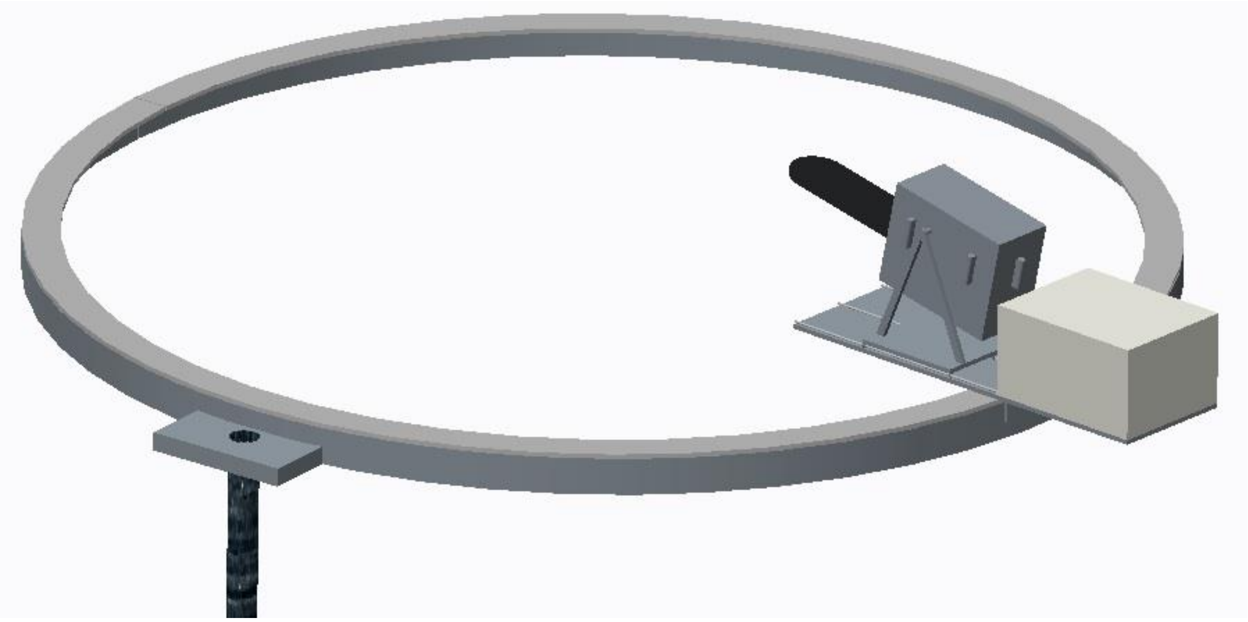


Figure 15: Circular Cutter Track

After performing finite element analysis (FEA) on the ring, the results showed that the largest stresses occurred near the pole, often reaching values close to 276 megapascals (MPa) [22], the yield strength of aluminum 6061. Since this ring will be 12 meters in the air, as well as contain the most dangerous components of the design—the cutter—it is essential that every precaution be taken to prevent it from failing. The FEA showed that the stresses incurred by the 6.33-millimeter thick ring would not provide an acceptable factor of safety. Therefore, the thickness was then increased to 9.525 millimeters and another FEA was repeated and is displayed in Figure 16.

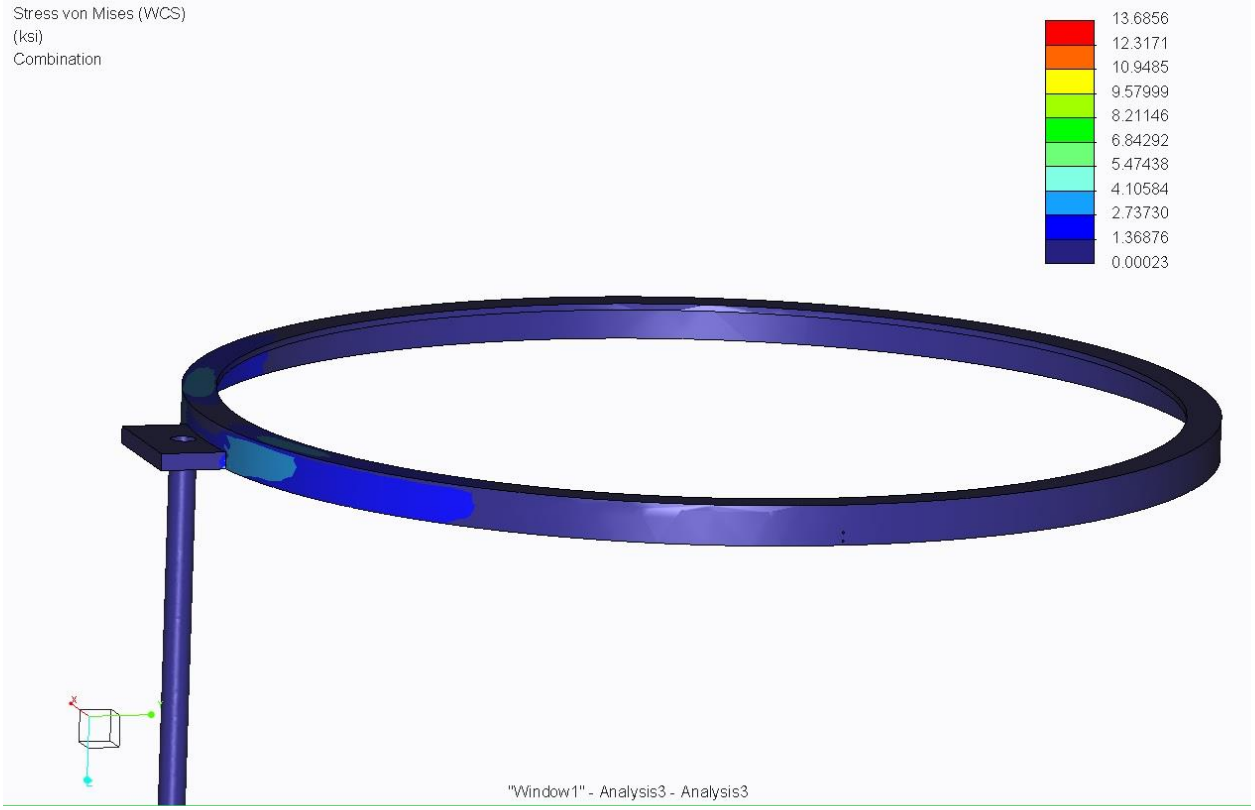


Figure 16: Stress Analysis of the Ring

Figure 16 shows that with the increase in ring thickness, the highest stresses experienced by the ring are around the pole mount and reach values of approximately 47 MPa (6.8 ksi). Since most of these stresses are concentrated around the pole mount, they can be further decreased by increasing the size of the pole mount to wrap around a larger portion of the ring. These stresses result in a factor of safety of approximately 2.8. Currently, the team considers the factor of safety of 2.8 to be acceptable.

Since only one side of the ring is secured to the pole and extends 1.5 meters away from it, its behavior will be similar to a cantilever beam. However, cantilever beams have greater risks of deflection than other structures. If the ring deflects too much, it could not only affect the functionality of the system by pushing the fruit bunches farther away, but repeated large deflections could cause fatigue to the material and result in the system's failure. The initial 6.35-

millimeter ring design exhibited large deflections, the highest of which reached 177.8 millimeters below the horizontal line. Considering the length of the chainsaw being used is only 203.2 millimeters, it is evident that this is an unacceptable amount of displacement. Thus, the 9.525-millimeter ring design was then analyzed for deflection by running a FEA and is depicted in Figure 17.

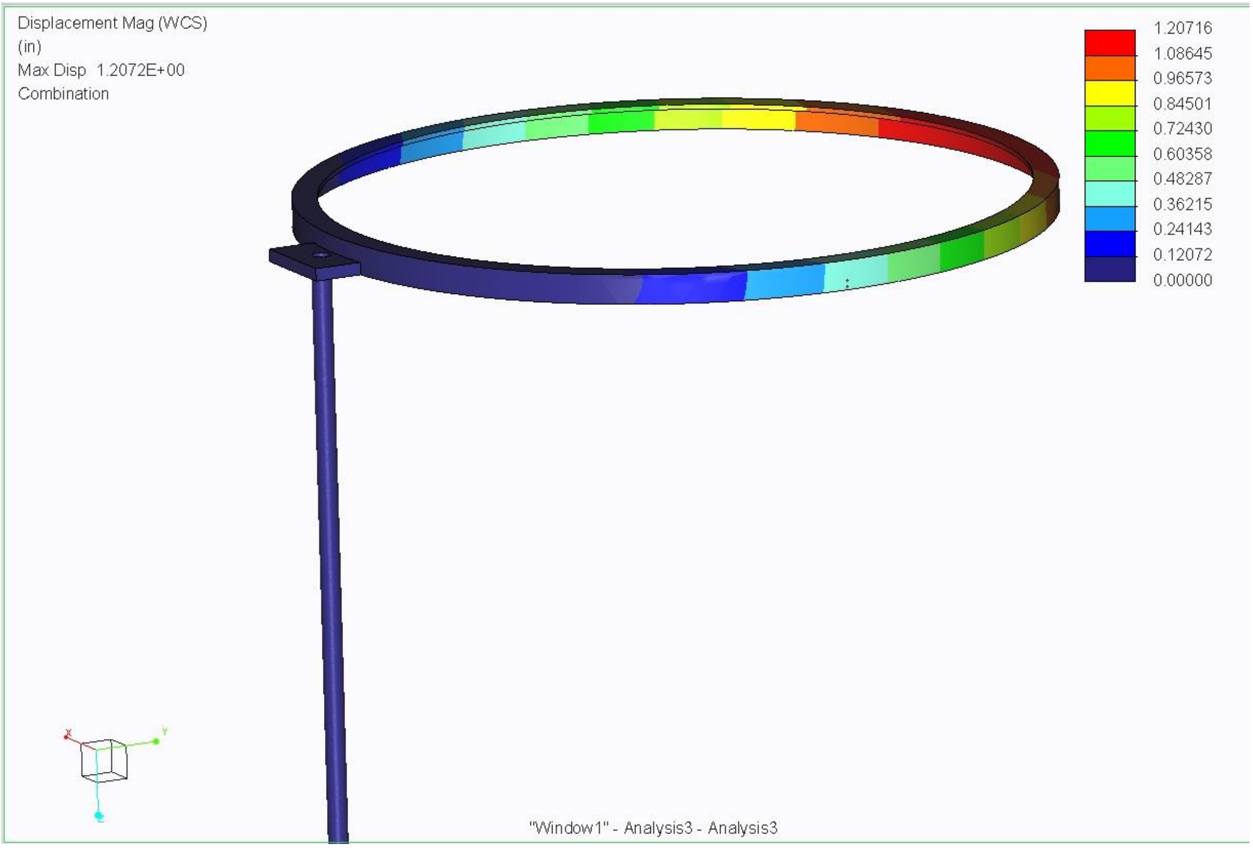


Figure 17: Displacement Analysis of the Ring

As Figure 17 shows, the 9.525-millimeter thick ring will not displace more than approximately 1.508 millimeters (0.059 inch) below the horizontal axis. Since the ring has a 1.524-meter diameter, this displacement represents less than 1 degree of deflection. For the current design, this displacement was deemed acceptable by the team. Each half of the ring will be made by cutting two long bands out of a 2438.4-millimeter long sheet of aluminum. A roller will then be used to give the bands their circular shape. The top of the ring will be cut from the same sheet and then welded on top of the circular bands, creating the L-shaped circle that is desired. The minimum size sheet that can be used to manufacture this ring is 965.2 millimeters high by 2438.4 millimeters wide. Unfortunately, this increase in thickness comes with a disadvantage. Since this process results in a significant amount of scrap material, simply increasing the ring's thickness by 3.175 millimeters nearly doubled the cost from approximately $600 to approximately $1,100. If further analysis indicates that the 9.525-millimeter thick ring is also unacceptable, another increase in thickness would likely be too expensive to be considered.

4.4 Cutting Mechanism

The cutting mechanism depicted in Figure 18 will be set on an aluminum platform that will traverse around the circumference of the ring by utilizing a direct current (DC) motor. A second platform is mounted on top of a lead screw that controls its forward and backward translation. Two guide shafts will be adjacent to the lead screw to keep the secondary platform stable and balanced. The secondary platform will have two sets of trusses that support the weight of a box containing a DC motor that controls the saw and the stepper motor that controls its pitch. The height of the trusses and the size of the box are designed to give the saw 90 degrees of pitch. Though a larger angle of pitch is possible, it is not necessary or recommended, because it would mean that the saw is cutting fruit bunches directly over the platform. The saw blade being used is a 203.2-millimeter long chain saw that remains from the Class of 2015's design.

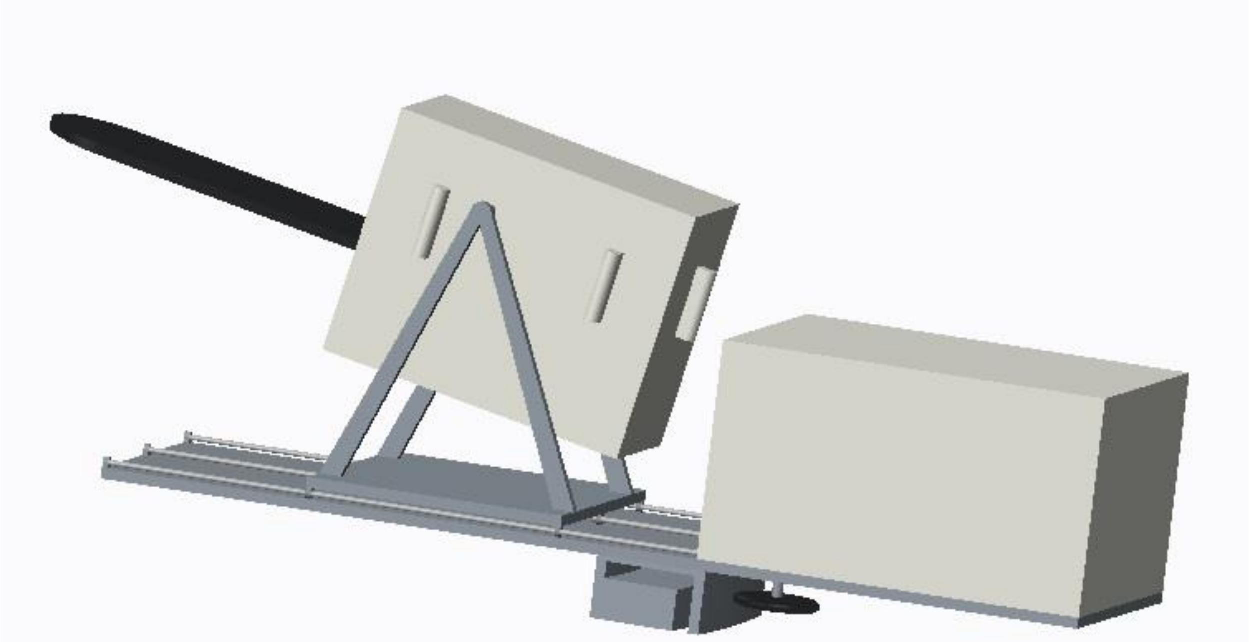


Figure 18: Cutting Mechanism

The cutting mechanism will be controlled using an Arduino UNO microcontroller similar to the one depicted in Figure 19 [23]. The Arduino UNO operates at 5 volts (V), has 14 digital input/output pins, 6 analog input pins, and 6 Pulse Width Modulation (PWM) input/output pins. The board operates at 16 megahertz, has 32 kilobytes (KB) of flash memory, and has 2 KB static random-access memory. The board will be powered by D cell batteries connected by a USB adapter. This controller will control 3 DC motors and a stepper motor. These motors will be controlled using multiple L293D dual H-bridge motor drivers, shown in Figure 20 [24]. The pin layout of L293D is depicted in Figure 21 [25]. Pins 1 and 9 need 5 V to enable to use of the driver and pin 16 will also need 5 V for the combinational logic inside it. Pin 8 takes the voltage that will be released to the motors. Pin 4, 5, 12, and 13 are all connected to ground to allow current flow. Pins 2, 7, 10, and 15 take inputs from the Arduino board. Pins 3, 6, 11, and 14 are outputs connected to the motors. Pins 2, 7, 10, and 15 control pins 3, 6, 11, and 14, respectively.

When one of the input pins receives a signal from the board, the corresponding output pin receives the voltage from pin 8 of the driver.

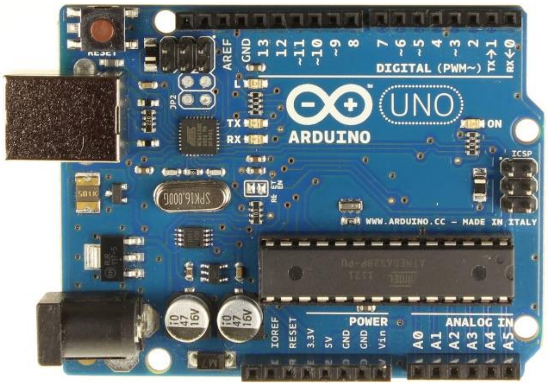


Figure 19: Arduino UNO Microcontroller [23]

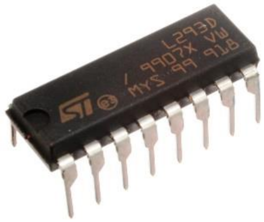


Figure 20: L293D H-bridge Motor Driver [24]

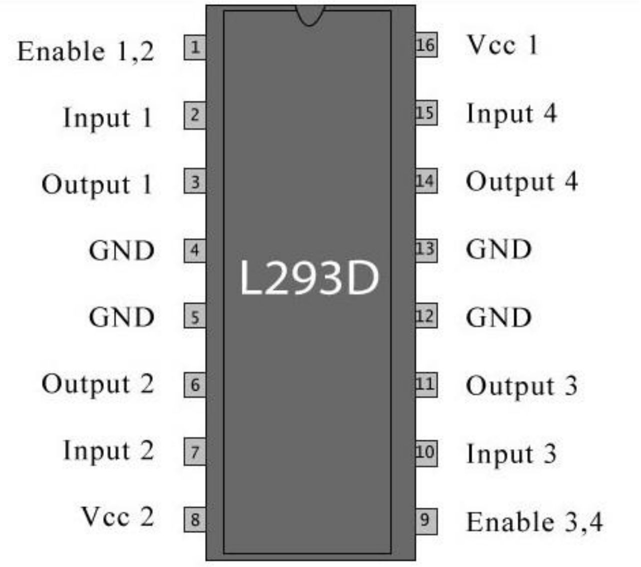


Figure 21: Pin layout of L293D [25]

For the DC motors to have the ability to run forward and backward, the positive end should be placed in one of the motor driver's output pins and the negative end in a different output pin. To go in one direction, one of the corresponding input pins must be set high, while the other remains low. The converse is true for the opposite direction. Two separate DC motors can be controlled with a single L293D H-bridge motor driver. The stepper motor selected has four phases and has four wires corresponding to each phase. Therefore, one complete motor driver must be used for the stepper motor. The stepper motor uses internal electromagnetic fields to move the magnet inside of the motor. When a current is applied to either of the two coils inside of the stepper motor, an electromagnetic field is created. The polarity of the electromagnetic field depends on the direction of the current. The two possible polarities of the electromagnetic field are each controlled by a wire. To control the direction of the stepper motor, the electromagnetic field of the coils must be turned on and off in sequence, as shown in Figure 22 [26].

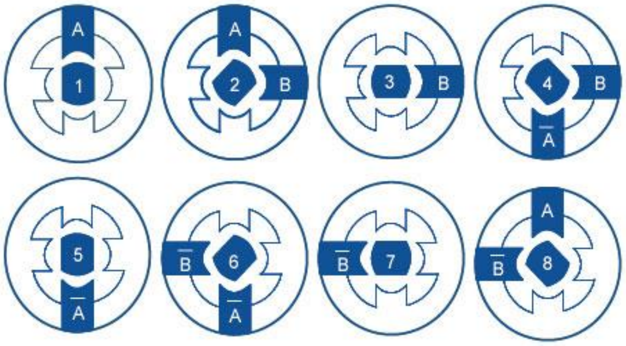


Figure 22: Stepper Motor Forward Sequence [26]

Two of the three DC motors that will be used are depicted in Figure 23 [27]. The stepper motor that will be used is depicted in Figure 24 [28].

Figure 23: DC Motor [27]

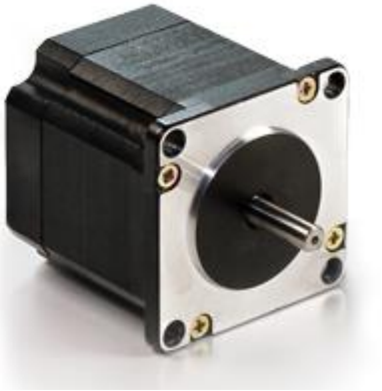


Figure 24: Stepper Motor [28]

Two DC motors and the stepper motor will be used for movement of the cutting mechanism. One DC motor will be used to traverse the track and the other will be used for the forward and backward translation of the saw. The two DC motors have a power of 96.9 watts, operate at 2,600 revolutions per minute (RPM), and run on 24 V. The RPM of the motor shown in Figure 23 will be geared downward to reach the required torque. A ratio of 1:5 was chosen to reduce the motor from 2,600 RPM to 520 RPM, but is subject to change due to the performance of the motors and the weight of the mechanism. The motors will be tested with a load similar to the load for the design. The duty cycle for the PWM signals will be determined through these tests. The gears will be fabricated using additive manufacturing so that new ones are available to be made at any time. If the cutting mechanism traverses around the ring too quickly once the prototype is assembled, it can destabilize the ring and cause it to separate from the tree. However, if the prototype's test results indicate that the speed of the motor needs to vary, it can be achieved using PWM signals. The third DC motor was acquired from the Black and Decker saw that remains from the Class of 2015's design. This motor operates at 18 V. The other specifications of the motor are unknown, because the manufacturer would not disclose the motor's specifications, but the motor is designed for the saw, guaranteeing smooth operation.

The stepper motor depicted in Figure 24 operates at 12 V, has an output torque of 4.237 newton meters, and requires 1 ampere per phase. All of the motors will be powered by 16 rechargeable D cell batteries with a rating of 10,000 milliamp hours. The resulting voltage of these batteries will be 24 V and will require the creation of a voltage regulator for the stepper motor and the saw motor. Using these batteries, the cutting mechanism will be able to run continuously for a minimum of 3.5 hours (assuming that the mechanism will be used in a 10-hour workday). However, the cutting mechanism will not be continuously powered for 3.5 hours. Assembly, disassembly, and operating time are each estimated to require 5 minutes each. The cutting mechanism will have sufficient power to last the entire period. An Arduino template file for the usage of all these motors has been created.

The full schematic cutting mechanism's electronics is depicted in Figure 25. A total of 11 input/output pins are used in the Arduino UNO board, which leaves three extra pins in case more are needed. The cutting mechanism will be controlled wirelessly by the user with the use of radio frequencies. The receiver and transmitter selected is shown in Figure 26 [29].These components operate at 433 hertz and are made for the Arduino microcontrollers. An Arduino library and template files for the operation of these devices have been obtained from online sources [30]. The receiver will be placed in the cutting mechanism and the transmitter will be inside the wireless controller. The transmitter will be able to send a signal to the cutting mechanism when powered with 12 V and an antenna of at least 152 millimeters. The controller will also be operated using an Arduino UNO microcontroller and will be powered using 8 AA cell batteries. An Arduino Joystick Shield will be used for user input and is depicted in Figure 27 [31].This shield is made specifically for the Arduino UNO. The left and right movement of the joystick will maneuver the cutting mechanism around the ring. The up and down movement of the joystick will move the saw in and out. Button D will turn the saw on and button A will turn it off. Button B will pitch the saw upward while button C will bring it downward. The schematic for the Joystick Shield connected to the Arduino UNO is shown in Figure 28 [32]. The transmitter will be connected to any of the unused pins. The casing for both the controller's electronics and the cutting mechanism will be created using additive manufacturing. The circuitry for the cutting mechanism will be soldered to decrease holding space. A camera will be screwed onto the casing of the cutting mechanism's electronics. The monitor of the camera will be screwed onto the casing of the controller. The camera and the monitor will both operate at 5 V. The camera and monitor are depicted in Figure 29 [33].

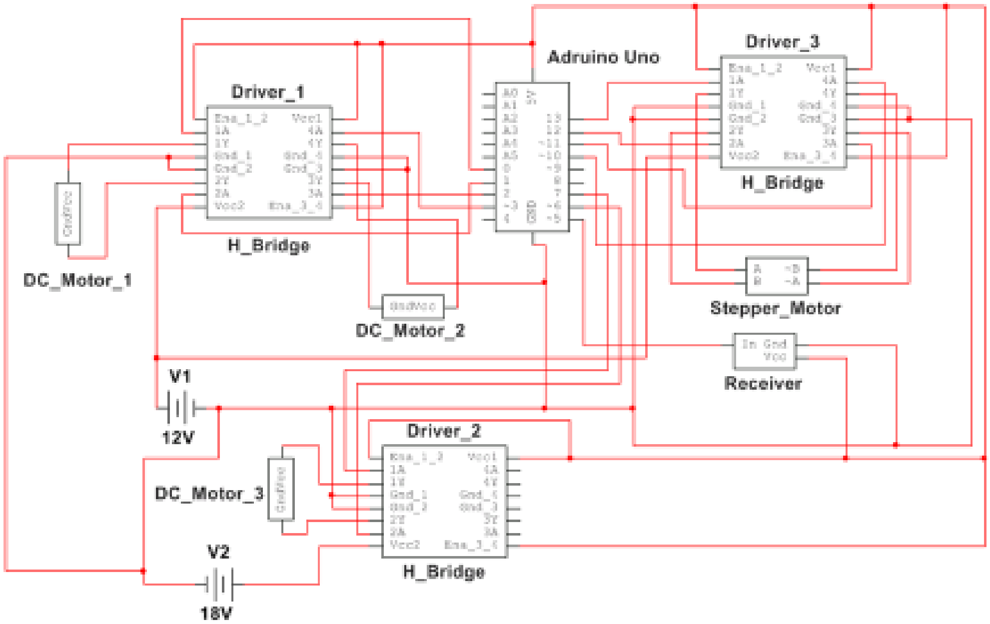


Figure 25: Cutting Mechanism Schematic

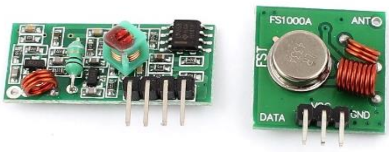


Figure 26: Receiver (left) and Transmitter (right) [29]

Figure 27: Arduino Joystick Shield [31]

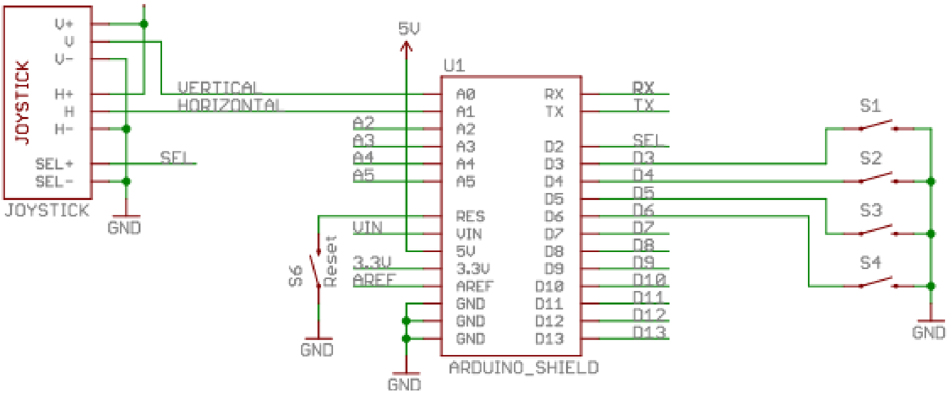


Figure 28: Joystick Shield Schematic [32]

Figure 29: Camera and Monitor [33]

4.5 The Base

The base of the system will consist of four legs joined together by links at a central point, as depicted in Figure 30. When the user is finished cutting the fruit bunches and disassembling the pole, the links will move upward and the stand will retract similar to a tripod.

Figure 30: Rendering of the Base

In addition to adding stability, the stand will also bear the weight of the pole, cutter, and ring, while the worker inserts additional pole sections from the bottom. Since this is a proof-of-concept design and expensive materials are not able to be used for the pole, the joint at the top of the base that holds the legs and pole in place must be able to support the weight of a 12-meter tall aluminum pole. Assuming that the heaviest pole that would be used would have a diameter of 50.8 millimeters and a thickness of 6.35 millimeters, a total pole weight of roughly 23 kilograms was set based on the density of aluminum. Moreover, the combined weight of the 7-kilogram cutter and the 11-kilogram aluminum ring resulted in the total applied weight on the joint being 41 kilograms. The FEA of the aluminum joint under this stress is depicted in Figure 31.

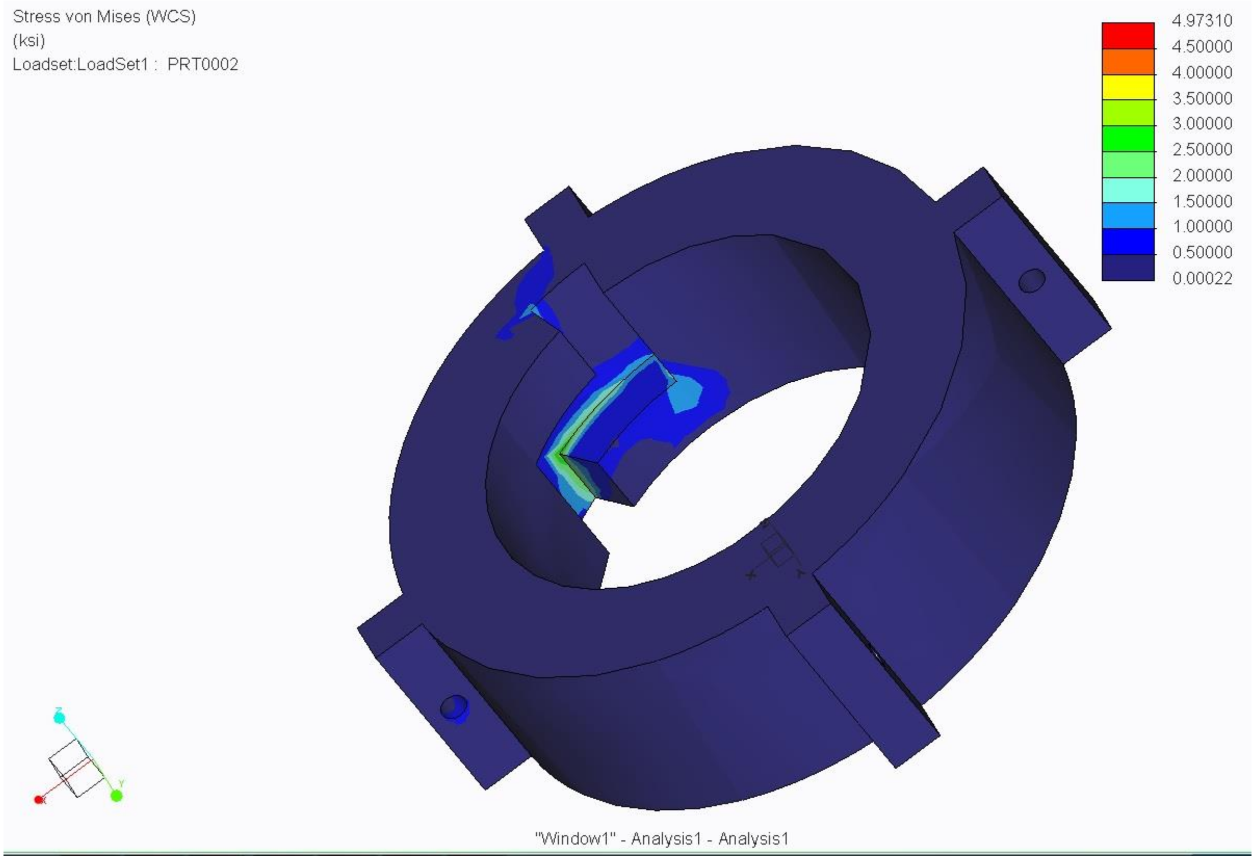


Figure 31: Stress Analysis of the Aluminum Joint, Top View

As shown in Figure 31, the majority of the weight will be concentrated on the locking mechanism. This joint will not experience more than 21 MPa (3 ksi) of stress on this side, which is far less than the yield stress of aluminum of 276 MPa [22]. The greatest stress is experienced by the pin hole on the other side as seen in Figure 32.

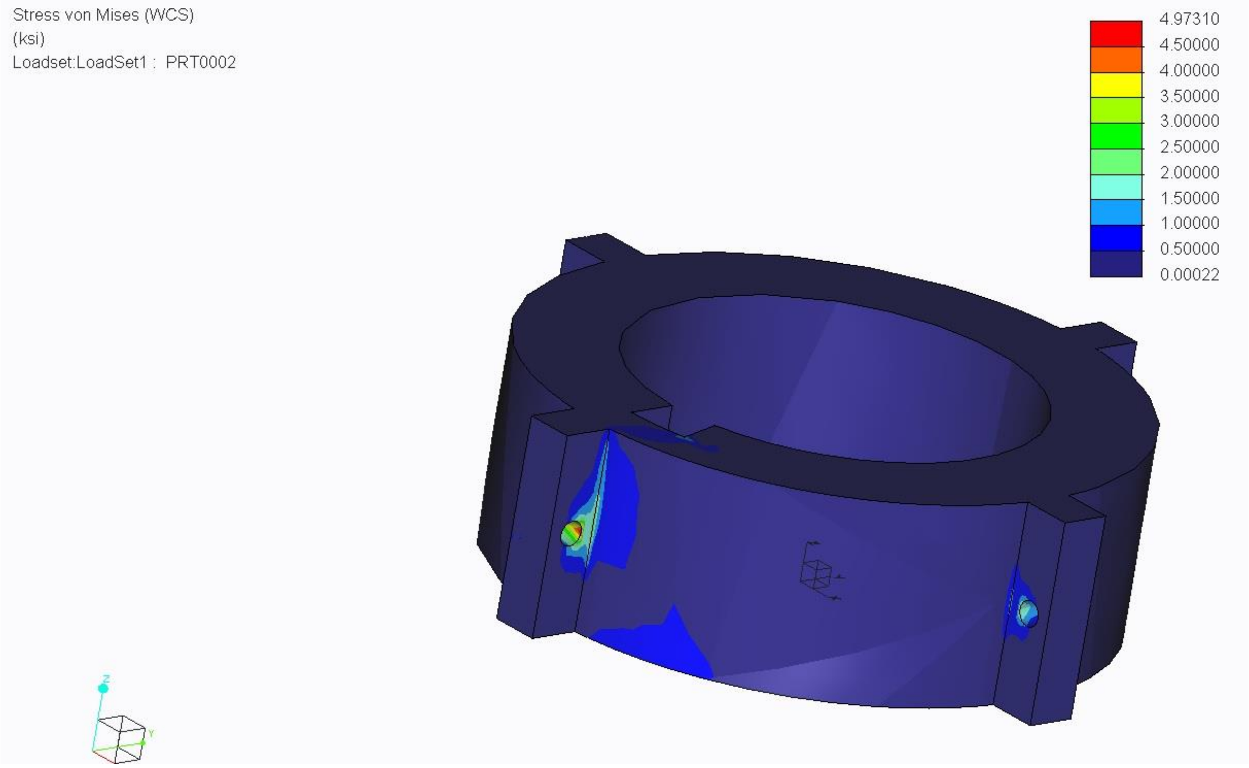


Figure 32: Stress Analysis of the Aluminum Joint, Side View

The pinhole closest to the locking slot experiences far greater stress than the other three, indicating that the weight is not evenly distributed among the pin holes. However, the highest stress shown is just under 35 MPa (5 ksi), which results in a factor of safety of about 3.8. The team decided this factor of safety is sufficient and does not necessitate redesign. However, if a higher factor of safety is desired, the locking slot could either be moved to distribute the weight better between an adjacent pinhole, more slots could be added to the interior of the joint, or the material could be changed to steel. Since the pin joints display non-uniform distribution of stress, it was necessary to also analyze the pins. In Figure 33, the total 41-kilogram weight was applied to the 6.35-millimeter section that is covered by the pinhole and was constrained at the ends of this section, because it is where the highest level of shear stress is expected to be experienced.

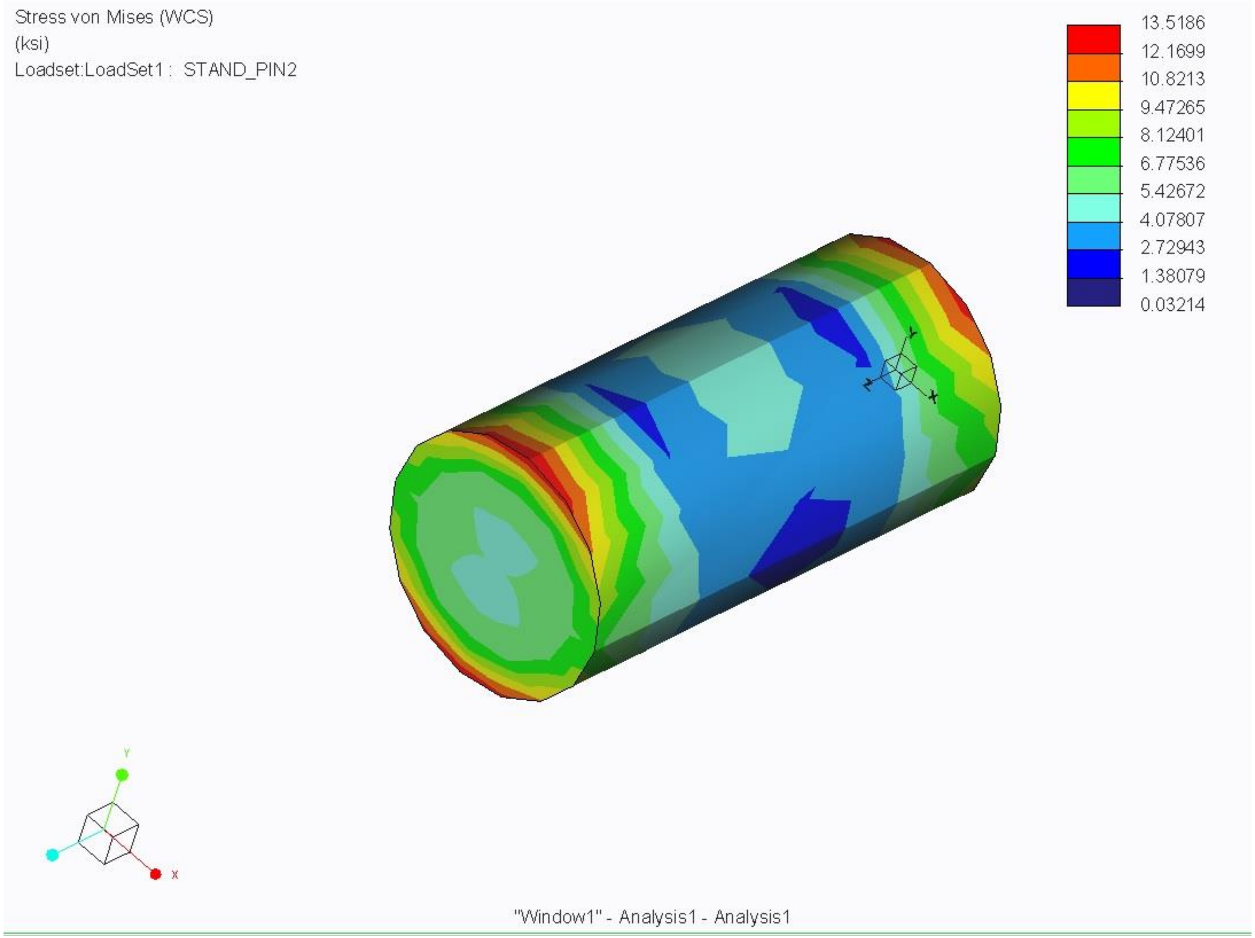


Figure 33: Stress Analysis of the Pin for Base Leg

The pin experiences a higher stress than the pinhole, because it is not as reinforced. The highest stress exhibited by the 3.175-millimeter diameter pin was about 93 MPa (13.5 ksi), which was far enough from the 131 MPa yield stress value of aluminum for it to produce an acceptable factor of safety. However, steel pins are more common and less expensive than aluminum pins and the yield strength of A36 steel is approximately 248 MPa [34]. Therefore, if a steel pin is used, it will give a minimum factor of safety of about 2.7, which was deemed acceptable by the team.

5. Analysis of Selected Design

5.1 Modifications

5.1.1 Cutter

During this phase, this cutter design was reevaluated for improvement. By rearranging the electrical components within the box, its size was able to be decreased from 228.6 millimeters by 7.127 millimeters by 127 millimeters (length by width by height) to 101.6 millimeters by 101.6 millimeters by 127 millimeters. Additionally, rather than having a wheel use friction to traverse around the circumference of the ring, a rack and pinion system will be used to reduce the likelihood of slippage. The platform upon which the cutter is mounted was also modified. Rather than a square-shaped platform with a triangular set of trusses, the new design uses a narrow rectangular platform and two thicker trusses for support. The thickness of the trusses will be 9.525 millimeters, allowing for greater vibration resistance and ease of manufacturing, since it will be made from the same stock material as the ring. Figure 34 depicts the new cutter design.

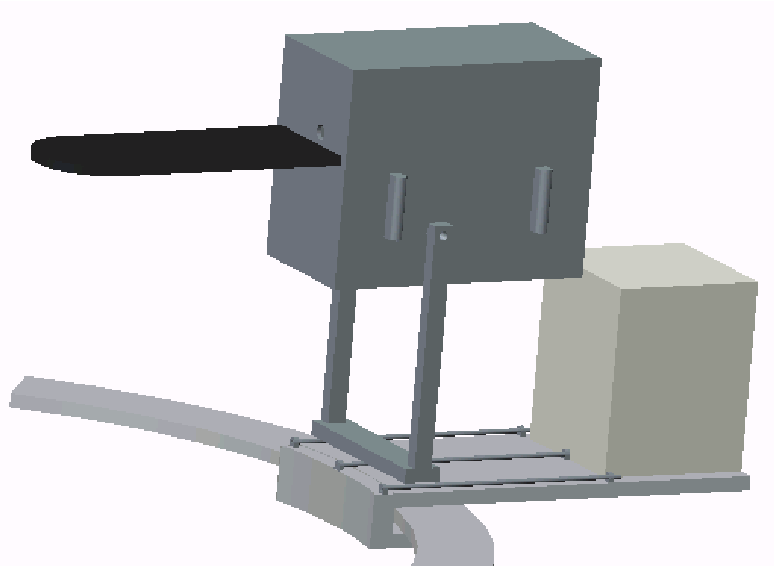


Figure 34: Modified Cutting Mechanism

5.1.2 Ring

The initial design for the ring consisted of a circular ring that would enclose the entire circumference of the tree's trunk, allowing for 360-degree access to the palm fruit. Due to budgetary constraints, aluminum was selected to fabricate the ring. In the Measure Phase, the ring was designed with an L-shaped cross section and a thickness of 9.525 millimeters. However, after a more complete analysis was conducted in this phase, it was found that with a thickness of 9.525 millimeters the L-shape would not be necessary to prevent excess deflection.

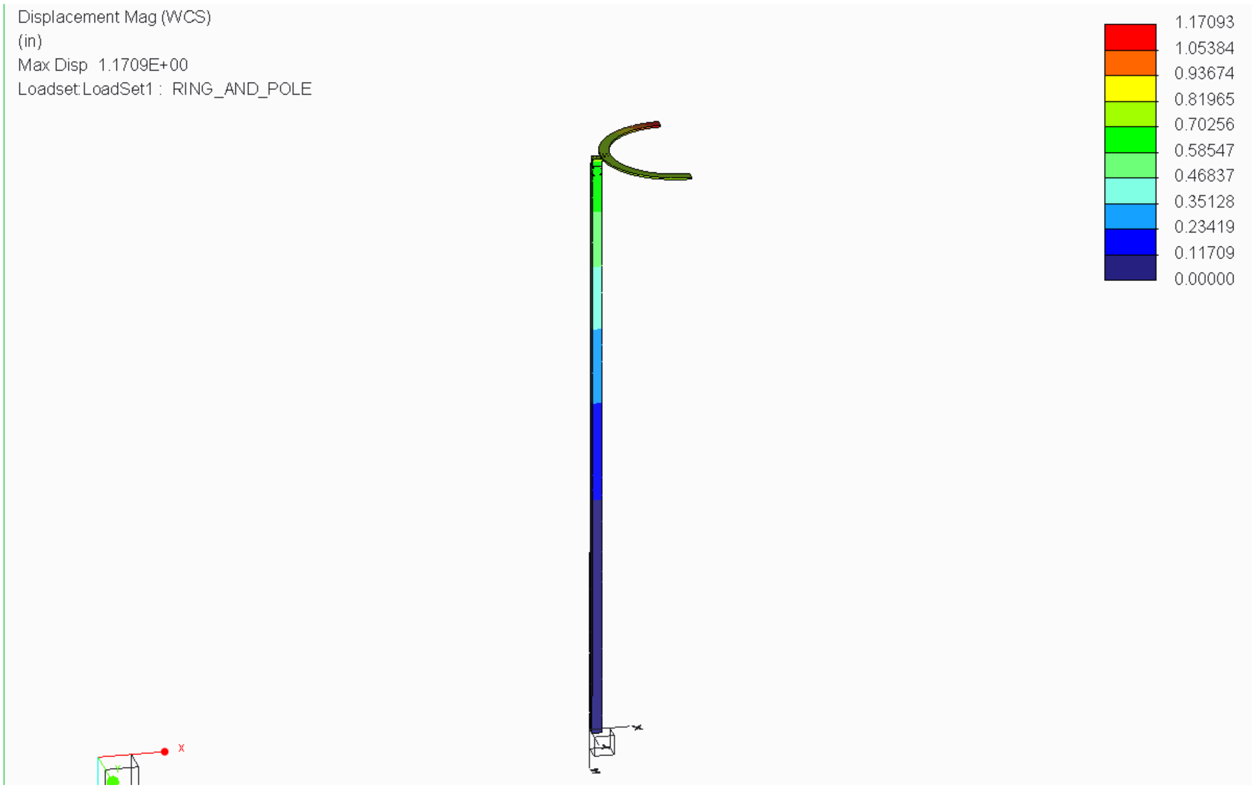


Figure 35: Deflection Analysis of Modified Ring

As shown in Figure 35, the new ring will actually experience slightly less deflection than the one designed in the Measure Phase, due to its lighter weight. The L-shape as a track was further proved obsolete with the use of the rack and pinion system. Additionally, to further decrease the weight of the ring, the fully circular ring was replaced with a semicircular ring and with the length of the cutting mechanism concentrated on the outer edge of the ring, the diameter was also able to be decreased from 1524 millimeters (60 inches) to 762 millimeters (30 inches). The ring will also be attached to the pole from its bottom, rather than its side, to further relieve the stresses acting upon it. After the ring design was completed, a FEA was conducted on it and is depicted in Figure 36.

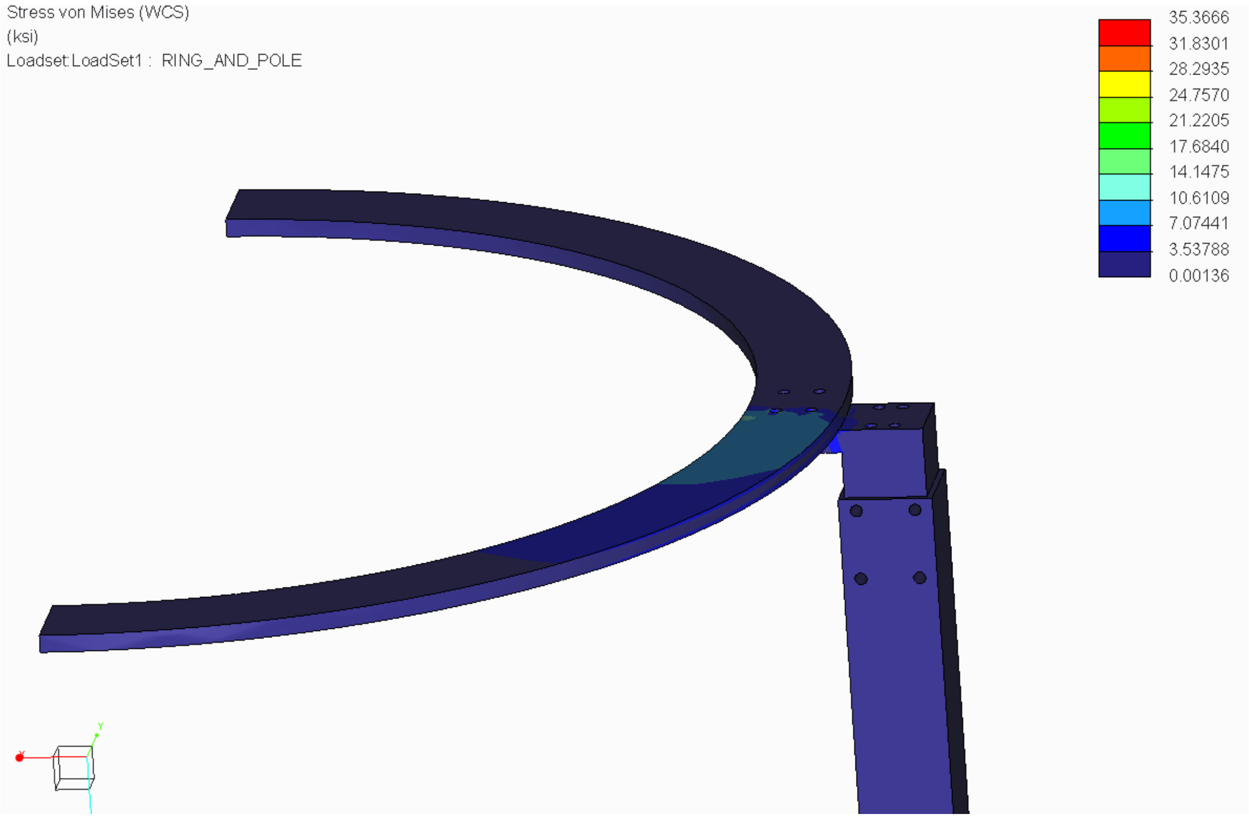


Figure 36: Stress Analysis of Modified Ring

Figure 36 shows that the highest stresses experienced by the actual ring will be no more than about 97 MPa (14 ksi), and with aluminum having a yield strength of 276 MPa (40 ksi) [22], this new design will give a factor of safety of about 2.9. The higher stresses of up to 241 MPa (35 ksi) depicted by the FEA will be felt by the block that connects the ring to the pole. According to the FEA, this will only be felt in a region thousandths of a millimeter wide and therefore will likely not cause excessive yielding throughout the rest of the block.

5.1.3 Pole

In the Measure Phase, a design for a poling system was selected but was not analyzed in time for the corresponding report, due to unknown errors in the FEA. The design consisted of a series of aluminum poles that were connected to one another with clamps and then lifted upward with the ring by the operator. However, this design was intended to be light enough to be carried by hand around a large plantation; after further analysis, it was determined that in order to withstand the column stresses associated with the weight of the ring and cutter, the pole would have to be over 101.6 millimeters in diameter. A pole of this diameter would mean that the total system weight would be approximately 45 kilograms, which would be far too heavy to be carried by hand. The design was then modified using the Class of 2015's telescoping poles. The telescoping poles are elevated using a system of pulleys shown in Figure 37 [9].

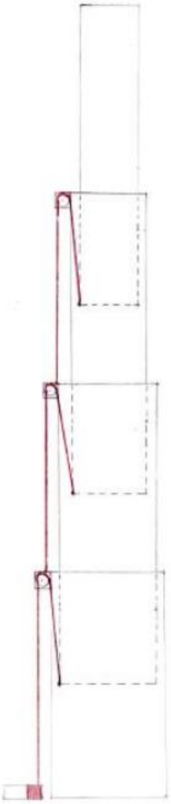


Figure 37: Class of 2015's Pulley Mechanism [9]

As shown in Figure 37, the pulley mechanism consists of three separate steel wires that are each grounded to a different pole. As the winch pulls the first wire and lifts the second pole, it will pull on the wire connected to the first stationary pole, which will cause the next pole to be lifted. The entire system will consist of four poles that are each 3 meters long, which sums to the required 12 meters. Each pole has a square cross section for easier machinability and component attachment; each pole’s outside widths, from the base pole to the top pole, are 127 millimeters, 101.6 millimeters, 76.2 millimeters, and 50.8 millimeters. The square cross section also allows for easier adaptation to the new ring and cutter mechanism, since it can be more easily attached.

The main benefit of using the poles from the Class of 2015’s design is that thorough analysis and testing has already been conducted on them. The Class of 2015 designed the poles to withstand high wind speeds and carry a weight of 18 kilograms. Their FEA is shown in Figure 38 [9].

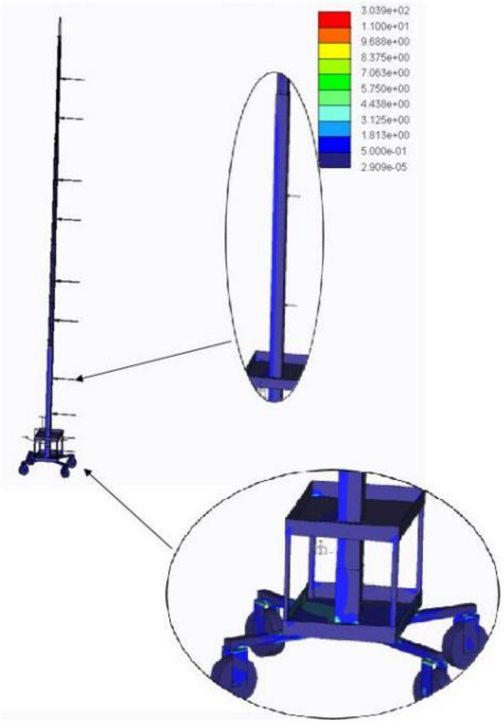


Figure 38: FEA (in MPa) of the Class of 2015's Design [9]

The results of the FEA indicate that the stress within the pole itself will not exceed 6 MPa. The higher stresses are felt within the cart that will be redesigned. Additionally, the Class of 2015 conducted a deflection analysis of the cart, shown in Figure 39 [9].

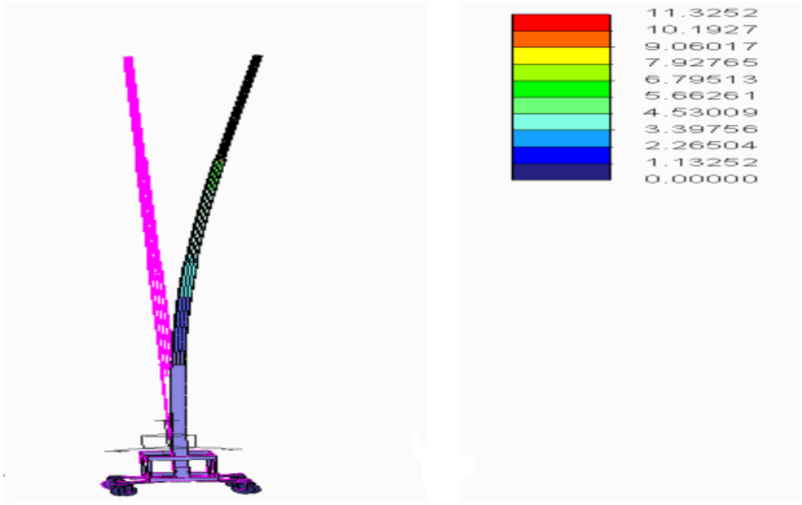


Figure 39: Deflection Analysis (in millimeters) of the Class of 2015's Design [9]

The analysis in Figure 39 indicated that with their applied loads, the Class of 2015's design would not exhibit more than 11 millimeters in deflection, which is acceptable for a mechanism of this size. The Class of 2015's poling system demonstrated that it was capable of lifting their 18-kilogramcutting mechanism without experiencing excess stress or deflection. Therefore, it is reasonable to conclude that it would be possible to attach the current team's cutting mechanism, which is expected to weigh less than 11 kilograms, to the top of the polling system with no added risk of failure. However, because the weight of the poles is expected to exceed over 45 kilograms and the weight of the winch and battery will add another 27 kilograms, the possibility of carrying the system by hand must be abandoned and an acceptable mobility platform must be designed.

5.1.4 Cart

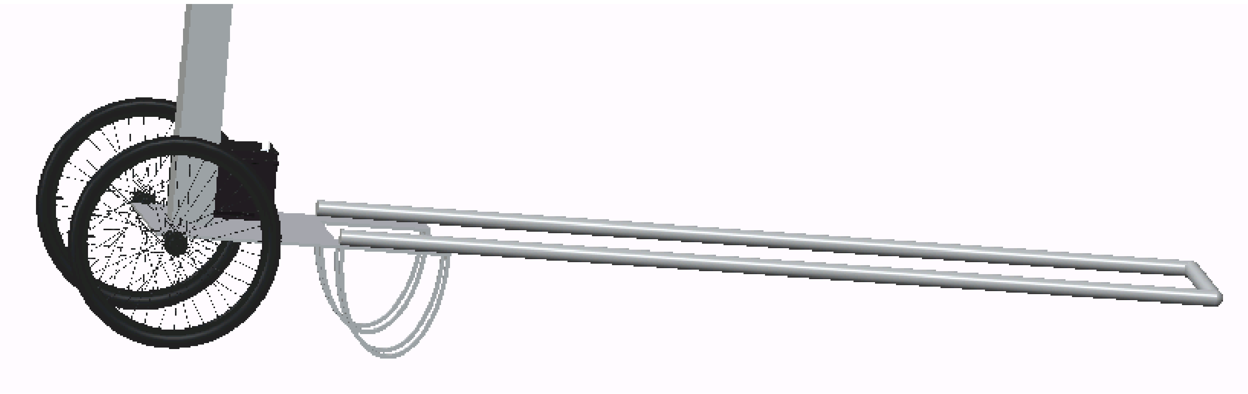


Figure 40: Cart

The mobility platform design that was selected is depicted in Figure 40. It is similar to the design of many modern rickshaws; by using long extended handles the operator is able to apply a large moment around the axis of the wheels, allowing them to lift and pull large amounts of weight. The handles in Figure 40 have a length of 3.35 meters. Unlike the Class of 2015's design, which utilized a four-wheeled cart, the mobility platform will use only two wheels, which will make it easier to maneuver on rough terrain. The cart's chassis will be modified from an existing 2-wheel wheelbarrow, to ensure that it is capable of withstanding the weight of the entire poling system. A FEA of the cart was conducted and is depicted in Figure 41.

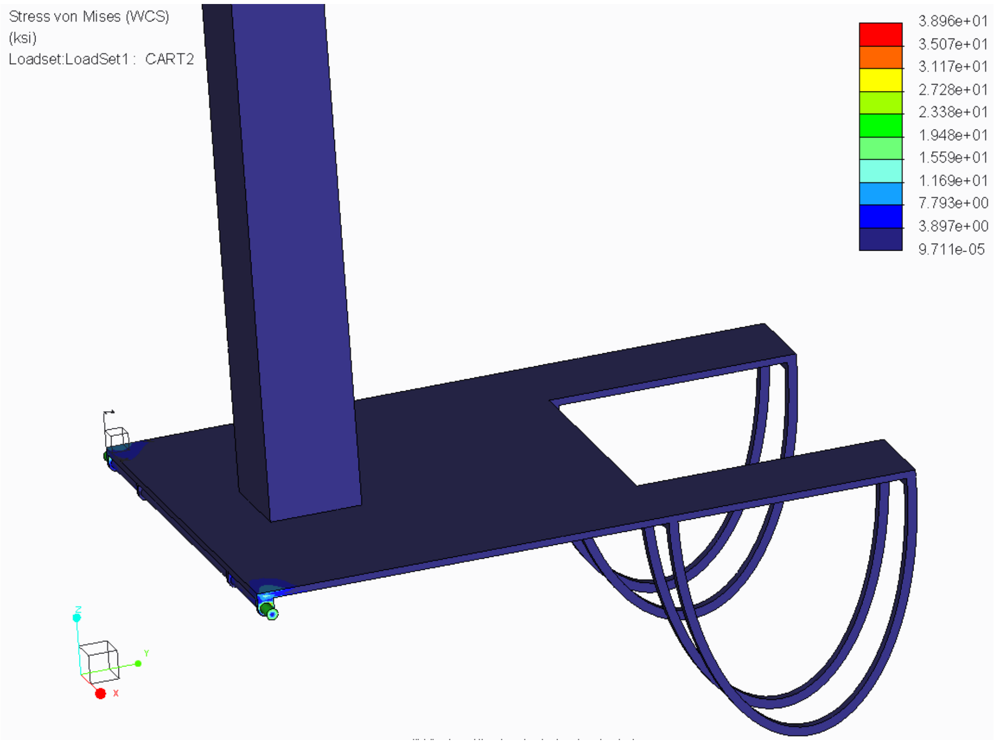


Figure 41: Stress Analysis of the Cart

As shown by the FEA in Figure 41, the platform itself will not experience stress above 110 MPa (16 ksi). Most of the higher stress values will be directed toward the wheelbarrow chassis, which is rated for 181 kilograms, far less than the weight of the polling system.

5.1.5 *Electrical Components*

A winch motor and a battery have been added to the base of the cart to assist with raising the telescoping pole. The winch motor selected is the Trakker 1-746-watt 907-kilogram Universal Winch and is shown in Figure 42 [35]. Since the weight of the telescoping pole and cutting mechanism is a small fraction compared to the capability of the winch, the motor will only need a fraction of its total power. Though the exact value of the amperes (A) drawn from this motor cannot be determined until it is tested, the team estimated that it will be between 20A–25A as a worst-case scenario; this estimation is half the value of the potential amperage the motor can draw. The battery that will power this winch is the 12-volt Super Start Marine – Deep

Cycle Battery and is shown in Figure 43 [36]. This battery is rated to last 225 minutes with a continuous draw of 23 amperes. The Palm Harvester group from Class of 2015 claimed that their telescoping pole using the same components took a total of 38 seconds to ascend and descend. Using this information and the energy capacity of the battery, this set up will allow the mechanism to ascend and descend a total of 355 times throughout one battery life. If the device were used for 12 hours, it would have to ascend and descend a tree 30 times every hour to drain the battery completely, which is unlikely to occur.

Figure 42: Winch Motor [35]

Figure 43: 12V Super Start Marine Deep Cycle Battery [36]

The addition of the components depicted in Figure 42 and Figure 43 will require an Arduino microcontroller at the base along with a motor driver and another receiver. The motor driver for this motor will need to be capable of supplying more amperage than the other motor drivers; therefore the team has selected the motor driver, shown in Figure 44 [37], that supports up to 30 amperes continuously. Having two different receivers will not cause an issue as long as the software is set up correctly. The second receiver has been ordered and is currently being delivered. Once the shipment is received, it will be connected to an Arduino microcontroller separate from the other transmitter and receiver and the functionality of the whole system will be tested.

Figure 44: Motor Driver for Winch Motor [37]

5.2 Testing

The Arduino wireless transmitter and receiver have been purchased and the order has arrived. The wireless components have been tested and the results suggest that they work properly. To test the functionality of these components, Derek and Alberto connected the receiver to an Arduino microcontroller and the transmitter to a separate microcontroller. The sample code for the components given from the manufacturer was utilized and altered for our test. The microcontroller connected to the transmitter was programmed to receive user input from a joystick (connected to the board) and then would transmit data depending on the user input. The microcontroller connected to the receiver was programmed to receive input from the transmitter and would use that input to decide which light-emitting diodes (LEDs), connected to the board, to toggle on or off. Using four LEDs, this simulated the manipulation of the motor driver to control two DC motors and the motor driver to control the stepper motor. With the transmitter operating at 9V volts and an antenna length of 101.6 millimeters, the receiver was able to pick up a signal wirelessly from approximately 49 meters. This would be enough distance to reach the cutting mechanism when it is erected, however, the team will be utilizing a design that will work from 80–100 meters when the transmitter is operated at 12 volts, with an antennae length of 152 millimeters. The circuits used for this test are depicted in Figure 45 and Figure 46.

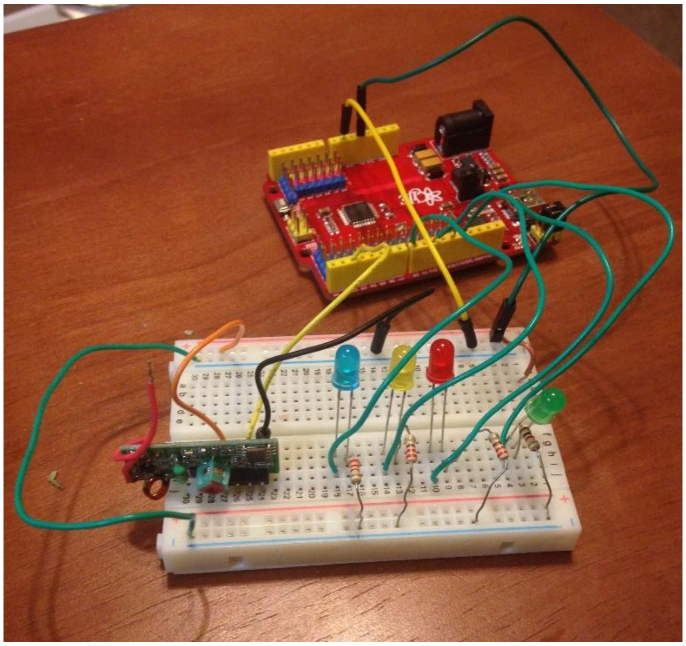


Figure 45: Receiver Testing Circuit

The code used to test the receiver circuit depicted in Figure 45 is given in Appendix A.

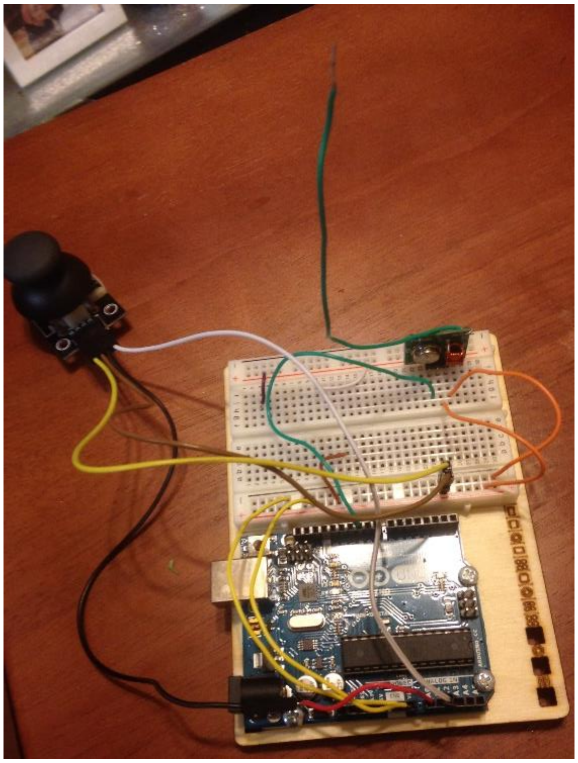


Figure 46: Transmitter Testing Circuit

The code used to test the transmitter circuit depicted in Figure 46 is given in Appendix B.

The Joystick Shield will act as the controller for the system; it has been ordered and is currently being shipped. Testing the controller will be similar to the testing of the wireless components. The previous code for the transmitter utilized a separate joystick for user input. The new code is modified to use the joystick on the Joystick Shield for user input along with the buttons on the shield. The controller code for the transmitter has been written and is shown in Appendix C, whereas the controller code for the receiver is shown in Appendix D. All different combinations will send a different signal that will toggle the LEDs in a unique pattern. Once the Joystick Shield works correctly, it will be used to as user input for the remaining tests. The controller will be deemed to have successfully passed its tests once every source of user input on it works properly.

The DC motors and winch will be controlled with a motor driver that will turn the motors on and off with their desired power. The motor driver is controlled by an Arduino microcontroller. These motors will be operated using Pulse Width Modulated (PWM) signals. The way a PWM signal works is shown in Figure 47 [38]. Code has been written to test the motors and is shown in Appendix E. This code is set for a PWM signal of 25% duty cycle. The code uses user input (from a joystick) to rotate a motor in each direction depending on the input. The team will test the motors with this code while the motors have no load, simply to test their functionality. Once they work, the only testing needed would be to find the appropriate duty cycle percentage. To do that, the motors will have to be tested with the load they will each have and the duty cycle must be increased or decreased depending on the motors performance. The two DC motors will operate at 22.2 volts and the winch will operate at 24 volts. The winch will be marked as functional once it can successfully manipulate the telescoping pole upward and downward. The DC motors will pass their tests when one of them can successfully traverse the ring left and right, and the other motor can successfully give the saw forward and backwards translation.

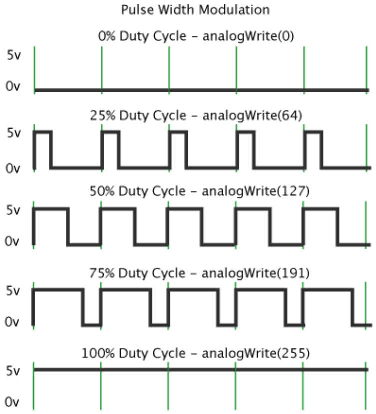


Figure 47: Graph Definition of PWM [38]

The stepper motor will also be controlled by a motor driver and the motor driver will be controlled by an Arduino microcontroller. The testing for a stepper motor is different than the DC motors. Since the stepper turns by making the internal magnets step one at a time, digital signals will be used instead of PWM signals. Therefore, the stepper motor has been tested without a load. This circuit is depicted in Figure 48. It will then be tested within the system with its load. The biggest challenge with testing the stepper motor will not be how it is controlled, but rather how it is physically set up instead of the system. This stepper motor will operate at 12 volts. The stepper motor passes its testing once it can successfully pitch the saw up and down. The code used to test the stepper motor circuit depicted in Figure 48 is given in Appendix F.

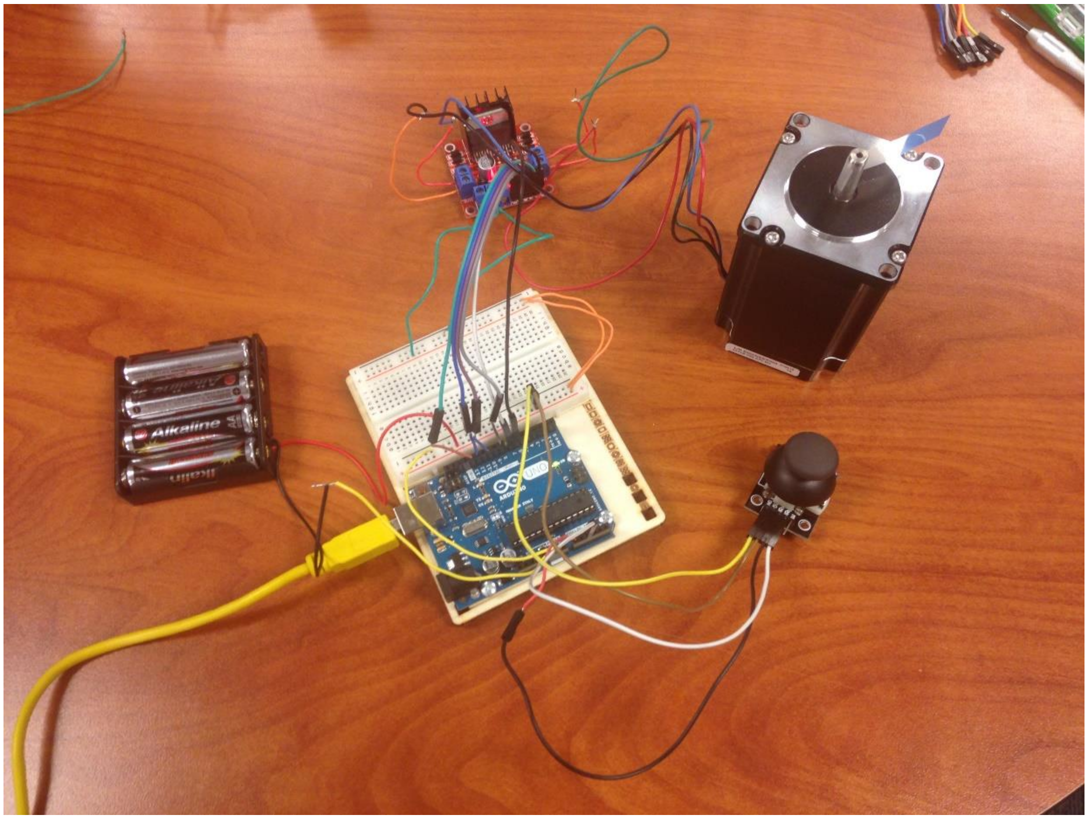


Figure 48: Stepper Motor Testing Circuit

The saw is operated by a DC motor. Like the DC motors, this motor will also be controlled by a motor driver. This DC motor differs from all the other motors for multiple reasons. Since this one is designed specifically to drive the saw, PWM signals will not be used and digital signals will be used instead. This motor, unlike the others, only needs to spin in one direction which simplifies the code even further. The code for this is given in Appendix G. The functionality of this system will be successful once the saw can be toggled on and off, through the push of a button on the controller.

Once every individual component has passed all of its tests, the whole system can be tested together. The complete cutting mechanism system will be tested on its own before being lifted up by the telescoping pole. When the cutting mechanism system can successfully traverse the ring left and right, pitch the saw up and down, provide forwards and backward translation of the saw, and turn the saw on and off, it is then ready to be attached to the poling. The first time the cutting mechanism is sent upward, the blade of the saw will be detached for extra safety. Once every single function seems to operate correctly, the saw blade can then be reattached and every function of the system will be tested once again.

6. Improving the Design

6.1 Optimizing Handle Length

The prototype design conceived in the Analyze Phase included long extended handle bars that would allow the operator to apply a large moment around the axis of the wheels to help lift and pull the device. The sponsor requested then that the team determine if the Occupational Safety and Health Administration (OSHA) had any guidelines regarding lifting devices over an eight-hour shift. Since this design’s handle bars had a length of 2.74 meters (9 feet), the sponsor wanted to see if the length of the handle bars could be shortened to improve the maneuverability of the cart, while ensuring that the operator did not injure himself or herself. OSHA does not publish guidelines regarding lifting, but instead refers to the National Institute for Occupational Safety and Health (NIOSH) [39]. The NIOSH publishes a lifting equation that is used by occupational health and safety professionals to assess the manual material handling risks associated with lifting tasks in the workplace.

The NIOSH lifting equation outputs a recommended weight limit (RWL) that is based on seven quantities. The NIOSH lifting equation is [40]:

$$RWL = LC \times HM \times VM \times DM \times AM \times FM \times CM$$

Table 32 describes the function of each quantity in the lifting equation [40].

Table 32: NIOSH Lifting Equation Quantities [40]

Task Variable	Abbreviation	Definition	Relevant Figure or Table (if applicable)
Load Constant	LC	Set to a constant 51 pounds, which represents the maximum load that should be lifted under ideal conditions [40]	Not applicable
Horizontal Multiplier	HM	Horizontal location of the object relative to the body	Figure 49 [40]
Vertical Multiplier	VM	Vertical location of the object relative to the floor	Figure 49 [40]
Distance Multiplier	DM	Distance the object is moved vertically	Not applicable
Asymmetry Multiplier	AM	Asymmetry angle	Figure 50 [40]
Frequency Multiplier	FM	Duration of lifting activity	Not applicable
Coupling Multiplier	CM	Quality of the workers grip on the object	Table 33 [40]
Load	L	The effective weight of the object lifted	Not Applicable

The HM requires the horizontal location of the hands at the origin and destination of the lifting task to be measured, as shown by the letter “H” in Figure 49 [40]. The VM requires the vertical location of the hands at the origin and destination of the lifting task, as shown by the letter “V” in Figure 49 [40]. Finally, the DM is determined by subtracting the vertical location at the origin from the vertical location at the destination.

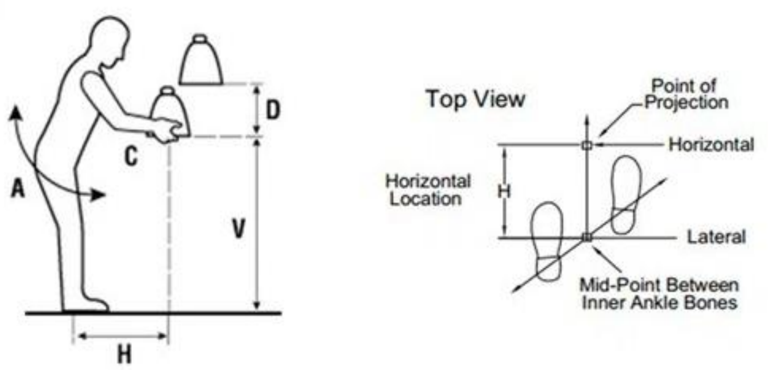


Figure 49: HM, VM, and DM Definitions [40]

The asymmetric angle measures how much the operator’s body will be required to twist during a lifting task, in degrees, as shown in Figure 50 [40] . If no twisting is required, the AM has a value of 0 degrees.

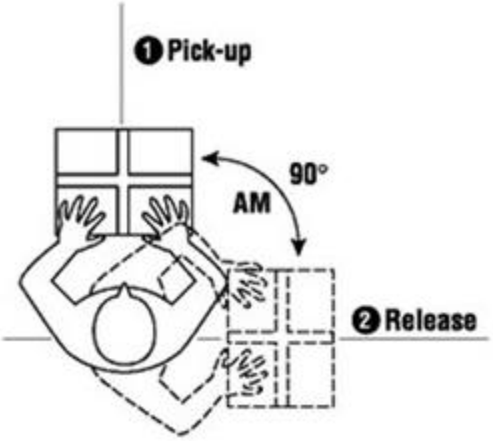


Figure 50: AM Definition [40]

The frequency multiplier uses the amount of lifts per minute to generate a value for the equation. These values are determined automatically by entering the frequency of lifts per minute in a NIOSH calculator [40].

The CM classifies the coupling between the worker's hands and the object as good, fair, or poor [40]. Good coupling will require the operator to exert less force holding the object being lifted, while poor coupling will require more force. The coupling classifications used for the NIOSH equation are given in Table 33 [40].

Table 33: NIOSH Coupling Classifications [40]

Coupling	Classification
Good	Used for objects that have optimally designed handles, or irregular objects where the operator's hands can easily wrapped around the object.
Fair	Used for objects with handles that are not optimally designed, or irregular objects where the hand must be flexed approximate 90 degrees.
Poor	Used for objects with no handles or cut-outs, or irregular objects that are bulky and difficult to handle, such as a sandbag.

The NIOSH equation will yield a RWL for the origin and destination lifting tasks. If the lifting task requires precision at the beginning and end of the task (e.g. moving a box with a fragile object inside of it), then the minimum RWL of the origin and destination should be used to determine the task's overall RWL [40].

Once the RWL is obtained, the lifting index (LI) can be obtained using the equation [40]:

$$LI = \frac{Weight}{RWL}$$

The LI is a quantitative measure of the risk involved in the lifting task. A LI value greater than 1.0 means that the task is high risk, while a LI value less than 1.0 indicates that the risk is nominal to healthy employees [40].

The team used the NIOSH lifting equation to compute the RWL and then computed the LI. These calculations are shown in Appendix J and yield an RWL of 14.80 kilograms (32.62 pounds) for the task.

Since the NIOSH equation allows a weight of 14.80 kilograms to be lifted, the free body diagram depicted in Figure 51 was used to determine the optimal length, x, of the cart handle.

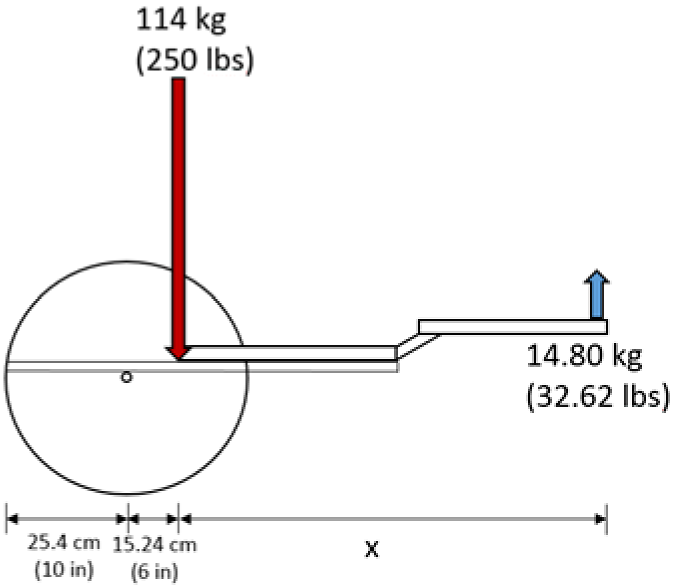


Figure 51: Free Body Diagram of the Cart

Using Figure 51, a moment equilibrium equation was used to compute the optimal length, x, of the cart handles. The forces that act in the counterclockwise direction relative to the free body diagram were given a positive value, while the clockwise forces were given a negative one. This calculation also specifies that the weight of the cart is 114 kilograms. Since the NIOSH equation outputted a value in pounds, the calculations were performed using United States customary units and then converted to metric ones.

$$\Sigma M = (-250\ lb \times 0.5\ ft) + (32.62\ lb \times x\ ft) = 0$$

$$125\ lb = (32.62\ lb \times x\ ft)$$

$$x = 3.83\ ft = 1.17\ meters$$

Thus, the minimum length of the handles for the cart is 1.17 meters. Extending the length of the handles will decrease the weight that the operator will lift. This calculation the team to shorten the length of the cart handles from 3.35 meters to 1.22 meters. The new cart is depicted in Figure 52.

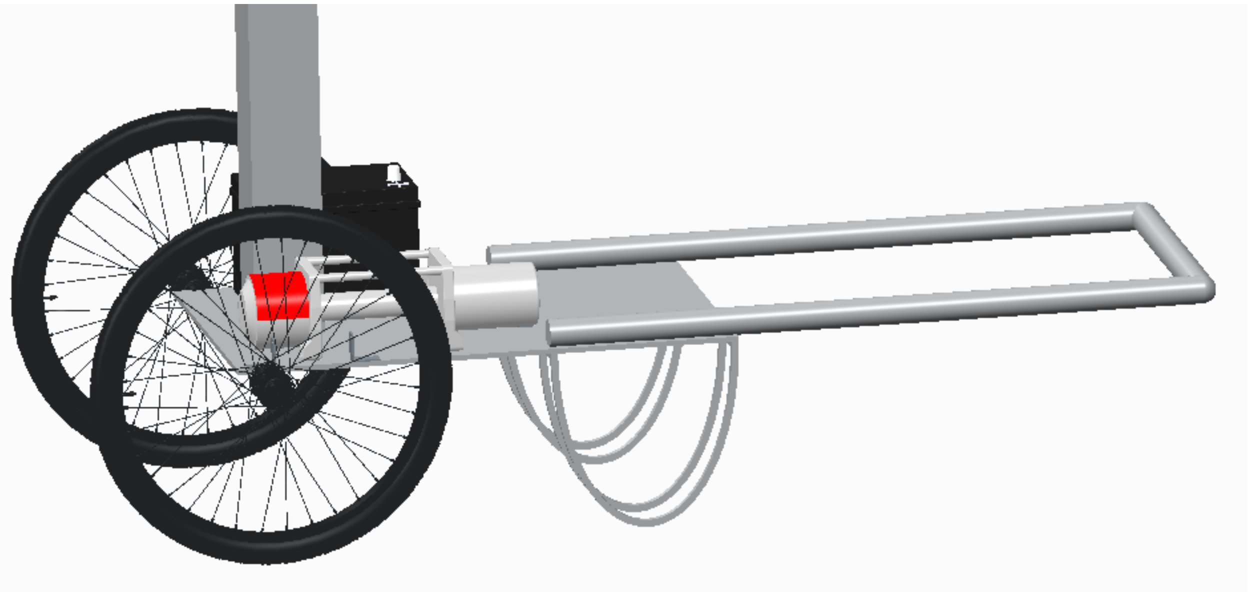


Figure 52: Optimized Cart Handle

6.2 Mounting Improvements

Previously, the pole was designed to be welded rigidly onto the cart. While initial analysis indicated that this method was capable of withstanding very high loads, it meant that the pole and the base plate could not be separated if work needed to be performed on any of the individual parts. In order to address this issue, the pole would have to be mounted using screws and nuts in a way that would not sacrifice its strength. The use of steel L-brackets was analyzed within the context of the expected loads and the FEA depicted in Figure 53 was developed.

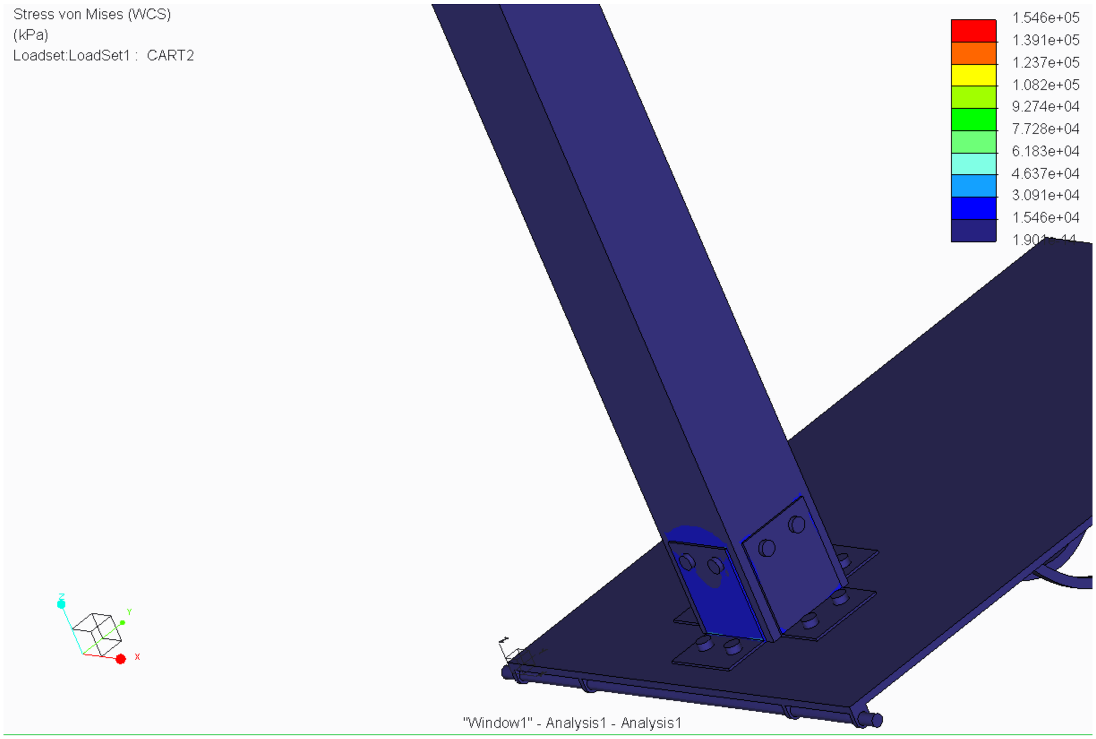


Figure 53: Bracket FEA

Using ½" steel nuts in 16 different locations and placing a 130-Newton force at a distance of the full 12 meters away, the highest stresses experienced were in small, isolated regions, with their maximum reaching 154 MPa. For the most part, however, the stress did not exceed 108 MPa. While the exact alloy of steel is not specified by the manufacturer, A-36 steel is a fairly weak steel and its yield stress is 250 MPa [41], which provides a factor of safety of about 1.5 to 2. The 130-Newton force is the equivalent of the system at a 10-degree angle. While this angle may seem small, at 12 meters away, that would mean that the top of the pole would be at a 2-

meter distance from the fruit, much too far for operation. Therefore, the forces during normal operation are likely to be much lower, providing even higher factors of safety.

6.3 Electrical Component Assembly and Testing

Electrical components that were received after the Analyze Phase were assembled and tested. The results are presented in this subsection.

6.3.1 Controller Assembly

The controller for the device was constructed using an Arduino Uno, a Joystick Shield, a transmitter, and a battery holder. The transmitter was taped behind the Joystick Shield. The battery holder contains six AA cell batteries that power the board with 9 V. The battery holder's wires were soldered to a barrel male plug and the joints were covered with heat shrink tubing. This plug connects directly to the Arduino and enables it to be powered without directly soldering the wires to the board. The controller is shown in Figure 54. The schematic of this controller is shown in Figure 55.

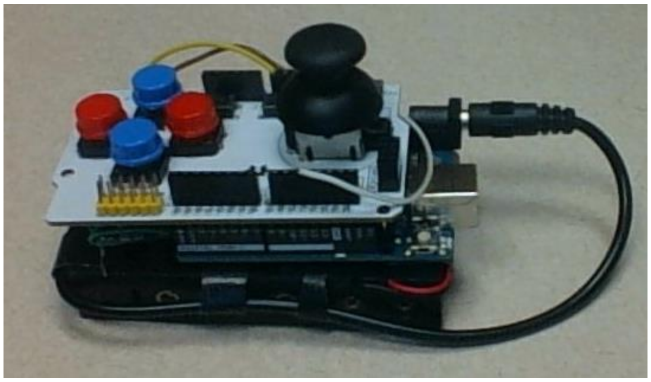


Figure 54: Controller

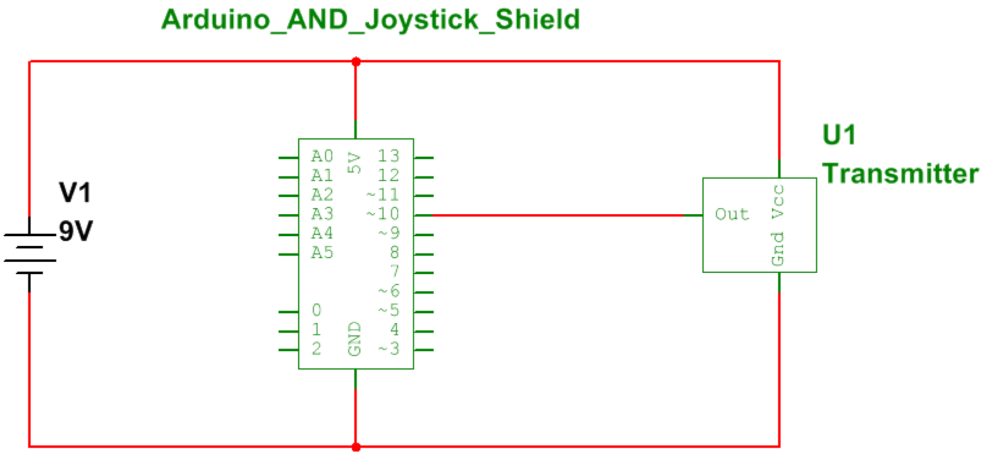


Figure 55: Controller Schematic

6.3.2 *Controller Testing*

The functionality of the controller was tested using a second Arduino connected to a receiver and several LEDs. This Arduino was programmed to receive the wireless signal from the controller and turn on an LED depending on the user input. This testing circuit is depicted in Figure 56.

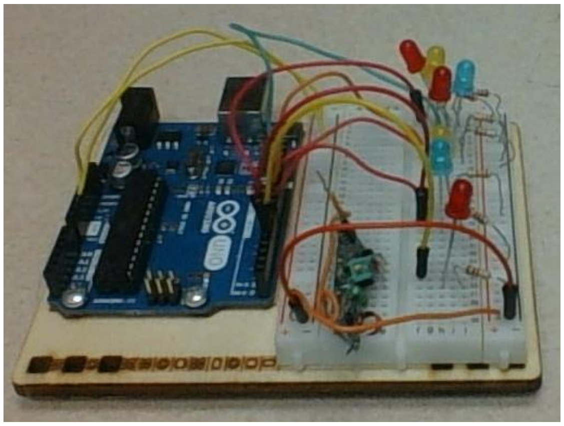


Figure 56: Receiver LED Testing Circuit

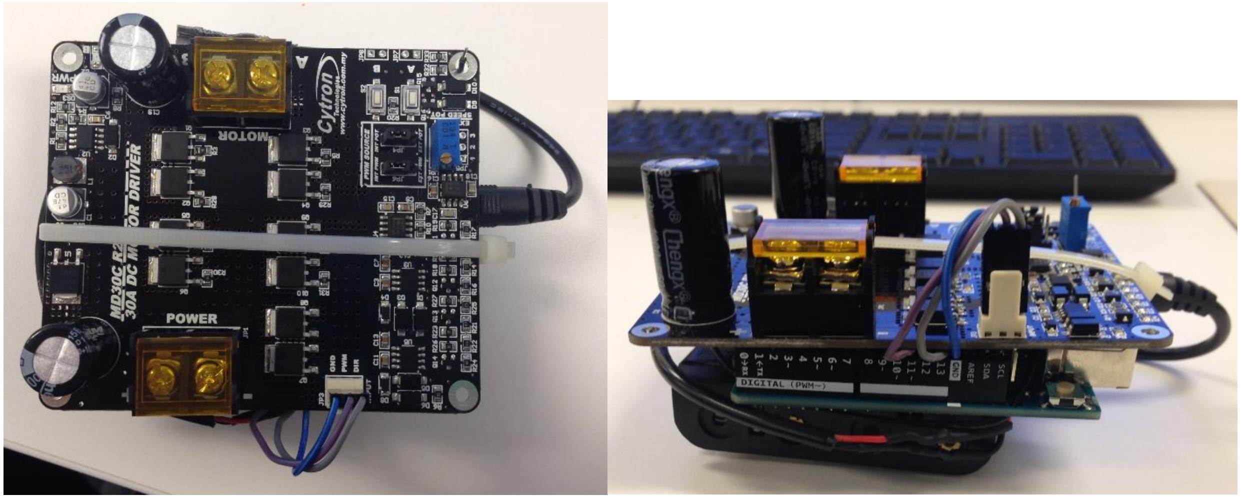
This test confirms that the controller is successfully transmitting a signal and the receiver is successfully receiving it. The LEDs in this test also simulate the toggling of motor drivers in the cutting mechanism. Using the same circuits, the team tested the distance from which a signal could be successfully received from the transmitter. The team found that the controller can operate over a distance of 90 meters. When any electrical components were constructed or altered, the power supply was disconnected and was only connected when the actual test was being conducted. Table 34 shows the outputs that correspond with each input from the controller. The testing code used is given in Appendix K.

Table 34: Inputs and Corresponding Outputs from the Controller

Input	Output
Joystick Up	Forward motion of saw toward tree
Joystick Down	Backward motion of saw away from tree
Joystick Left	Traverse counter clockwise around ring
Joystick Right	Traverse clockwise around ring
Button A	Pitch saw upward
Button B	Pitch saw downward
Button C	Moves pole downward
Button D	Moves pole upward
Button E	Turn on saw
Button F	Turn off saw

6.3.3 Cart Electronics

The electronics for the cart have been assembled and are depicted in Figure 57. An Arduino Uno is connected to a receiver, a motor driver, and is powered by four AA cell batteries. The schematic for these electronics is shown in Figure 58.



(Top View) **(Side View)**

Figure 57: Cart Electronics

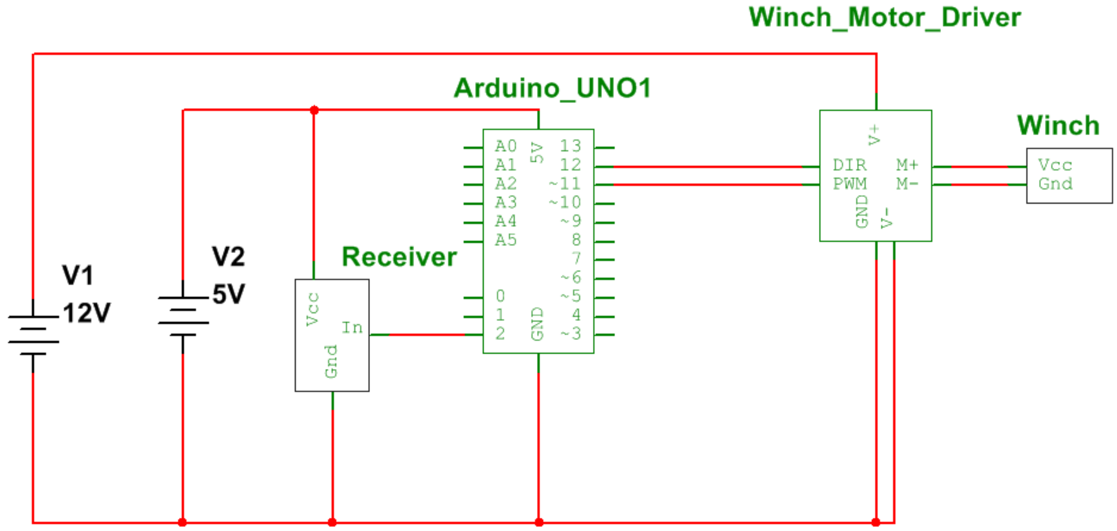


Figure 58: Schematic of Cart Electronics

The motor driver connects to the boat battery and the winch. The board is programmed to receive a signal from the controller and will instruct the motor driver in which direction to turn the winch. The input for operating the winch is through Button C and Button D of the controller. The buttons allow for more precise movement of the pole than the Joystick. The cart electronics were tested using the circuit depicted in Figure 59. This test simply rotated the winch in one direction and then in the other direction. The same test will be used to test the pole’s upward and downward movement; the only difference is that the winch will be connected to the pole. The code used for these tests is given in Appendix K.

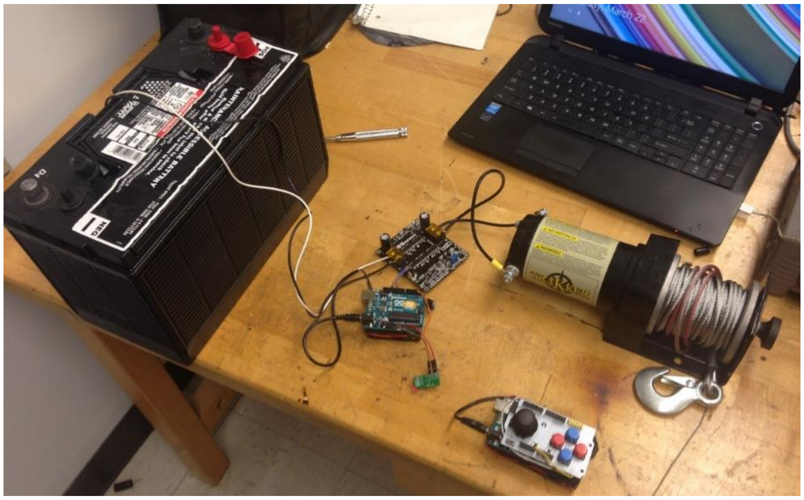


Figure 59: Functionality Test for Cart Electronics

6.3.4 Cutting Mechanism

The motors and motor drivers were constructed and tested for functionality. Figure 60 depicts the no-load testing circuit.

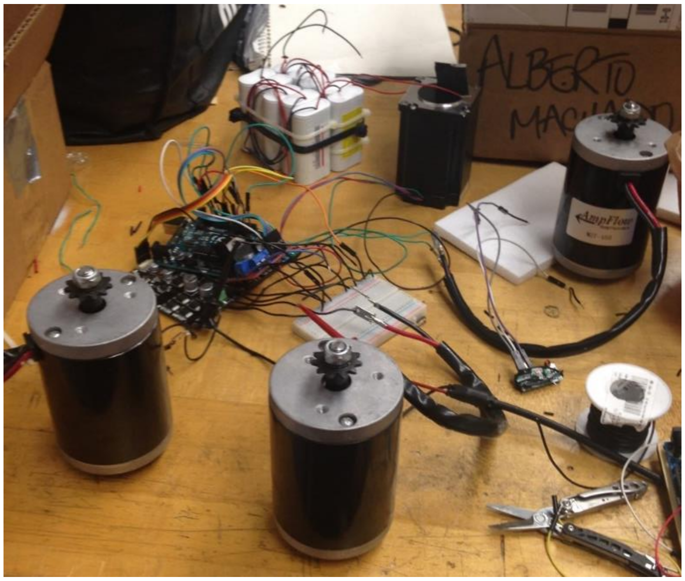


Figure 60: Functionality Test for Motor Drivers and Motors

The Joystick Shield was attached to a board containing the transmitter. When the user inputs a command on the Shield, a corresponding signal is transmitted. Another Arduino attached to the receiver obtains the signal and controls the motors through motor drivers powered from an 18.5 V power supply. In this test, movement of the Joystick upward and downward rotated a DC motor forward and backward, whereas moving the Joystick leftward and rightward rotated the second DC motor. The buttons “A” and “B” rotated the stepper motor clockwise and counterclockwise, respectively. The button “E” turned on the saw motor and button “F” turned off the saw motor. These tests showed that the motors operated successfully. The final schematic for the cutting mechanism electronics is depicted in Figure 61.

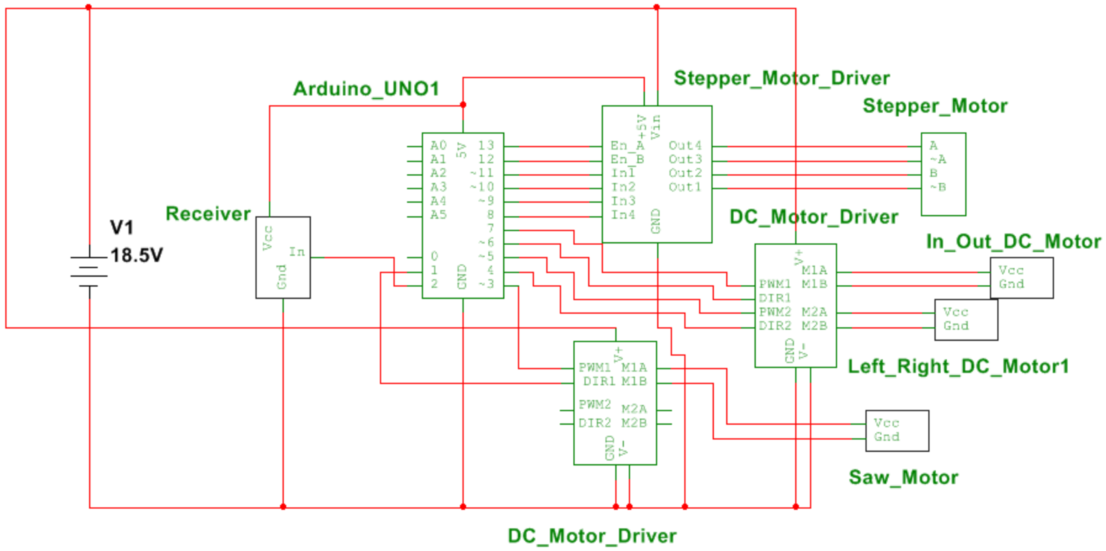


Figure 61: Final Cutting Mechanism Schematic

To ensure the team’s safety, the power source remained in the off position until it was ready to be tested. If any changes were needed during testing, the power source was turned off until the modifications were completed. The same test for functionality will be done when testing the completed cutting mechanism system. After all components are placed in their correct spots with the correct connections, each degree of freedom will be tested individually. The mechanism is found to be completely functional once each degree of freedom operates correctly and that the saw turns on and off. The testing code used is given in Appendix K.

6.3.5 Batteries

The previously selected batteries for the cutting mechanism are 16 rechargeable D cell batteries, connected in series, which output 24 V with a capacity of 10 amp-hours. Due to purchase order restrictions at the FAMU-FSU College of Engineering, these particular batteries were unable to be ordered. Instead, the team ordered and received ten of the lithium-ion batteries shown in Figure 62 [42].

Figure 62: Selected Batteries for Cutter Mechanism [42]

These batteries are rechargeable and have a voltage of 3.7 V each and a capacity of 4.4 amp-hours. Figure 63 depicts the batteries assembled and connected in series.

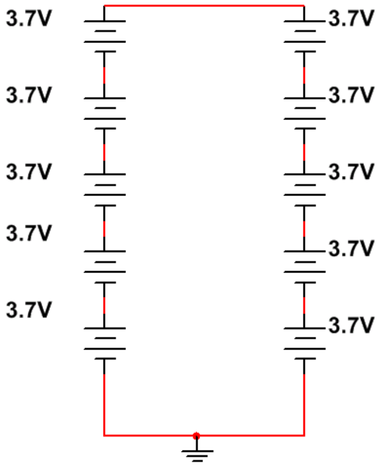


Figure 63: Layout of Cutter Mechanism Batteries

Ten batteries were split into two sets of five; each set of five batteries is connected in series to output 18.5 V. The two sets are then connected in parallel to increase the capacity from 4.4 amp-hours to 8.8 amp-hours. The terminals of the batteries were soldered together in series and covered by heat shrink tubing. The two sets were then secured using zip ties. These batteries are shown in Figure 64. The total weight of these batteries is approximately 0.68 kilogram.

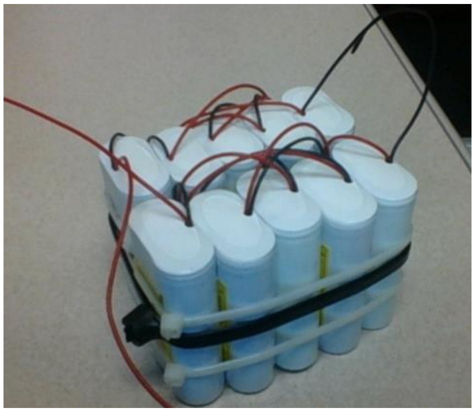


Figure 64: Battery Pack for the Cutting Mechanism

7. Final Prototype

7.1 Prototype Assembly

A safety analysis was first performed and is discussed in Section 7.1.1. The cart assembly discussed in Section 7.1.2 has been completed. As of this writing, the cutter assembly discussed in Section 7.1.3 has not yet been completed. The cutter should be assembled by April 19, 2016.

7.1.1 Safety Considerations

The team developed a safety plan prior to assembly, to determine the protective measures required to avoid any injuries. Table 35 explains dangerous tasks and the actions that should be taken to minimize any risks.

Table 35: Safety Plan

Risk	Who might be harmed and how?	How is the risk managed?	Performed by	Action performed by	Completion date
Strained muscles from lifting	ME and assembly team. Bad lift positions and weight.	Assemble prototype with several workers.	Assembly Team	03/14/2016 – 03/31/2016	04/12/2016
Cutting saw/drill	ME and assembly team. Risk of cuts and wounds with working equipment.	Cover the cutter's saw and use gloves to change the drill bit	Assembly Team	03/14/2016 – 04/04/2016	04/12/2016
Slippery ground/floor	ME and assembly team. Staff may be injured if they trip over prototype's components.	Make use of tarps and ensure that dry the working area.	Assembly Team	03/14/2016 – 03/24/2016	04/12/2016
Inclement weather	ME and assembly team. Poor good environment for assembly.	Check the weather forecast and possibly work with an umbrella.	Assembly Team	03/14/2016 – 03/31/2016	04/12/2016
Loss of equipment	Staff. Disrupts assembly and would result in additional expenditures.	Store device in a secure location.	Assembly Team	03/14/2016 – 04/12/2016	04/12/2016

7.1.2 Cart Assembly

1) Using a water jet, cut out a 24” x 36” plate of aluminum and a 30” diameter semi-circle out of the 42” x 45” sheet of aluminum.
2) Attach the ring to the mount using ¼”-20 screws.
3) Using ¼”-20 screws again, mount the ring assembly to the smallest pole using the insert block.
4) Using a ½” drill bit, screw two holes into the base plate in order to attach the wheelbarrow axle.
5) Attach the wheels to the axle using the pins provided by the manufacturer.
6) Using a ½” inch drill bit, drill eight holes into the bottom pole, as well as eight holes into the base plate.
7) Attach the pole to the cart using eight L-brackets and 16 ½” nuts and bolts
8) Attach a steel rope to the bottom of the second pole and slide the second pole into the first pole.
9) Loop the steel rope through the pulley attached to the top of the first pole and then attach it to the winch.
10) Attach a second steel rope to the bottom of the third pole and slide the third pole into the second pole.
11) Loop the rope around the pulley attached to the top of the second pole and attach it to the top of the first pole.
12) Follow Steps 8–11, looping the rope through the pulley on the top of the third pole and attaching the rope to the top of the second pole.
13) Using a 5/16” drill bit, drill two holes in the cart and mount the winch using the screws provided by the manufacturer.

14) Out of two 2”x4”x96” wooden boards, saw two 45° cuts into each board.

15) Screw the cut pieces together in such a way that they form a Z-shape.

16) Using board mounts, attach the two Z-shaped handles to the cart by drilling eight ½” holes onto the base.

17) Secure the handles to one another by screwing a board in between them.

18) Secure the battery inside the battery box and screw four ¼” holes into the base.

19) Attach the jack to the cart using four ¼” screws and lower it to a height that provides a level platform.

20) The cart is now ready for operation. The completed cart is depicted in Figure 65.

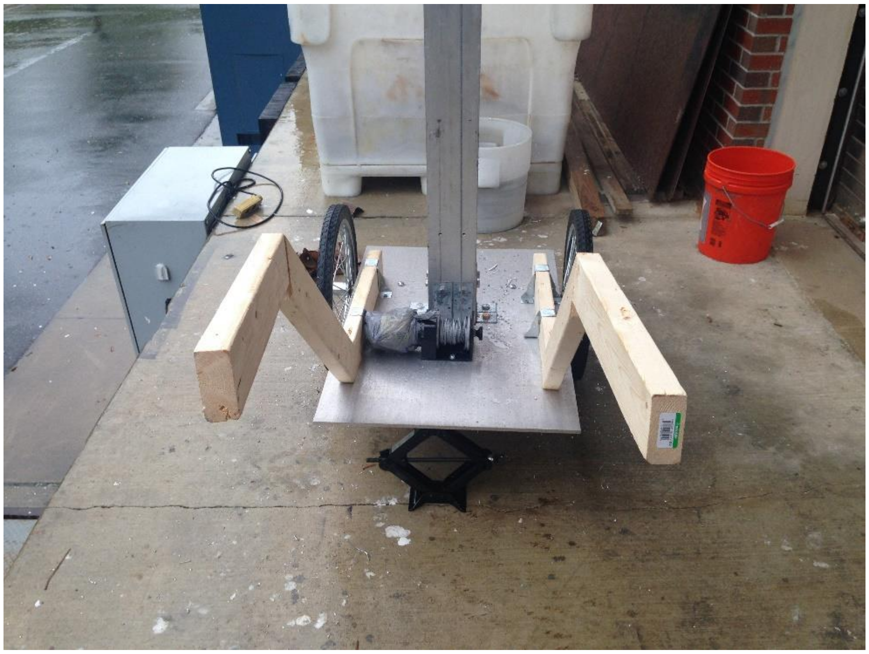


Figure 65: Completed Cart

7.1.3 Cutter Assembly

1) Using a 3D Printer, print out the housing for the electronics and the saw.

2) Insert the saw and pitch motor into the 3D printed housing, as well as their power supply and electronics.

3) Fabricate the two aluminum platforms, as well as the mounts for the cutter out of the 42” x 45” aluminum sheet, utilizing a water jet.
4) Weld the mounts onto the forward/backward translating platform.
5) Weld the side platform for the traversing motor onto the main platform.
6) Screw in the linear bearings and lead screw nut onto the bottom of the translating platform.
7) Mount on the lead screw and guide shafts onto the main cutter platform.
8) Attach the translating platform to the main platform using the lead screw and guide shafts.
9) Mount the cutter box onto the translating platform by press fitting the motor shaft to the mounts.
10) Slide in the electronics box onto the slot on the main platform and connect all components.
11) Screw in the traversing motor to side platform and attach pinion on bottom side.
12) Using an adhesive, attach the rack onto the ring.
13) Position the cutting mechanism onto the ring such that the pinion fits into the rack.

7.2 Operating Instructions

The device is designed to be very simple to operate. The user maneuvers the cart like a wheelbarrow by using the handles, and positions it in front of a tree. The operator then adjusts the jack at the front of the cart to make sure the cart is level. The controller is then used to lift the poles upward, utilizing the winch, to the appropriate height. The user can then adjust the position of the cart along the circumference of the ring, as well as its translational distance from the tree and its pitch using the Joystick and buttons on the controller. Once the appropriate amount of fruit is cut, the user can then lower the poles downward again and move the cart to the other side of the tree and repeat the process.

7.3 Specifications

The sponsor’s requirements were discussed in the voice of the customer diagram depicted in Figure 6 and in the house of quality depicted in Figure 9. Table 36 shows how the prototype meets each of the sponsor’s requirements.

Table 36: Verification of Sponsor’s Requirements

Required Specification	Prototype Results
Reach fruit 12 meters from the ground	Winch-assisted telescoping poles lift saw blade up to 14 meters.
Waterproof	All electronics are contained in waterproof polylactic acid (PLA) housings.
Lightweight/Portable	1.22-meter moment arm provides an equivalent lifting weight of 12.70 kilograms, which is under the NIOSH recommended limit of 14.80 kilograms for a worker.
Harvest fruit in under 20 minutes per tree (faster than a worker climbing the tree)	Prototype was able to ascend, traverse, and descend in a total time of 8.63 minutes.
One operator	The controller and handles allow for the whole process to be conducted by only one worker.
Harvest fruit around the whole circumference of tree	Design can traverse around half the tree and then be moved to the other half and still be faster than the average worker.

8. Business Analysis

8.1 Economic Analysis

Last year’s team was allotted a budget of $2,500 to build an oil palm harvesting device [9]. However, this device did not meet the customer’s requirements, because it was not portable. The team is tasked with designing a portable harvesting device with the same budget of $2,500.

If more money is required to complete the design, the sponsor is willing to expand the budget. Despite the high initial cost of purchasing a mechanical harvesting device, the product should cost less to maintain than the annual salary of a worker. Data for Malaysian workers were used to calculate the return on investment, since Malaysia is a leading producer of oil palm fruit [3]. These calculations assume that a Malaysian worker earns a minimum wage of $297 per month, oil palm plantations contain hundreds of trees, oil palms are harvested daily for eight hours [2], and that the device would be sold for $2,000 (Table 1). The calculations shown in Appendix H yield a return on investment of 78.20%, which means that the long-term labor savings outweigh the high initial purchase price. Currently, the only money lost to current harvesting methods involves the equipment and human labor required to climb trees and manually cut fruit bunches [2].

8.2 Environmental Impact

When creating a final design, the team considered various outcomes to reduce the environmental impact of the design. The team has selected three manufacturing processes to complete the design: water jetting, additive printing and rolling. None of the selected manufacturing processes directly affect the environment. While production will involve the mechanical assembly of modeled parts, no components will be made from toxic or caustic materials. A variety of batteries were selected as the energy source for the final device, if handled with care, it is unlikely that they will transfer any hazardous waste to the surrounding environment. The main environmental concern for this project is damaging the oil palm tree while the harvesting device is used. The selected design does not attach to the palm tree in any way, which avoids any puncturing of the tree’s trunk. Thus, only applied, concentrated, and fixed forces should exist in the prototype, to ensure that the device will not damage the oil palm tree when being operated.

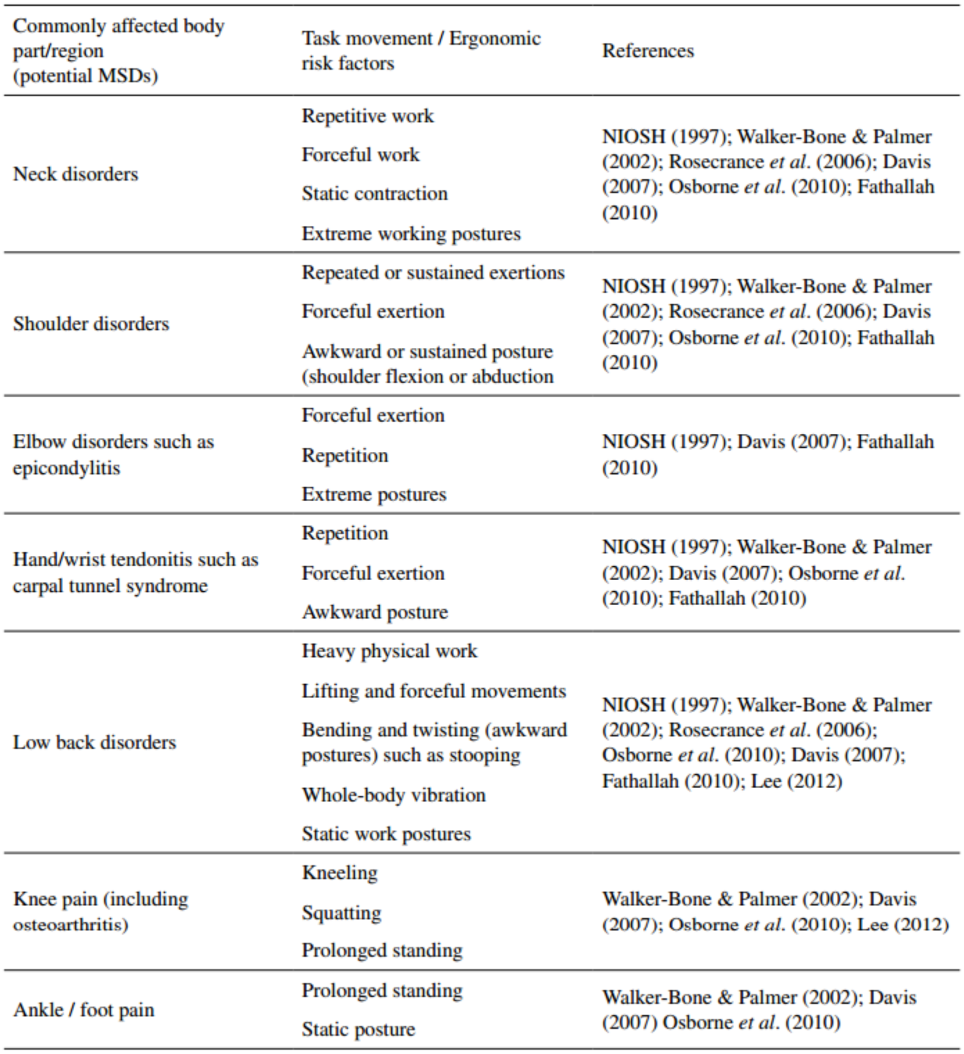
8.3 Ethical Considerations

Since the device will increase the palm harvesting efficiency, fewer workers would be required to do the task. This situation could cause lower employment. There is another cost to using any efficient oil palm harvesting device, because increasing oil palm fruit production is directly related to increasing deforestation [11]. Deforestation poses a threat to the endangered species that inhabit the rainforests in these areas [11]. Any documentation the team creates for the final device will inform the operator that there is a tradeoff between increasing oil palm fruit production and decreasing deforestation. This section may be updated in future phases with more ethical issues that may arise once the prototype is assembled and tested.

8.4 Health and Safety

The target weight for the device is less than 136 kilograms, to prevent workers from becoming fatigued. All electrical components will be located inside of a waterproof box to reduce the risk of electrocution. Since the selected design will be controlled far from the base of an oil palm tree, there is a low risk of any cutting mechanism or fruit bunches falling on a worker. Any selected cutting mechanism will have a regulated speed to ensure that it remains stable during operation. Table 37 depicts ergonomic risk factors for workers on oil palm plantations [43].

Table 37: Ergonomic Risk Factors on Oil Palm Plantations [43]



Commonly affected body part/region (potential MSDs)	Task movement / Ergonomic risk factors	References
Neck disorders	Repetitive work Forceful work Static contraction Extreme working postures	NIOSH (1997); Walker-Bone & Palmer (2002); Rosecrance *et al*. (2006); Davis (2007); Osborne *et al*. (2010); Fathallah (2010)
Shoulder disorders	Repeated or sustained exertions Forceful exertion Awkward or sustained posture (shoulder flexion or abduction	NIOSH (1997); Walker-Bone & Palmer (2002); Rosecrance *et al*. (2006); Davis (2007); Osborne *et al*. (2010); Fathallah (2010)
Elbow disorders such as epicondylitis	Forceful exertion Repetition Extreme postures	NIOSH (1997); Davis (2007); Fathallah (2010)
Hand/wrist tendonitis such as carpal tunnel syndrome	Repetition Forceful exertion Awkward posture	NIOSH (1997); Walker-Bone & Palmer (2002); Davis (2007); Osborne *et al.* (2010); Fathallah (2010)
Low back disorders	Heavy physical work Lifting and forceful movements Bending and twisting (awkward postures) such as stooping Whole-body vibration Static work postures	NIOSH (1997); Walker-Bone & Palmer (2002); Rosecrance *et al*. (2006); Osborne *et al*. (2010); Davis (2007); Fathallah (2010); Lee (2012)
Knee pain (including osteoarthritis)	Kneeling Squatting Prolonged standing	Walker-Bone & Palmer (2002); Davis (2007); Osborne *et al*. (2010); Lee (2012)
Ankle / foot pain	Prolonged standing Static posture	Walker-Bone & Palmer (2002); Davis (2007) Osborne *et al*. (2010)

To increase the prototype's maneuverability, the length of the cart's arms was reduced from 2.74 meters to 1.22 meters. This design change reduces the probability that the operator is injured.

8.5 Social and Political Considerations

Oil palm fruit harvesters in developing countries would benefit from an electromechanical harvesting device; farmers would be able to harvest more fruit for a lower cost and increase profits, because the harvesting process would be efficient, simple, and safe. If the oil palm harvesting process is improved, more individuals in developing countries may wish to purchase the harvesting device. However, since the demand for palm oil is inelastic [44], the demand for palm oil would not necessarily increase.

However, there will end up being a surplus of workers competing for an even smaller number of jobs, which could actually increase the unemployment rate of oil palm harvesters [45]. This may cause social resentment among oil palm workers, because some individuals will inevitably be terminated, while their coworkers will remain employed. Since workers have to compete against each other to avoid termination, their relationship with management can be affected.

8.6 Sustainability

The sustainability of any oil palm fruit-harvesting device is heavily dependent on the materials' strength, durability, and the number of electromechanical components. The strength of the materials used in the device and its durability will affect the product's life cycle. For example, the device must be able to resist oxidation in a moist rainforest environment. Furthermore, minimizing the number of components will result in fewer parts that need to be replaced throughout the product's life cycle. Once the prototype is assembled and tested, more information regarding the sustainability of the design may be added to this section.

9. Project Progress

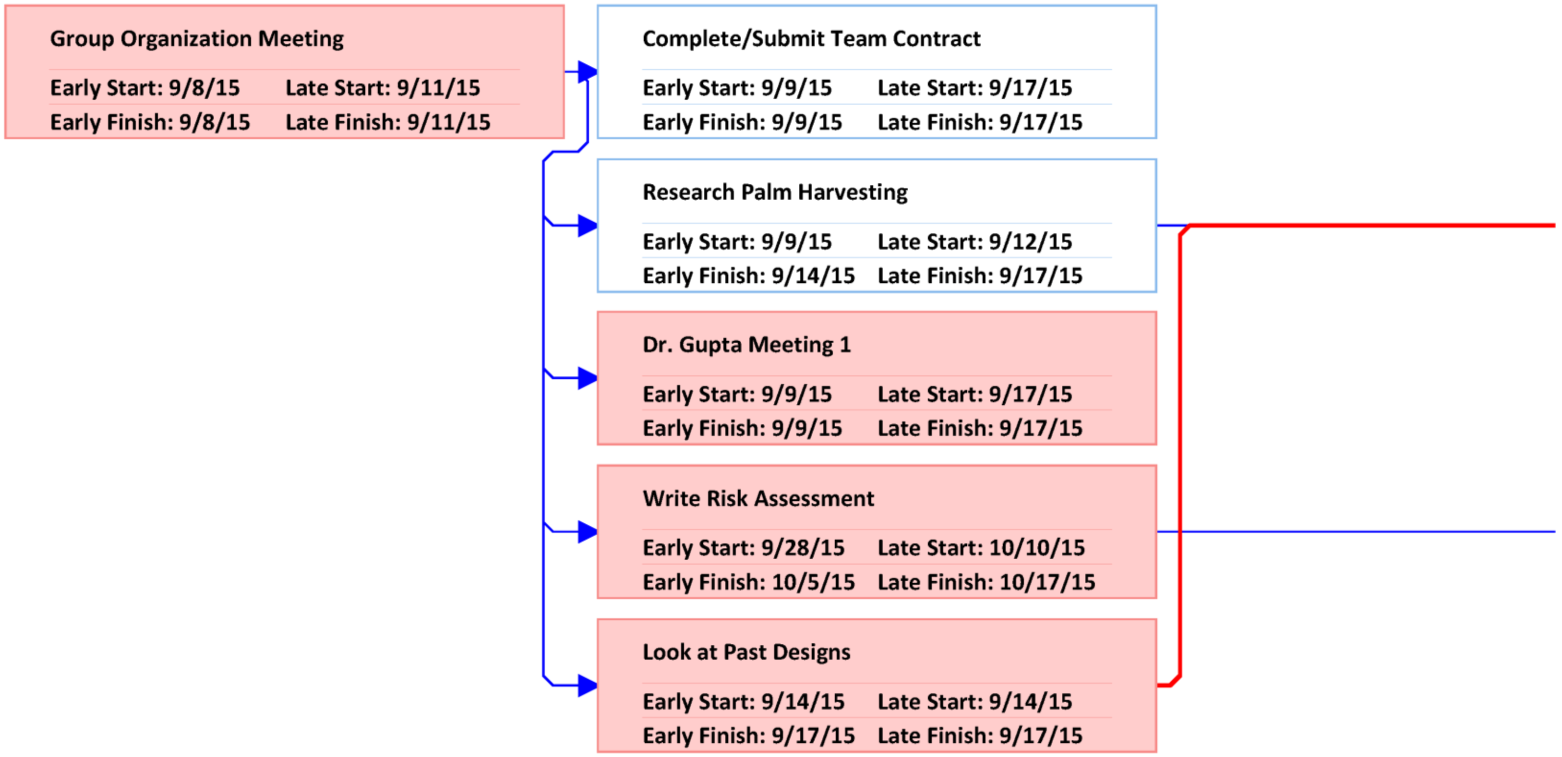
9.1 Milestones and Schedule

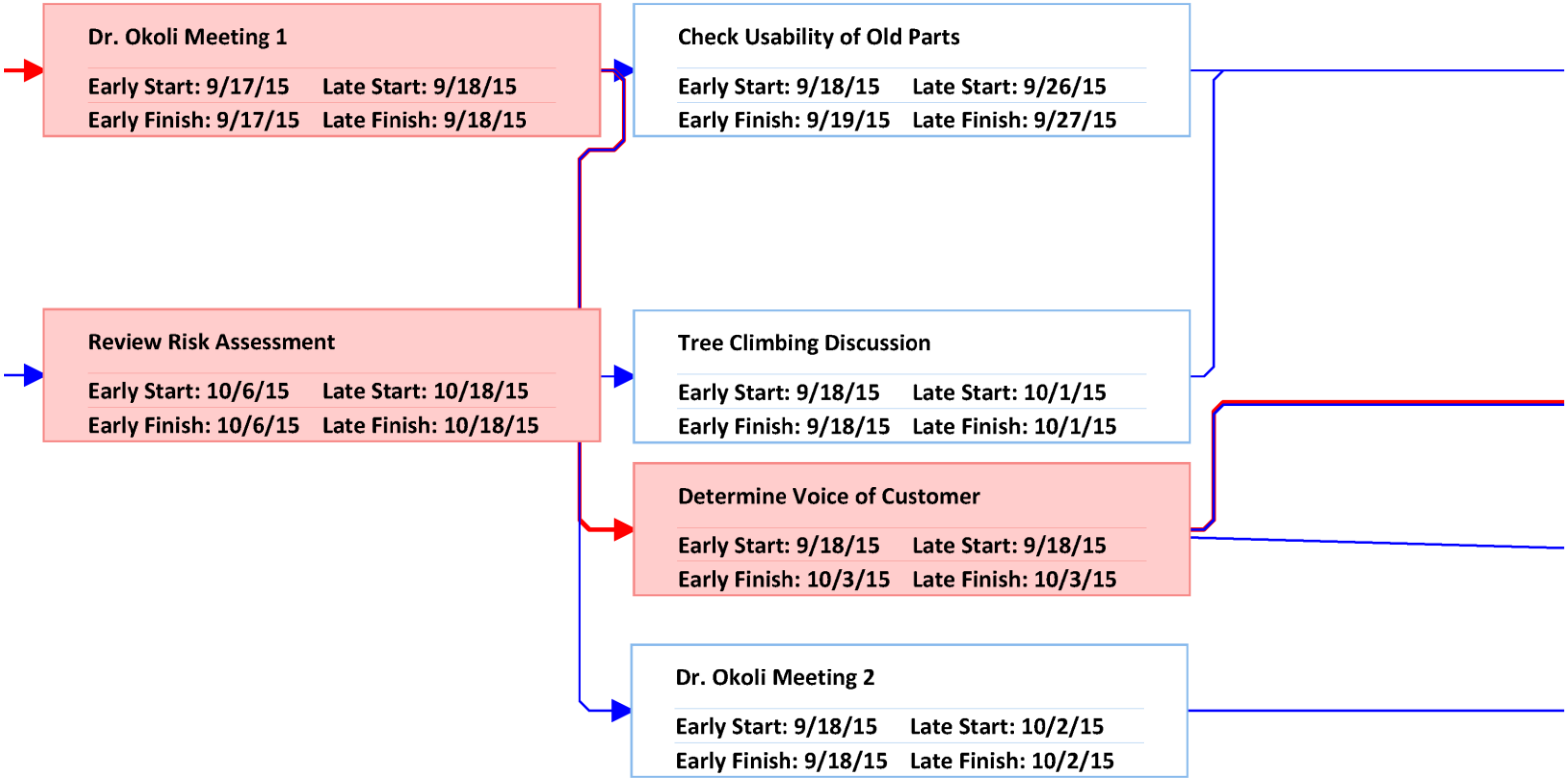
9.1.1 Define Phase Tasks

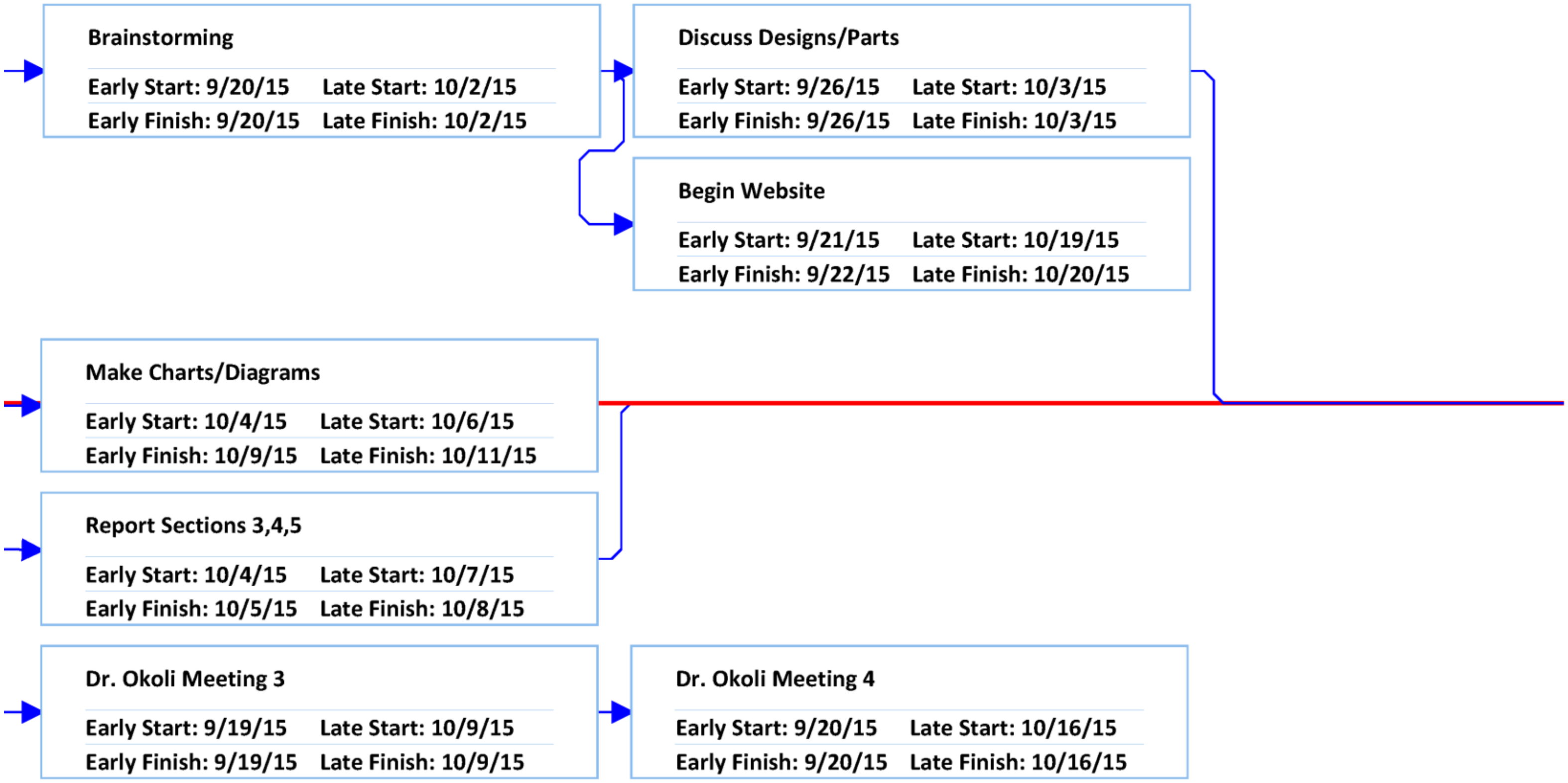
Major tasks that are required to be completed by the end of the Design Phase are discussed in Table 38. Figure 66 depicts the network flow diagram for the Design Phase, which includes the specific tasks necessary to complete the ones given in Table 38. Quantitative information regarding the specific tasks for the Define Phase depicted in Figure 66 is given in Table 39.

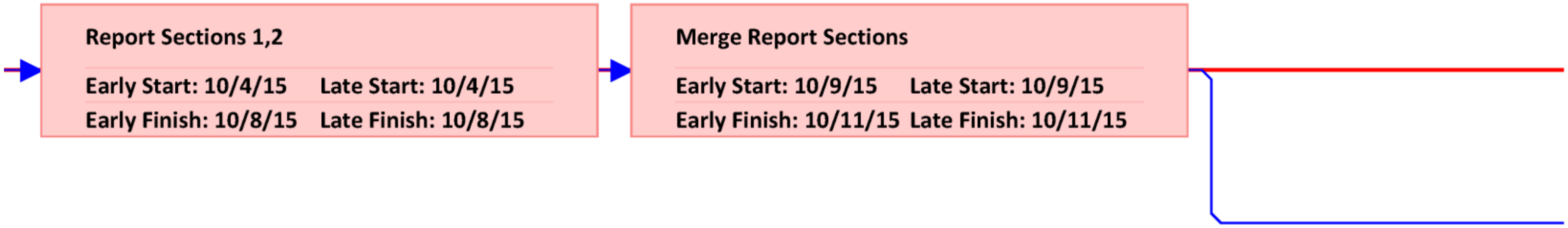
Table 38: Major Tasks for the Define Phase

Task	Explanation
Writing the group’s team contract.	This task ensures all team members agree on the policies and procedures that will be used throughout this project.
Contacting and meeting with Dr. Okoli.	This task allows the team to obtain the sponsor’s customer requirements and demands for the oil palm fruit harvesting device.
Making a voice of the customer diagram.	This task verifies that all of the customer’s requirements were successfully understood.
Constructing the house of quality.	This task converts the customer’s requirements into technical requirements and determine the most important elements to consider.
Conducting background research.	This task includes conducting background research into past prototypes and design methodology. It also includes researching current oil palm fruit harvesting methods and the variables involved. This task is significant, because a prototype cannot be designed without knowledge of the current harvesting process.
Writing the group’s Risk Assessment.	This task ensures the safety of all group members during the construction and testing of any prototype design.
Brainstorming.	This task allows group members to discuss ideas regarding harvesting device designs.
Choosing a design selection deadline.	This task ensures the team receives the necessary materials by the beginning of the Analyze Phase.
Writing the Define Phase report.	This task allows the group to communicate to the sponsor and stakeholders the team’s approach to the project and the current status of any design concepts.
Presenting the group’s project status.	This task allows the group to demonstrate a firm understanding of the project to the sponsor and stakeholders, as well as provide a synopsis of the Define Phase report.


Group Organization Meeting
Early Start: 9/8/15
Late Start: 9/11/15
Early Finish: 9/8/15
Late Finish: 9/11/15
Complete/Submit Team Contract
Early Start: 9/9/15
Late Start: 9/17/15
Early Finish: 9/9/15
Late Finish: 9/17/15
Research Palm Harvesting
Early Start: 9/9/15
Late Start: 9/12/15
Early Finish: 9/14/15
Late Finish: 9/17/15
Dr. Gupta Meeting 1
Early Start: 9/9/15
Late Start: 9/17/15
Early Finish: 9/9/15
Late Finish: 9/17/15
Write Risk Assessment
Early Start: 9/28/15
Late Start: 10/10/15
Early Finish: 10/5/15
Late Finish: 10/17/15
Look at Past Designs
Early Start: 9/14/15
Late Start: 9/14/15
Early Finish: 9/17/15
Late Finish: 9/17/15


Dr. Okoli Meeting 1
Early Start: 9/17/15
Late Start: 9/18/15
Early Finish: 9/17/15
Late Finish: 9/18/15
Review Risk Assessment
Early Start: 10/6/15
Late Start: 10/18/15
Early Finish: 10/6/15
Late Finish: 10/18/15
Check Usability of Old Parts
Early Start: 9/18/15
Late Start: 9/26/15
Early Finish: 9/19/15
Late Finish: 9/27/15
Tree Climbing Discussion
Early Start: 9/18/15
Late Start: 10/1/15
Early Finish: 9/18/15
Late Finish: 10/1/15
Determine Voice of Customer
Early Start: 9/18/15
Late Start: 9/18/15
Early Finish: 10/3/15
Late Finish: 10/3/15
Dr. Okoli Meeting 2
Early Start: 9/18/15
Late Start: 10/2/15
Early Finish: 9/18/15
Late Finish: 10/2/15


Brainstorming
Early Start: 9/20/15 Late Start: 10/2/15
Early Finish: 9/20/15 Late Finish: 10/2/15
Discuss Designs/Parts
Early Start: 9/26/15 Late Start: 10/3/15
Early Finish: 9/26/15 Late Finish: 10/3/15
Begin Website
Early Start: 9/21/15 Late Start: 10/19/15
Early Finish: 9/22/15 Late Finish: 10/20/15
Make Charts/Diagrams
Early Start: 10/4/15 Late Start: 10/6/15
Early Finish: 10/9/15 Late Finish: 10/11/15
Report Sections 3,4,5
Early Start: 10/4/15 Late Start: 10/7/15
Early Finish: 10/5/15 Late Finish: 10/8/15
Dr. Okoli Meeting 3
Early Start: 9/19/15 Late Start: 10/9/15
Early Finish: 9/19/15 Late Finish: 10/9/15
Dr. Okoli Meeting 4
Early Start: 9/20/15 Late Start: 10/16/15
Early Finish: 9/20/15 Late Finish: 10/16/15


Report Sections 1,2
Early Start: 10/4/15
Late Start: 10/4/15
Early Finish: 10/8/15
Late Finish: 10/8/15
Merge Report Sections
Early Start: 10/9/15
Late Start: 10/9/15
Early Finish: 10/11/15
Late Finish: 10/11/15

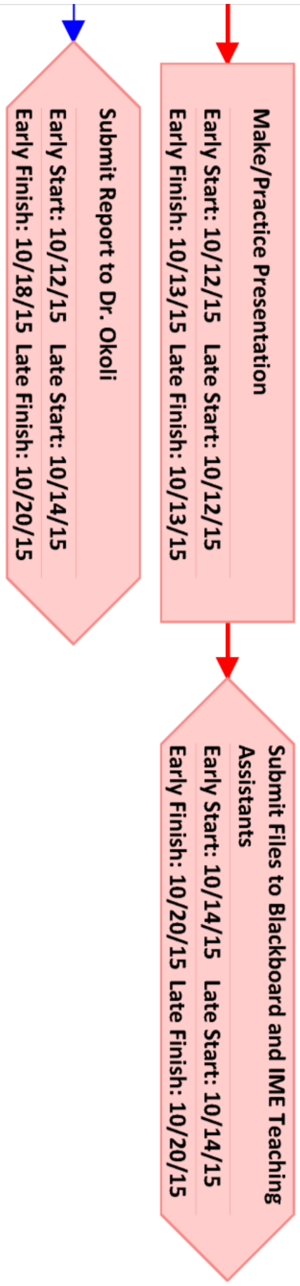


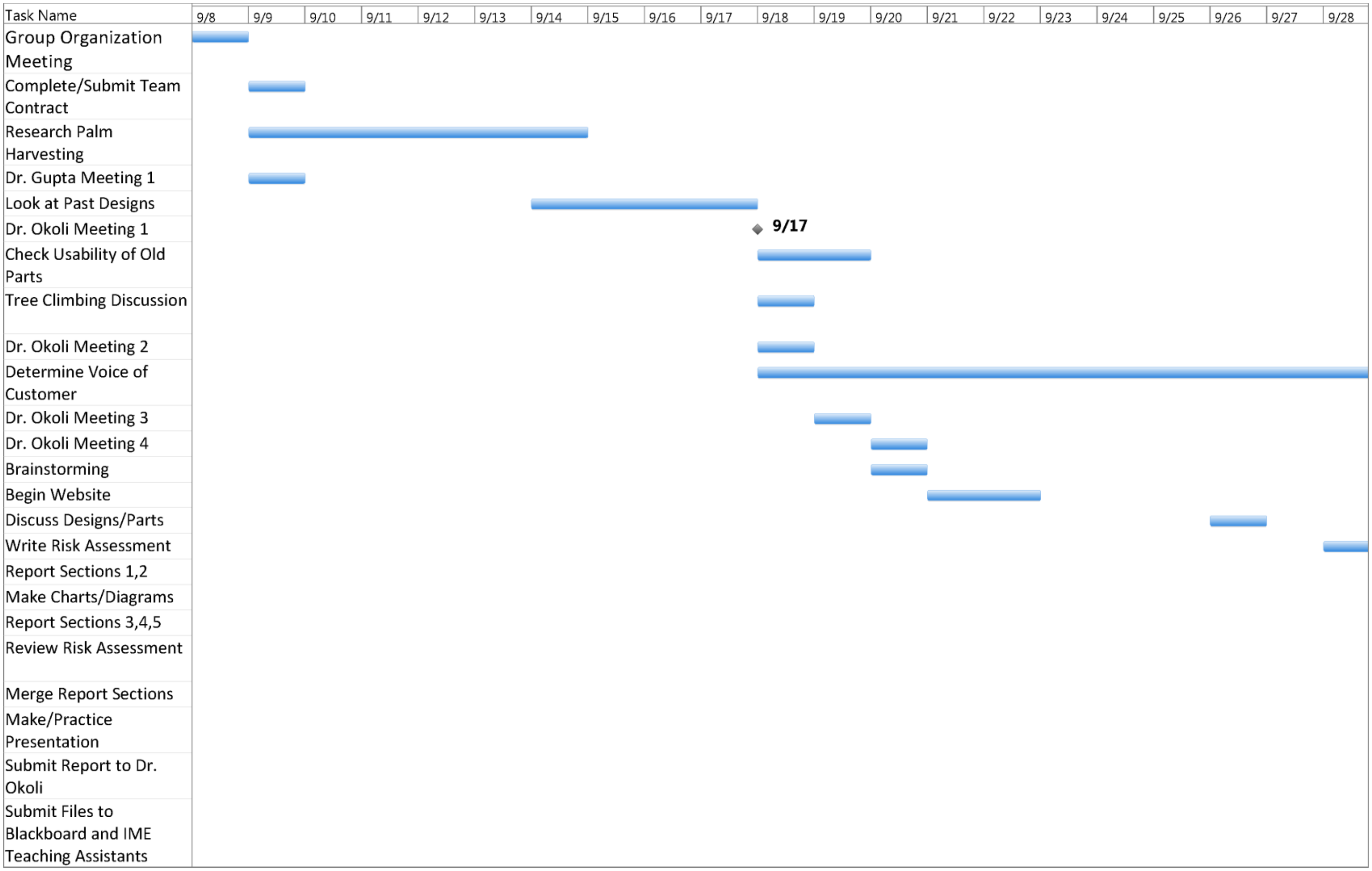
Figure 66: Network Flow Diagram for the Define Phase

Table 39: Detailed Network Flow Diagram Information for Define Phase Tasks

Task Name	Start	Finish	Free Slack	Total Slack	Early Start	Early Finish	Late Start	Late Finish
Group Organization Meeting	9/8/15	9/8/15	0 days	3 days	9/8/15	9/8/15	9/11/15	9/11/15
Complete/Submit Team Contract	9/9/15	9/9/15	8 days	8 days	9/9/15	9/9/15	9/17/15	9/17/15
Research Palm Harvesting	9/9/15	9/14/15	3 days	3 days	9/9/15	9/14/15	9/12/15	9/17/15
Dr. Gupta Meeting 1	9/9/15	9/9/15	8 days	8 days	9/9/15	9/9/15	9/17/15	9/17/15
Look at Past Designs	9/14/15	9/17/15	0 days	0 days	9/14/15	9/17/15	9/14/15	9/17/15
Dr. Okoli Meeting 1	9/17/15	9/17/15	0 days	0 days	9/17/15	9/17/15	9/18/15	9/18/15
Check Usability of Old Parts	9/18/15	9/19/15	0 days	8 days	9/18/15	9/19/15	9/26/15	9/27/15
Tree Climbing Discussion	9/18/15	9/18/15	1 day	13 days	9/18/15	9/18/15	10/1/15	10/1/15
Dr. Okoli Meeting 2	9/18/15	9/18/15	0 days	14 days	9/18/15	9/18/15	10/2/15	10/2/15
Determine Voice of Customer	9/18/15	10/3/15	0 days	0 days	9/18/15	10/3/15	9/18/15	10/3/15
Dr. Okoli Meeting 3	9/19/15	9/19/15	0 days	20 days	9/19/15	9/19/15	10/9/15	10/9/15
Dr. Okoli Meeting 4	9/20/15	9/20/15	26 days	26 days	9/20/15	9/20/15	10/16/15	10/16/15
Brainstorming	9/20/15	9/20/15	0 days	12 days	9/20/15	9/20/15	10/2/15	10/2/15
Begin Website	9/21/15	9/22/15	28 days	28 days	9/21/15	9/22/15	10/19/15	10/20/15
Discuss Designs/Parts	9/26/15	9/26/15	7 days	7 days	9/26/15	9/26/15	10/3/15	10/3/15
Write Risk Assessment	9/28/15	10/5/15	0 days	12 days	9/28/15	10/5/15	10/10/15	10/17/15
Report Sections 1,2	10/4/15	10/8/15	0 days	0 days	10/4/15	10/8/15	10/4/15	10/8/15
Make Charts/Diagrams	10/4/15	10/9/15	2 days	2 days	10/4/15	10/9/15	10/6/15	10/11/15
Report Sections 3,4,5	10/4/15	10/5/15	3 days	3 days	10/4/15	10/5/15	10/7/15	10/8/15
Review Risk Assessment	10/6/15	10/6/15	12 days	12 days	10/6/15	10/6/15	10/18/15	10/18/15
Merge Report Sections	10/9/15	10/11/15	0 days	0 days	10/9/15	10/11/15	10/9/15	10/11/15
Make/Practice Presentation	10/12/15	10/13/15	0 days	0 days	10/12/15	10/13/15	10/12/15	10/13/15
Submit Report to Dr. Okoli	10/12/15	10/18/15	2 days	2 days	10/12/15	10/18/15	10/14/15	10/20/15
Submit Files to Bb and TAs	10/14/15	10/20/15	0 days	0 days	10/14/15	10/20/15	10/14/15	10/20/15

Free slack refers to the number of days an activity can be delayed before it delays any succeeding activities, while total slack (also known as float) denotes the number of days an activity can be delayed before it delays the entire project [46]. All activities with a total slack value of zero (0) in Table 39 are along the Define Phase's critical path, which is denoted by red boxes and arrows in Figure 66. These critical tasks must be completed by the specified deadline, or the Define Phase will be delayed. Table 39 shows that the first part of the Define Phase's critical path starts on 9/14/15 and ends on 10/20/15. Thus, the critical path of the Define Phase is 36 days.

A Gantt chart of the Define Phase's activities was constructed and is depicted in Figure 67. A Gantt chart is a project management tool used to visualize a project from start to finish. This includes, but it not limited to, a list of all project activities, when each activity begins and finishes, the expected duration of each activity, and where any activities may overlap with one another.


Task Name
9/8
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9/19
9/20
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9/25
9/26
9/27
9/28
Group Organization Meeting
Complete/Submit Team Contract
Research Palm Harvesting
Dr. Gupta Meeting 1
Look at Past Designs
Dr. Okoli Meeting 1
9/17
Check Usability of Old Parts
Tree Climbing Discussion
Dr. Okoli Meeting 2
Determine Voice of Customer
Dr. Okoli Meeting 3
Dr. Okoli Meeting 4
Brainstorming
Begin Website
Discuss Designs/Parts
Write Risk Assessment
Report Sections 1,2
Make Charts/Diagrams
Report Sections 3,4,5
Review Risk Assessment
Merge Report Sections
Make/Practice Presentation
Submit Report to Dr. Okoli
Submit Files to Blackboard and IME Teaching Assistants

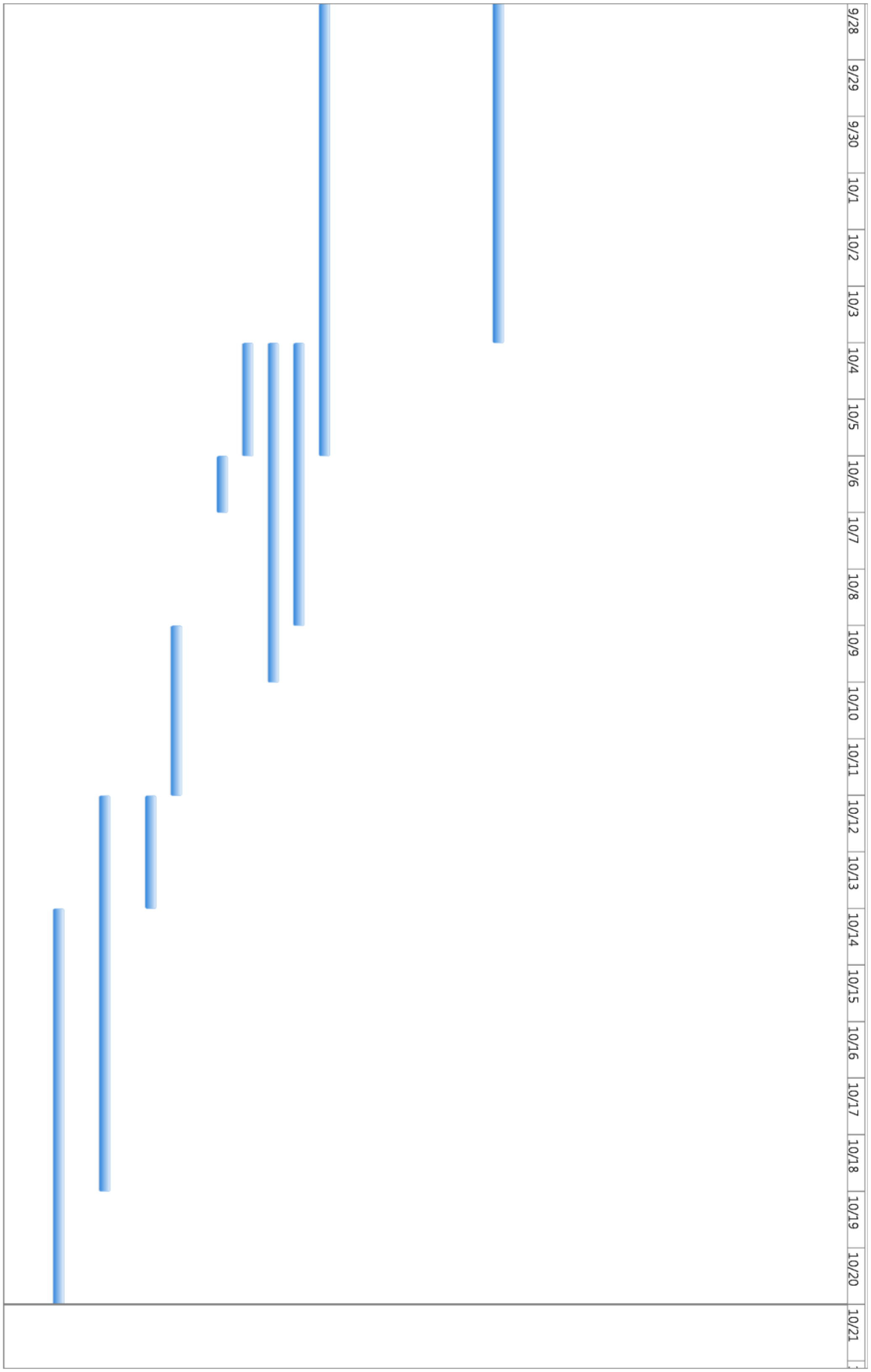


Figure 67: Gantt Chart for the Define Phase

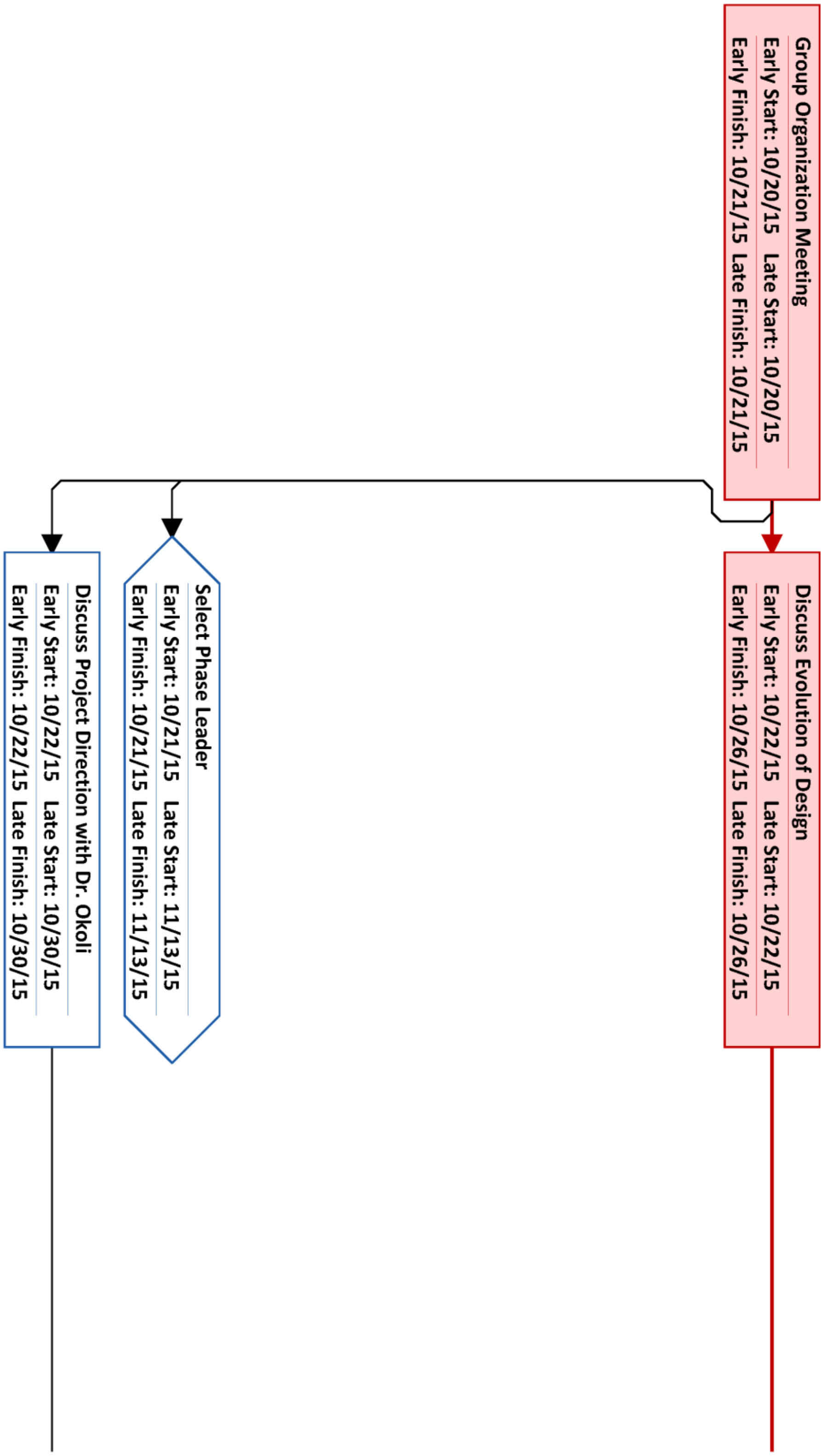
Using Figure 66 and Figure 67, the earliest the Define Phase can end is 10/20/15. The latest the Define Phase can end is also 10/20/15. The reason the early and late finish dates are the same is due to the aforementioned critical path and total slack times, as well as the fact that the Define Phase requires a significant amount of time to ensure all customer requirements are defined properly. In Figure 66 and Figure 67, four days were allotted to submitting the report to the project's stakeholders. If critical tasks are not completed by their late finish deadlines, then the amount of time needed to submit the report at the end of the Define Phase must be reduced. In order to accomplish this task, the team would be required to work in time that was previously not designated for the project.

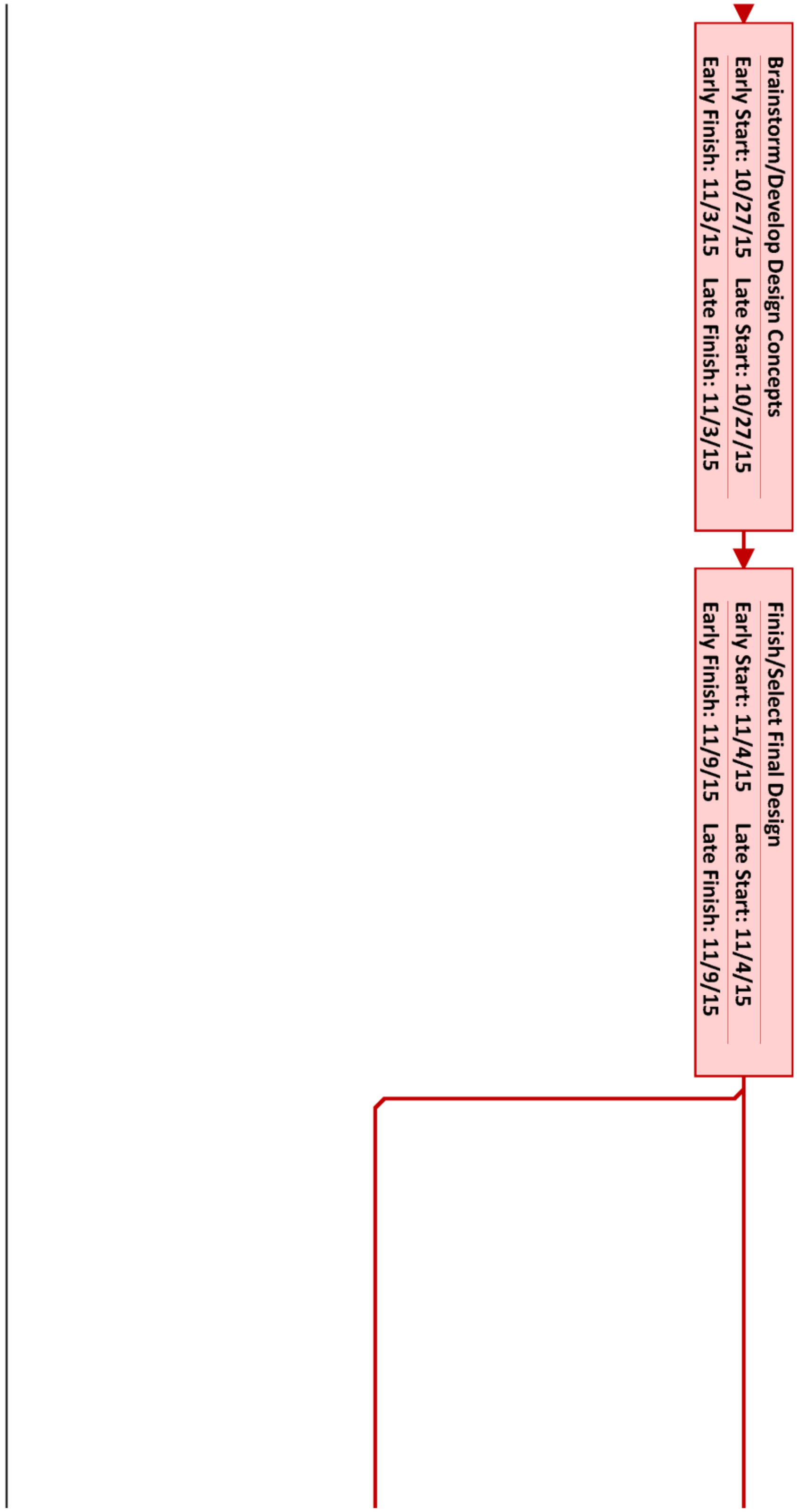
9.1.2 Measure Phase Tasks

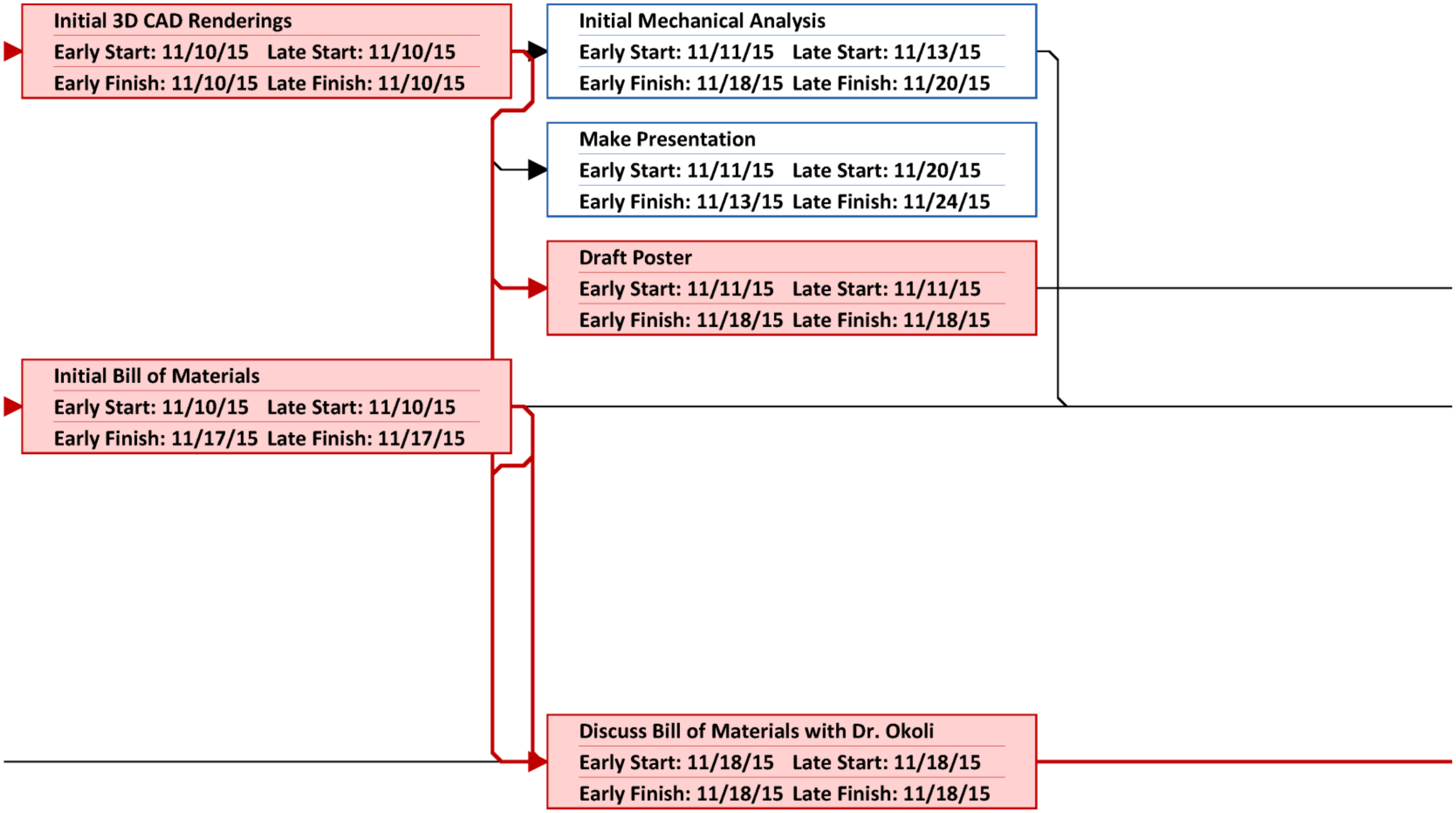
Major tasks that are required to be completed by the end of the Measure Phase are discussed in Table 40. Figure 68 depicts the network flow diagram for the Measure Phase, which includes the tentative planning of the beginning of the Measure Phase in detail, along with a broader plan of the end of the phase. Quantitative information regarding the specific tasks depicted in Figure 68 is given in Table 41.

Table 40: Major Tasks for the Measure Phase

Task	Explanation
Contact and meeting with Dr. Okoli.	This ensures that any designs developed by the group are desirable by the sponsor.
Brainstorming.	Group members discuss ideas regarding harvesting device designs.
Discuss the evolution of the team's designs.	Team members discuss which palm harvesting ideas are feasible, given the time constraints of the project.
Final design selection.	A design that meets the sponsor's requirements must be selected.
Generate three-dimensional design renderings.	This visualizes how the palm harvesting prototype will appear after it is built and allows for any design issues to be identified before construction begins.
Write the Measure Phase report.	This communicates to the sponsor and stakeholders the team's design selection and the steps that must be taken before it is constructed.
Present the group's project status.	This demonstrates that a design was selected and materials were ordered to the sponsor and stakeholders, as well as provide a synopsis of the Measure report.
Order the materials needed for the selected palm harvesting device design.	Makes sure materials arrive to complete a prototype by the end of the project.


Group Organization Meeting
Early Start: 10/20/15 Late Start: 10/20/15
Early Finish: 10/21/15 Late Finish: 10/21/15
Discuss Evolution of Design
Early Start: 10/22/15 Late Start: 10/22/15
Early Finish: 10/26/15 Late Finish: 10/26/15
Select Phase Leader
Early Start: 10/21/15 Late Start: 11/13/15
Early Finish: 10/21/15 Late Finish: 11/13/15
Discuss Project Direction with Dr. Okoli
Early Start: 10/22/15 Late Start: 10/30/15
Early Finish: 10/22/15 Late Finish: 10/30/15


Brainstorm/Develop Design Concepts
Early Start: 10/27/15 Late Start: 10/27/15
Early Finish: 11/3/15 Late Finish: 11/3/15
Finish/Select Final Design
Early Start: 11/4/15 Late Start: 11/4/15
Early Finish: 11/9/15 Late Finish: 11/9/15


Initial 3D CAD Renderings
Early Start: 11/10/15 Late Start: 11/10/15
Early Finish: 11/10/15 Late Finish: 11/10/15
Initial Mechanical Analysis
Early Start: 11/11/15 Late Start: 11/13/15
Early Finish: 11/18/15 Late Finish: 11/20/15
Make Presentation
Early Start: 11/11/15 Late Start: 11/20/15
Early Finish: 11/13/15 Late Finish: 11/24/15
Draft Poster
Early Start: 11/11/15 Late Start: 11/11/15
Early Finish: 11/18/15 Late Finish: 11/18/15
Initial Bill of Materials
Early Start: 11/10/15 Late Start: 11/10/15
Early Finish: 11/17/15 Late Finish: 11/17/15
Discuss Bill of Materials with Dr. Okoli
Early Start: 11/18/15 Late Start: 11/18/15
Early Finish: 11/18/15 Late Finish: 11/18/15

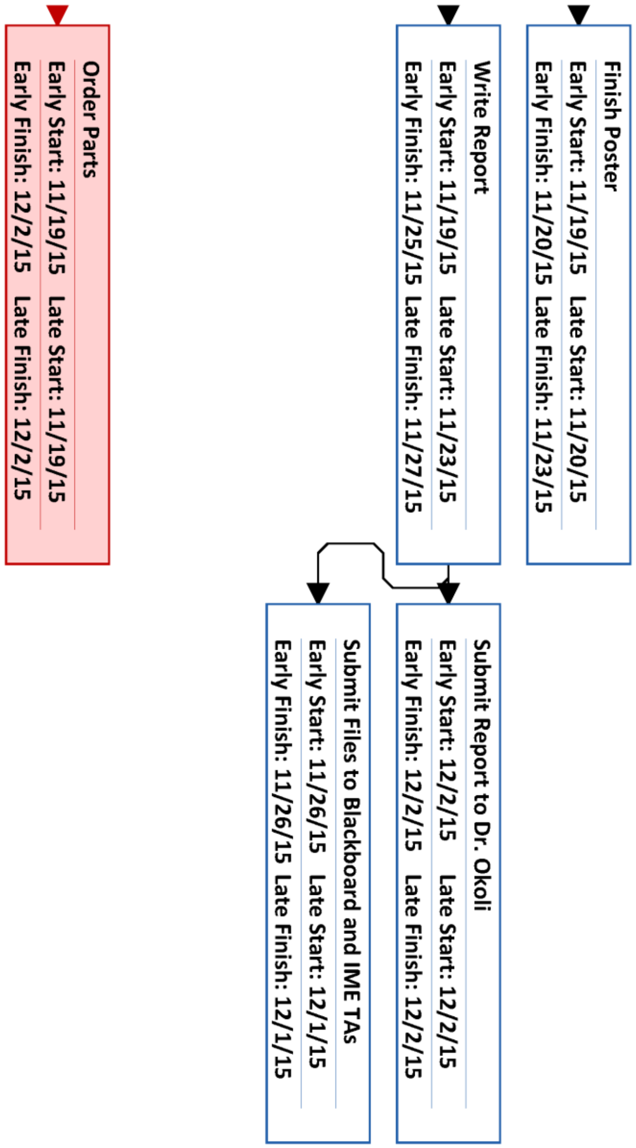


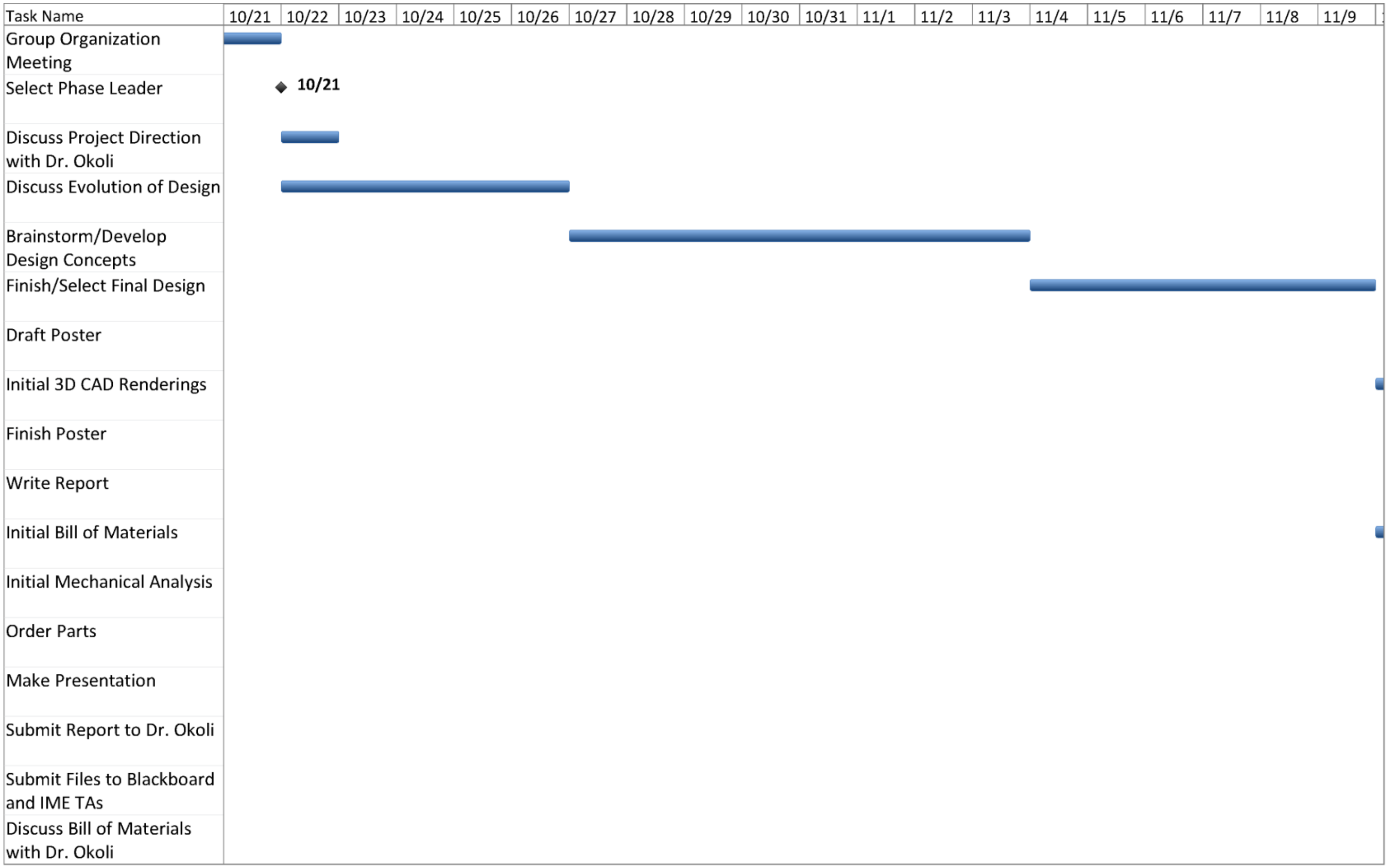
Figure 68: Network Flow Diagram for the Measure Phase

Table 41: Detailed Network Flow Diagram Information for Measure Phase Tasks

Task Name	Start	Finish	Free Slack	Total Slack	Early Start	Early Finish	Late Start	Late Finish
Group Organization Meeting	10/20/15	10/21/15	0 days	0 days	10/20/15	10/21/15	10/20/15	10/21/15
Select Phase Leader	10/21/15	10/21/15	17 days	17 days	10/21/15	10/21/15	11/13/15	11/13/15
Discuss Project Direction with Dr. Okoli	10/22/15	10/22/15	6 days	6 days	10/22/15	10/22/15	10/30/15	10/30/15
Discuss Evolution of Design	10/22/15	10/26/15	0 days	0 days	10/22/15	10/26/15	10/22/15	10/26/15
Brainstorm/Develop Design Concepts	10/27/15	11/3/15	0 days	0 days	10/27/15	11/3/15	10/27/15	11/3/15
Finish/Select Final Design	11/4/15	11/9/15	0 days	0 days	11/4/15	11/9/15	11/4/15	11/9/15
Initial 3D CAD Renderings	11/10/15	11/10/15	0 days	0 days	11/10/15	11/10/15	11/10/15	11/10/15
Initial Bill of Materials	11/10/15	11/17/15	0 days	0 days	11/10/15	11/17/15	11/10/15	11/17/15
Draft Poster	11/11/15	11/18/15	0 days	0 days	11/11/15	11/18/15	11/11/15	11/18/15
Initial Mechanical Analysis	11/11/15	11/18/15	0 days	2 days	11/11/15	11/18/15	11/13/15	11/20/15
Make Presentation	11/11/15	11/13/15	7 days	7 days	11/11/15	11/13/15	11/20/15	11/24/15
Discuss Bill of Materials with Dr. Okoli	11/18/15	11/18/15	0 days	0 days	11/18/15	11/18/15	11/18/15	11/18/15
Finish Poster	11/19/15	11/20/15	1 day	1 day	11/19/15	11/20/15	11/20/15	11/23/15
Write Report	11/19/15	11/25/15	0 days	2 days	11/19/15	11/25/15	11/23/15	11/27/15
Order Parts	11/19/15	12/2/15	0 days	0 days	11/19/15	12/2/15	11/19/15	12/2/15
Submit Files to Blackboard and IME TAs	11/26/15	11/26/15	3 days	3 days	11/26/15	11/26/15	12/1/15	12/1/15
Submit Report to Dr. Okoli	12/2/15	12/2/15	0 days	0 days	12/2/15	12/2/15	12/2/15	12/2/15

Free slack and total slack (float) were discussed in Section 9.1.1. All activities with a total slack value of zero (0) in Table 41 are along the Measure Phase's critical path, which is denoted by red boxes and arrows in Figure 68. These critical tasks must be completed by the specified deadline, or the Measure Phase will be delayed. Table 41 shows that the first part of the Measure Phase's critical path starts on 10/20/15 and ends on 12/2/15. Thus, the critical path of the Measure Phase is 43 days.

Gantt charts were discussed in Section 9.1.1. A Gantt chart of the Measure Phase's planned activities was constructed and is depicted in Figure 69.


Task Name
10/21
10/22
10/23
10/24
10/25
10/26
10/27
10/28
10/29
10/30
10/31
11/1
11/2
11/3
11/4
11/5
11/6
11/7
11/8
11/9
Group Organization Meeting
Select Phase Leader
10/21
Discuss Project Direction with Dr. Okoli
Discuss Evolution of Design
Brainstorm/Develop Design Concepts
Finish/Select Final Design
Draft Poster
Initial 3D CAD Renderings
Finish Poster
Write Report
Initial Bill of Materials
Initial Mechanical Analysis
Order Parts
Make Presentation
Submit Report to Dr. Okoli
Submit Files to Blackboard and IME TAs
Discuss Bill of Materials with Dr. Okoli

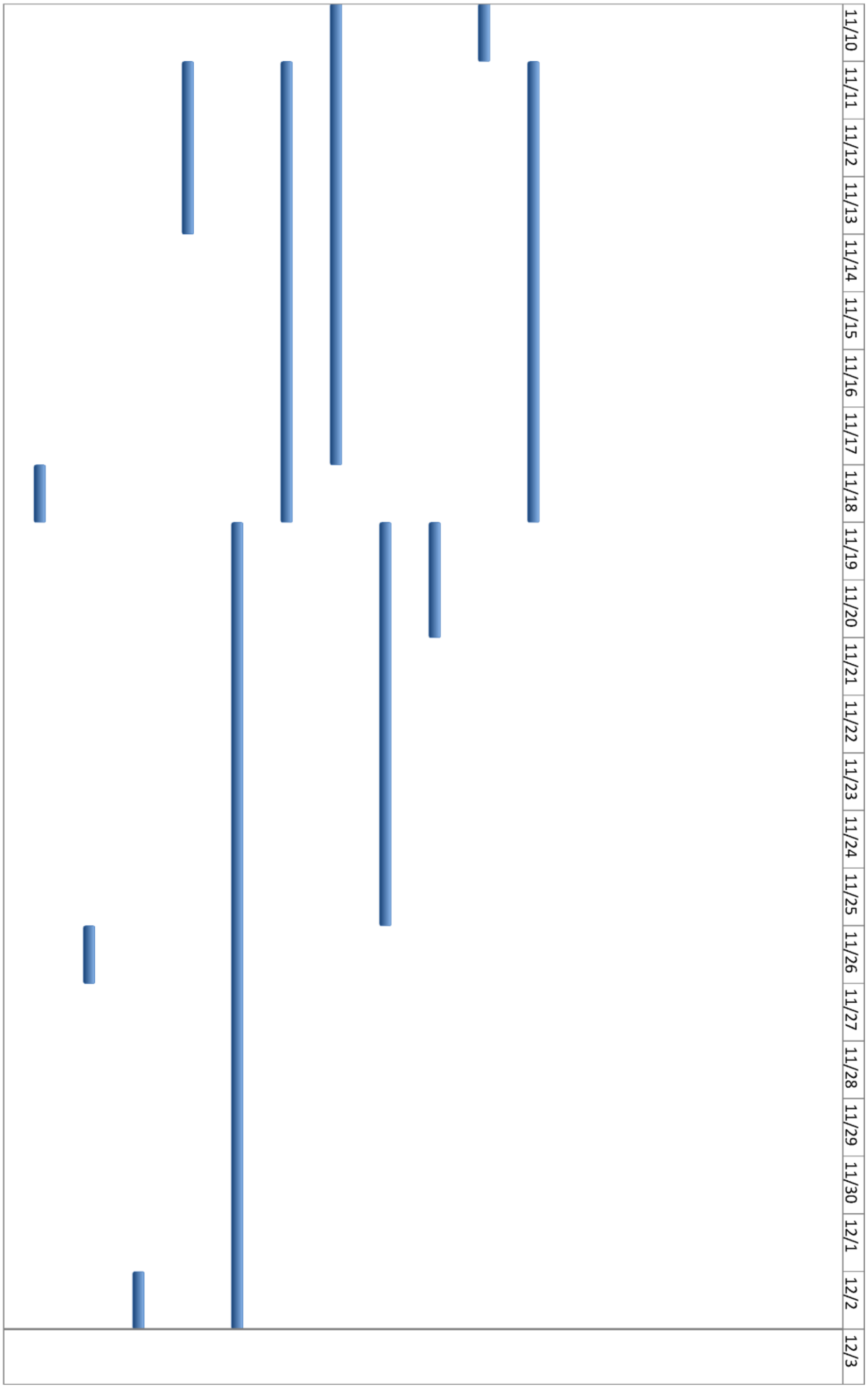


Figure 69: Gantt Chart for the Measure Phase

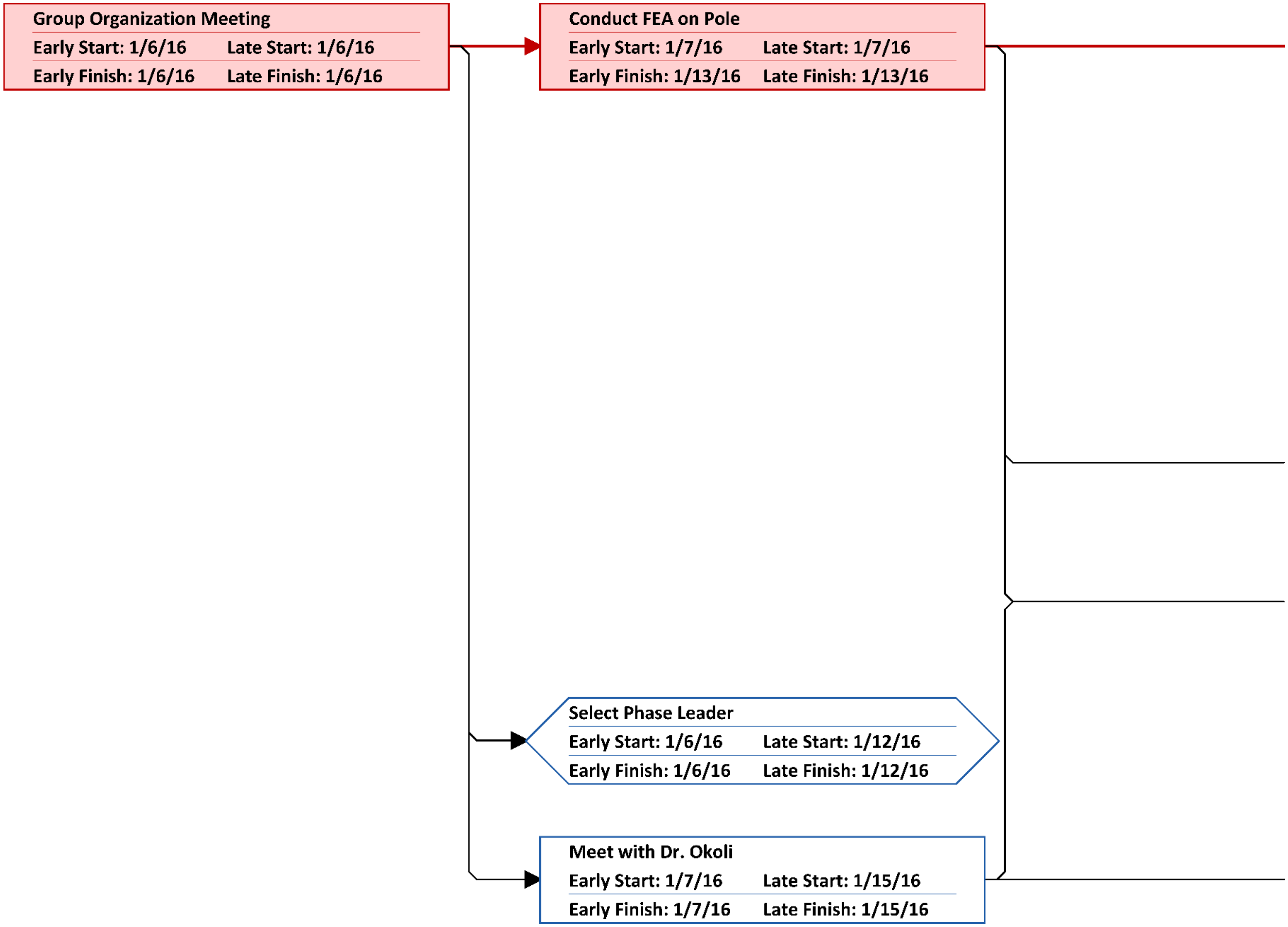
Using Figure 68 and Figure 69, the earliest the Measure Phase can end is 12/2/15. The latest the Measure Phase can end is also 12/2/15.

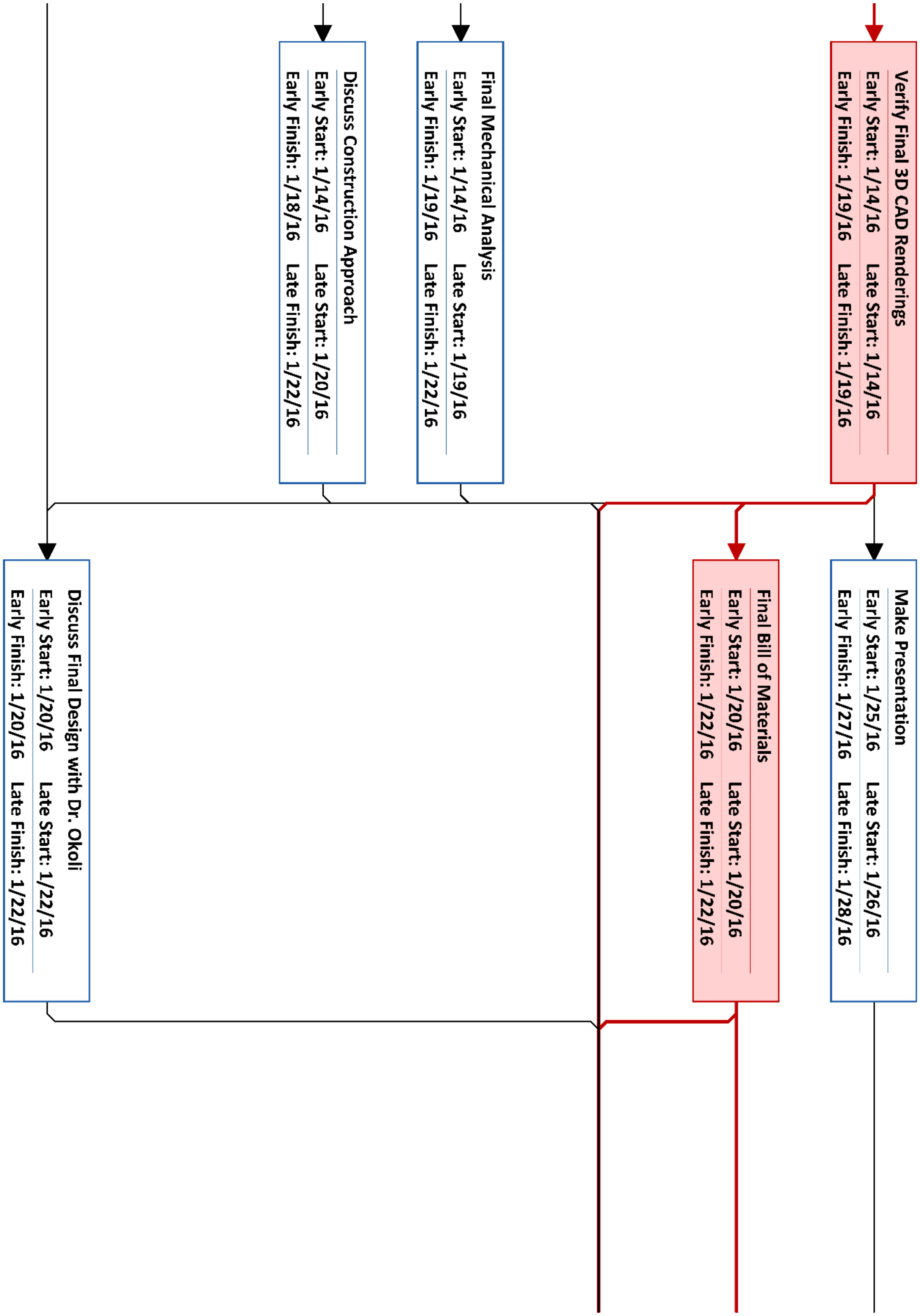
9.1.3 Analyze Phase Tasks

Major tasks that are required to be completed by the end of the Analyze Phase are discussed in Table 42. Figure 70 depicts the network flow diagram for the Analyze Phase, which includes an outline of the tasks that need to be completed. Quantitative information regarding the specific tasks depicted in Figure 70 is given in Table 43.

Table 42: Major Tasks for the Analyze Phase

Task	Explanation
Contacting and meeting with Dr. Okoli.	This ensures that any designs developed by the group do not need any final adjustments before being constructed.
Conduct pole FEA.	FEA on the pole must be conducted to determine if the design is feasible.
Verify design and CAD renderings	Based on the results of the pole FEA, the design and CAD renderings may need to be updated.
Test electrical components	Electrical components must be tested to ensure they will work in the prototype.
Write the Analyze Phase report.	This allows the group to communicate to the sponsor and stakeholders the team’s analysis results and any future plans of action.
Present the group’s project status.	This allows the group to demonstrate that a design was analyzed, as well as provide a synopsis of the Analyze Phase report.


Group Organization Meeting
Early Start: 1/6/16
Late Start: 1/6/16
Early Finish: 1/6/16
Late Finish: 1/6/16
Conduct FEA on Pole
Early Start: 1/7/16
Late Start: 1/7/16
Early Finish: 1/13/16
Late Finish: 1/13/16
Select Phase Leader
Early Start: 1/6/16
Late Start: 1/12/16
Early Finish: 1/6/16
Late Finish: 1/12/16
Meet with Dr. Okoli
Early Start: 1/7/16
Late Start: 1/15/16
Early Finish: 1/7/16
Late Finish: 1/15/16


Verify Final 3D CAD Renderings
Early Start: 1/14/16 Late Start: 1/14/16
Early Finish: 1/19/16 Late Finish: 1/19/16
Final Mechanical Analysis
Early Start: 1/14/16 Late Start: 1/19/16
Early Finish: 1/19/16 Late Finish: 1/22/16
Discuss Construction Approach
Early Start: 1/14/16 Late Start: 1/20/16
Early Finish: 1/18/16 Late Finish: 1/22/16
Make Presentation
Early Start: 1/25/16 Late Start: 1/26/16
Early Finish: 1/27/16 Late Finish: 1/28/16
Final Bill of Materials
Early Start: 1/20/16 Late Start: 1/20/16
Early Finish: 1/22/16 Late Finish: 1/22/16
Discuss Final Design with Dr. Okoli
Early Start: 1/20/16 Late Start: 1/22/16
Early Finish: 1/20/16 Late Finish: 1/22/16

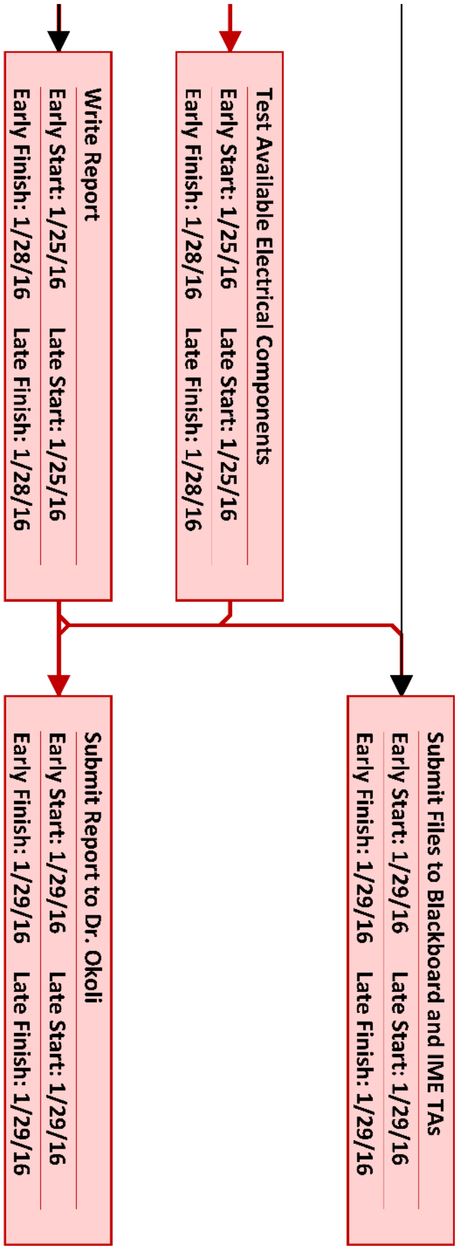


Figure 70: Network Flow Diagram for the Analyze Phase

Table 43: Detailed Network Flow Diagram Information for Analyze Phase Tasks

Task Name	Duration	Start	Finish	Free Slack	Total Slack	Early Start	Early Finish	Late Start	Late Finish
Group Organization Meeting	1 day	1/6/16	1/6/16	0 days	0 days	1/6/16	1/6/16	1/6/16	1/6/16
Select Phase Leader	0 days	1/6/16	1/6/16	4 days	4 days	1/6/16	1/6/16	1/12/16	1/12/16
Meet with Dr. Okoli	1 day	1/7/16	1/7/16	4 days	6 days	1/7/16	1/7/16	1/15/16	1/15/16
Conduct FEA on Pole	5 days	1/7/16	1/13/16	0 days	0 days	1/7/16	1/13/16	1/7/16	1/13/16
Discuss Construction Approach	3 days	1/14/16	1/18/16	4 days	4 days	1/14/16	1/18/16	1/20/16	1/22/16
Verify Final 3D CAD Renderings	4 days	1/14/16	1/19/16	0 days	0 days	1/14/16	1/19/16	1/14/16	1/19/16
Final Mechanical Analysis	4 days	1/14/16	1/19/16	3 days	3 days	1/14/16	1/19/16	1/19/16	1/22/16
Final Bill of Materials	3 days	1/20/16	1/22/16	0 days	0 days	1/20/16	1/22/16	1/20/16	1/22/16
Discuss Final Design with Dr. Okoli	1 day	1/20/16	1/20/16	2 days	2 days	1/20/16	1/20/16	1/22/16	1/22/16
Write Report	4 days	1/25/16	1/28/16	0 days	0 days	1/25/16	1/28/16	1/25/16	1/28/16
Make Presentation	3 days	1/25/16	1/27/16	1 day	1 day	1/25/16	1/27/16	1/26/16	1/28/16
Test Available Electrical Components	4 days	1/25/16	1/28/16	0 days	0 days	1/25/16	1/28/16	1/25/16	1/28/16
Submit Report to Dr. Okoli	1 day	1/29/16	1/29/16	0 days	0 days	1/29/16	1/29/16	1/29/16	1/29/16
Submit Files to Blackboard and IME TAs	1 day	1/29/16	1/29/16	0 days	0 days	1/29/16	1/29/16	1/29/16	1/29/16

Free slack and total slack (float) were discussed in Section 9.1.1. All activities with a total slack value of zero (0) in Table 43 are along the Analyze Phase’s critical path, which is denoted by red boxes and arrows in Figure 70. These critical tasks must be completed by the specified deadline, or the Analyze Phase will be delayed. Table 43 illustrates that the first part of the Analyze Phase's critical path starts on 1/6/16 and ends on 1/29/16. Thus, the critical path of the Analyze Phase is 23 days.

Gantt charts were discussed in Section 9.1.1. A Gantt chart of the Measure Phase's planned activities was constructed and is depicted in Figure 71.

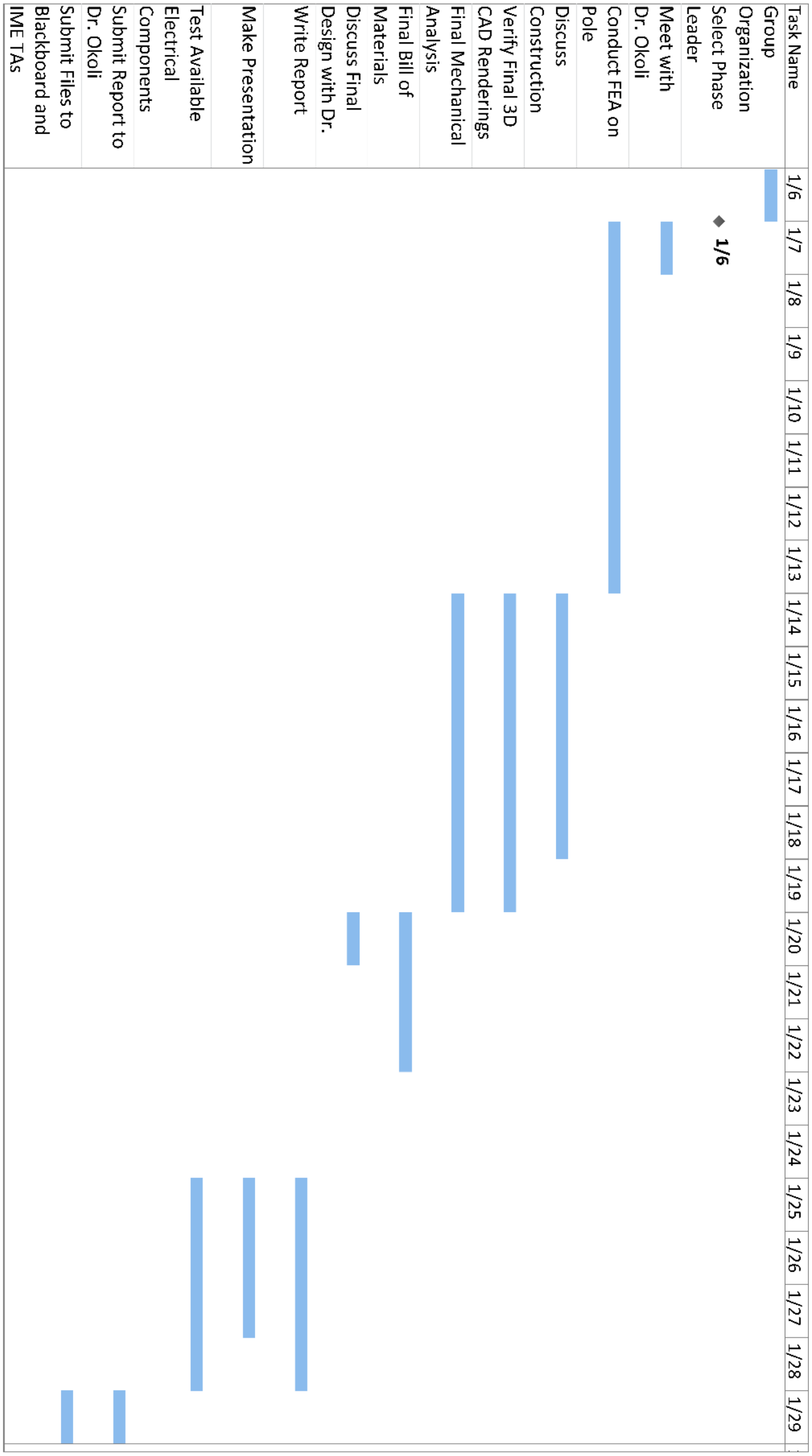


Figure 71: Gantt Chart for the Analyze Phase

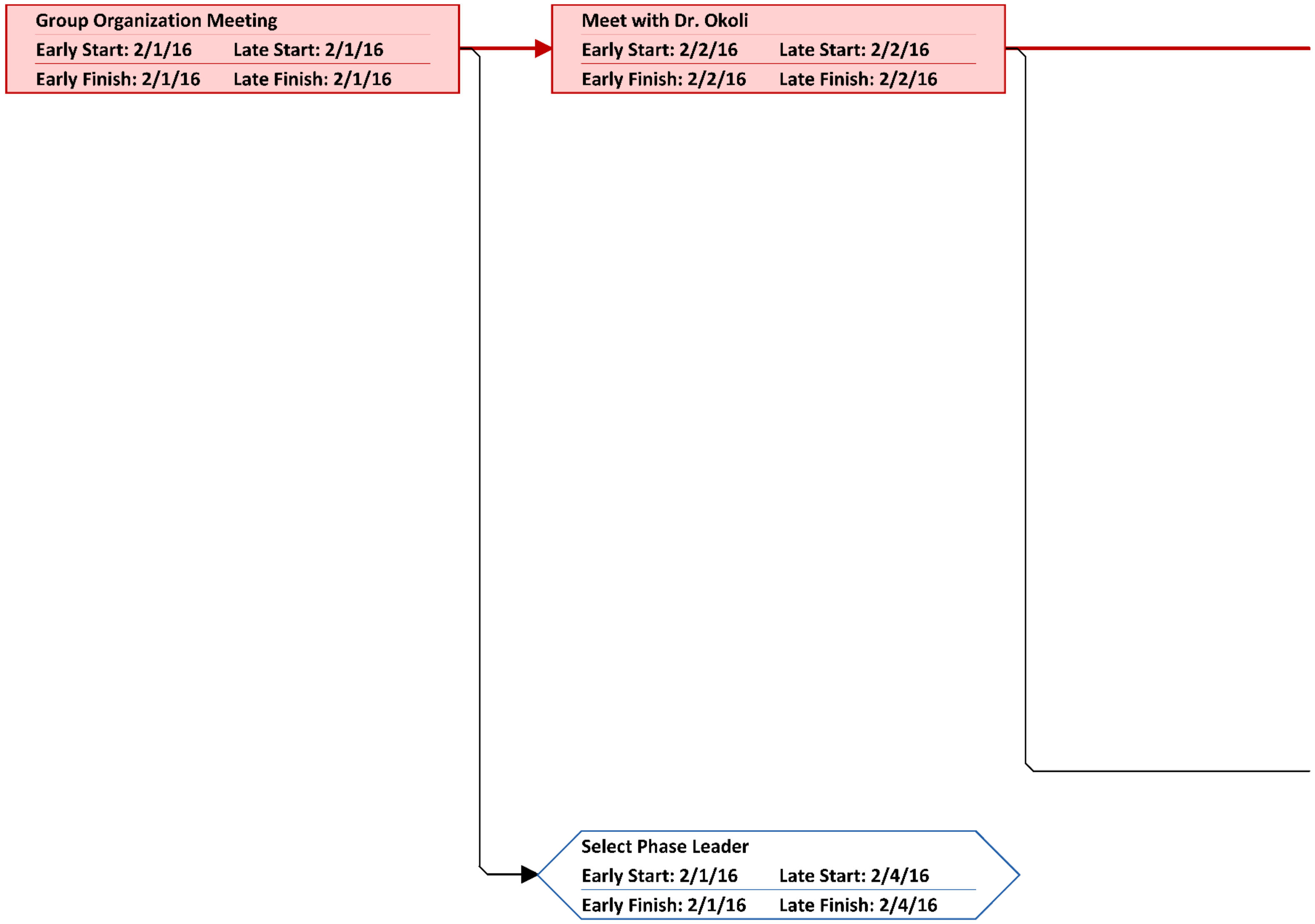
Using Figure 70 and Figure 71, the earliest that the Analyze Phase can end is 1/29/16. The latest the Analyze Phase can end is also 1/29/16.

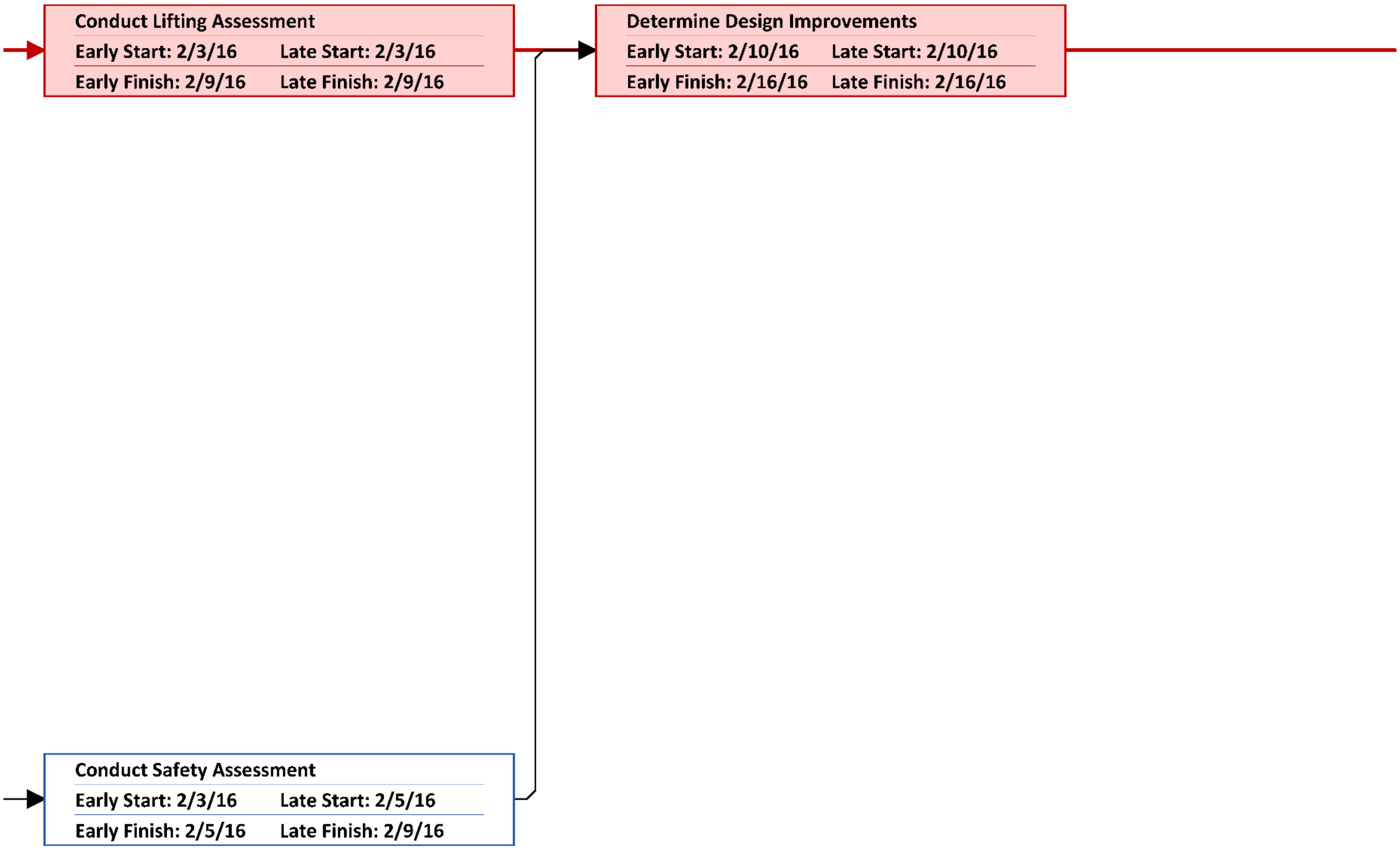
9.1.4 Improve Phase Tasks

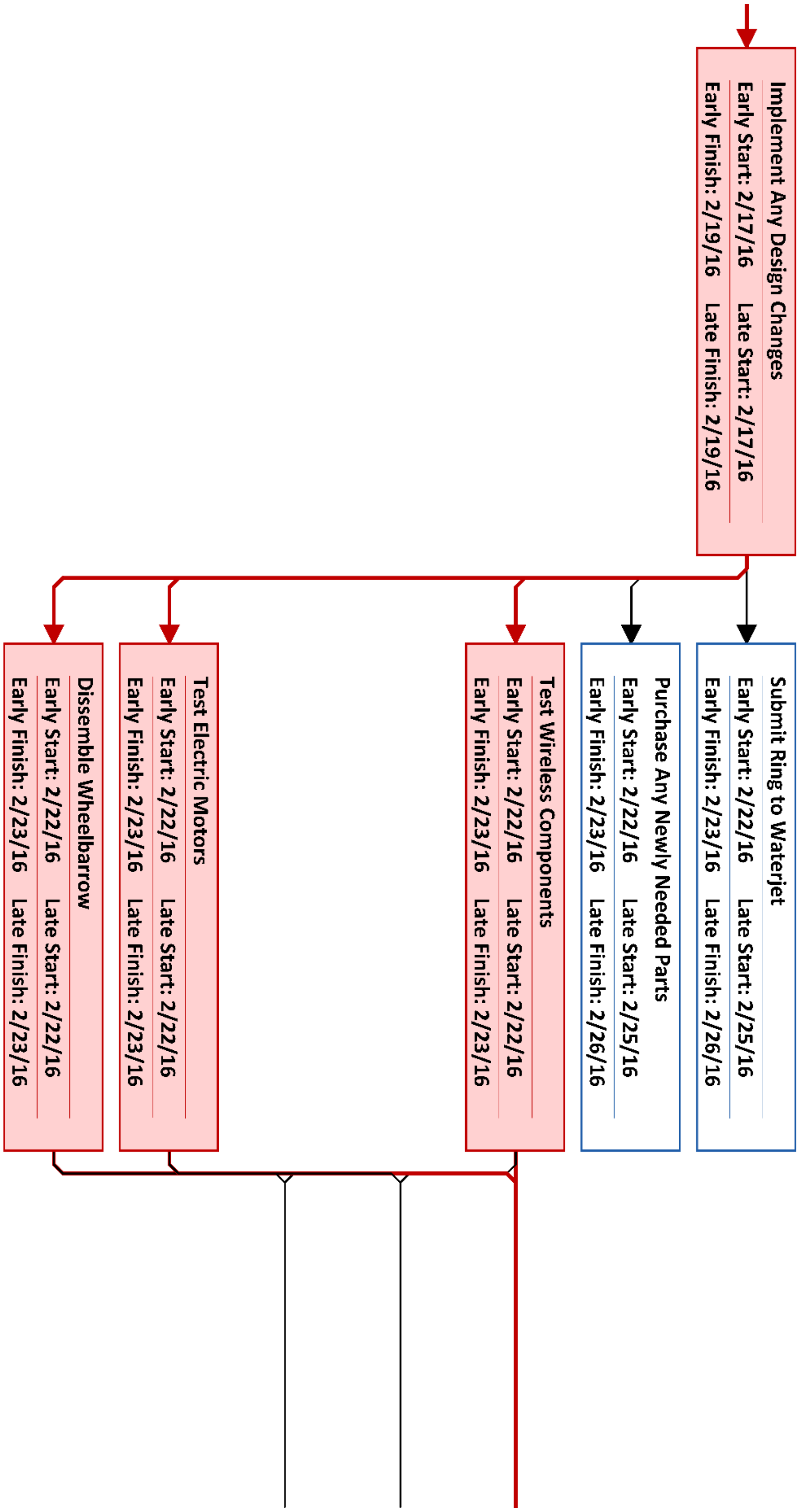
Major tasks that are required to be completed by the end of the Improve Phase are discussed in Table 44. Figure 72 depicts the network flow diagram for the Improve Phase, which includes a broad outline of the tasks that need to be completed. Quantitative information regarding the specific tasks depicted in Figure 72 is given in Table 45.

Table 44: Major Tasks for the Improve Phase

Task	Explanation
Contacting and meeting with Dr. Okoli.	The sponsor can inform the group of any changes that are desired to the constructed prototype.
Conduct lifting assessment.	Determine if the weight that the operator would be lifting is allowed by the United States Occupational Safety and Health Administration.
Conduct safety assessment.	Determine possible hazards that could occur during testing.
Determine design improvements.	Optimize the design based on the lifting and safety assessments.
Dissemble Wheelbarrow	This step is required before the cart can be assembled in the Control Phase.
Presenting the group’s project status.	This allows the group to demonstrate progress toward a prototype to the sponsor and stakeholders, as well as give a synopsis of the Improve Phase’s tasks.


Group Organization Meeting
Early Start: 2/1/16
Late Start: 2/1/16
Early Finish: 2/1/16
Late Finish: 2/1/16
Meet with Dr. Okoli
Early Start: 2/2/16
Late Start: 2/2/16
Early Finish: 2/2/16
Late Finish: 2/2/16
Select Phase Leader
Early Start: 2/1/16
Late Start: 2/4/16
Early Finish: 2/1/16
Late Finish: 2/4/16


Conduct Lifting Assessment
Early Start: 2/3/16
Late Start: 2/3/16
Early Finish: 2/9/16
Late Finish: 2/9/16
Determine Design Improvements
Early Start: 2/10/16
Late Start: 2/10/16
Early Finish: 2/16/16
Late Finish: 2/16/16
Conduct Safety Assessment
Early Start: 2/3/16
Late Start: 2/5/16
Early Finish: 2/5/16
Late Finish: 2/9/16


Implement Any Design Changes
Early Start: 2/17/16 Late Start: 2/17/16
Early Finish: 2/19/16 Late Finish: 2/19/16
Submit Ring to Waterjet
Early Start: 2/22/16 Late Start: 2/25/16
Early Finish: 2/23/16 Late Finish: 2/26/16
Purchase Any Newly Needed Parts
Early Start: 2/22/16 Late Start: 2/25/16
Early Finish: 2/23/16 Late Finish: 2/26/16
Test Wireless Components
Early Start: 2/22/16 Late Start: 2/22/16
Early Finish: 2/23/16 Late Finish: 2/23/16
Test Electric Motors
Early Start: 2/22/16 Late Start: 2/22/16
Early Finish: 2/23/16 Late Finish: 2/23/16
Dissemble Wheelbarrow
Early Start: 2/22/16 Late Start: 2/22/16
Early Finish: 2/23/16 Late Finish: 2/23/16

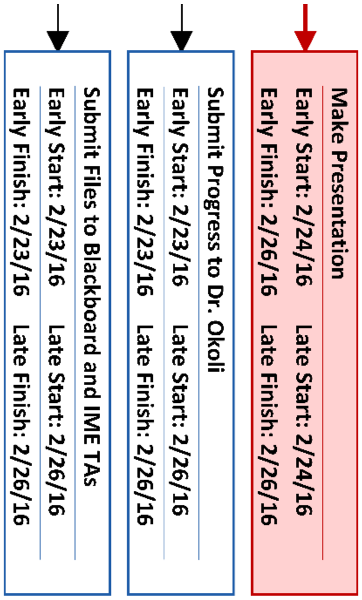


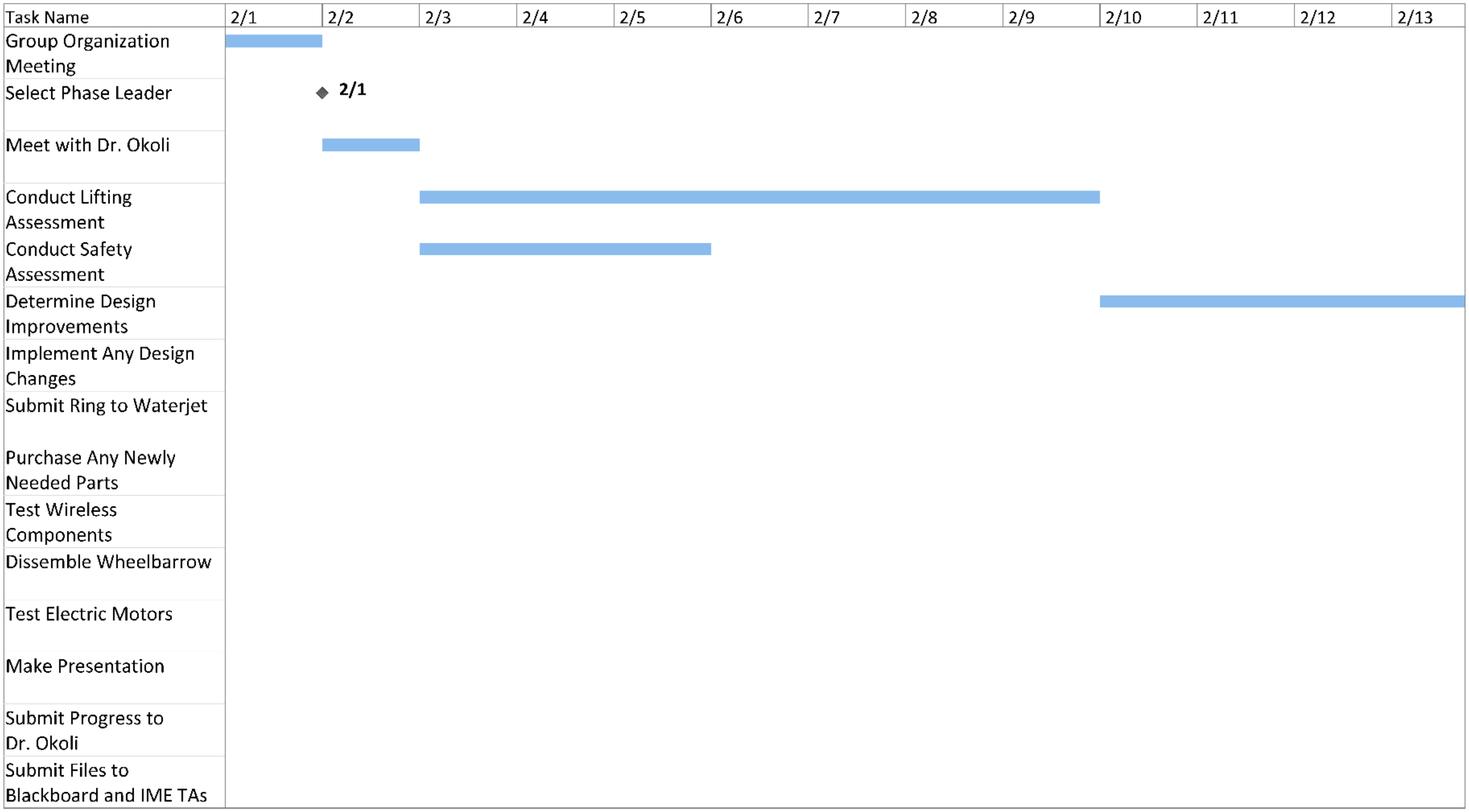
Figure 72: Network Flow Diagram for the Improve Phase

Table 45: Detailed Network Flow Diagram Information for Improve Phase Tasks

Task Name	Duration	Start	Finish	Free Slack	Total Slack	Early Start	Early Finish	Late Start	Late Finish
Group Organization Meeting	1 day	2/1/16	2/1/16	0 days	0 days	2/1/16	2/1/16	2/1/16	2/1/16
Select Phase Leader	0 days	2/1/16	2/1/16	2 days	2 days	2/1/16	2/1/16	2/4/16	2/4/16
Meet with Dr. Okoli	1 day	2/2/16	2/2/16	0 days	0 days	2/2/16	2/2/16	2/2/16	2/2/16
Conduct Lifting Assessment	5 days	2/3/16	2/9/16	0 days	0 days	2/3/16	2/9/16	2/3/16	2/9/16
Conduct Safety Assessment	3 days	2/3/16	2/5/16	2 days	2 days	2/3/16	2/5/16	2/5/16	2/9/16
Determine Design Improvements	5 days	2/10/16	2/16/16	0 days	0 days	2/10/16	2/16/16	2/10/16	2/16/16
Implement Any Design Changes	3 days	2/17/16	2/19/16	0 days	0 days	2/17/16	2/19/16	2/17/16	2/19/16
Submit Ring to Waterjet	2 days	2/22/16	2/23/16	3 days	3 days	2/22/16	2/23/16	2/25/16	2/26/16
Purchase Any Newly Needed Parts	2 days	2/22/16	2/23/16	3 days	3 days	2/22/16	2/23/16	2/25/16	2/26/16
Test Wireless Components	2 days	2/22/16	2/23/16	0 days	0 days	2/22/16	2/23/16	2/22/16	2/23/16
Dissemble Wheelbarrow	2 days	2/22/16	2/23/16	0 days	0 days	2/22/16	2/23/16	2/22/16	2/23/16
Test Electric Motors	2 days	2/22/16	2/23/16	0 days	0 days	2/22/16	2/23/16	2/22/16	2/23/16
Make Presentation	3 days	2/24/16	2/26/16	0 days	0 days	2/24/16	2/26/16	2/24/16	2/26/16
Submit Progress to Dr. Okoli	1 day	2/24/16	2/24/16	2 days	2 days	2/24/16	2/24/16	2/26/16	2/26/16
Submit Files to Blackboard and IME TAs	1 day	2/24/16	2/24/16	2 days	2 days	2/24/16	2/24/16	2/26/16	2/26/16

Free slack and total slack (float) were discussed in Section 9.1.1. All activities with a total slack value of zero (0) in Table 45 are along the Improve Phase’s critical path, which is denoted by red boxes and arrows in Figure 72. These critical tasks must be completed by the specified deadline, or the Improve Phase will be delayed. Table 45 illustrates that the first part of the Improve Phase's critical path starts on 2/1/16 and ends on 2/26/16. Thus, the critical path of the Improve Phase is 25 days.

Gantt charts were discussed in Section 9.1.1. A Gantt chart of the Improve Phase's planned activities was constructed and is depicted in Figure 73.


Task Name
2/1
2/2
2/3
2/4
2/5
2/6
2/7
2/8
2/9
2/10
2/11
2/12
2/13
Group Organization Meeting
Select Phase Leader
2/1
Meet with Dr. Okoli
Conduct Lifting Assessment
Conduct Safety Assessment
Determine Design Improvements
Implement Any Design Changes
Submit Ring to Waterjet
Purchase Any Newly Needed Parts
Test Wireless Components
Dissemble Wheelbarrow
Test Electric Motors
Make Presentation
Submit Progress to Dr. Okoli
Submit Files to Blackboard and IME TAs

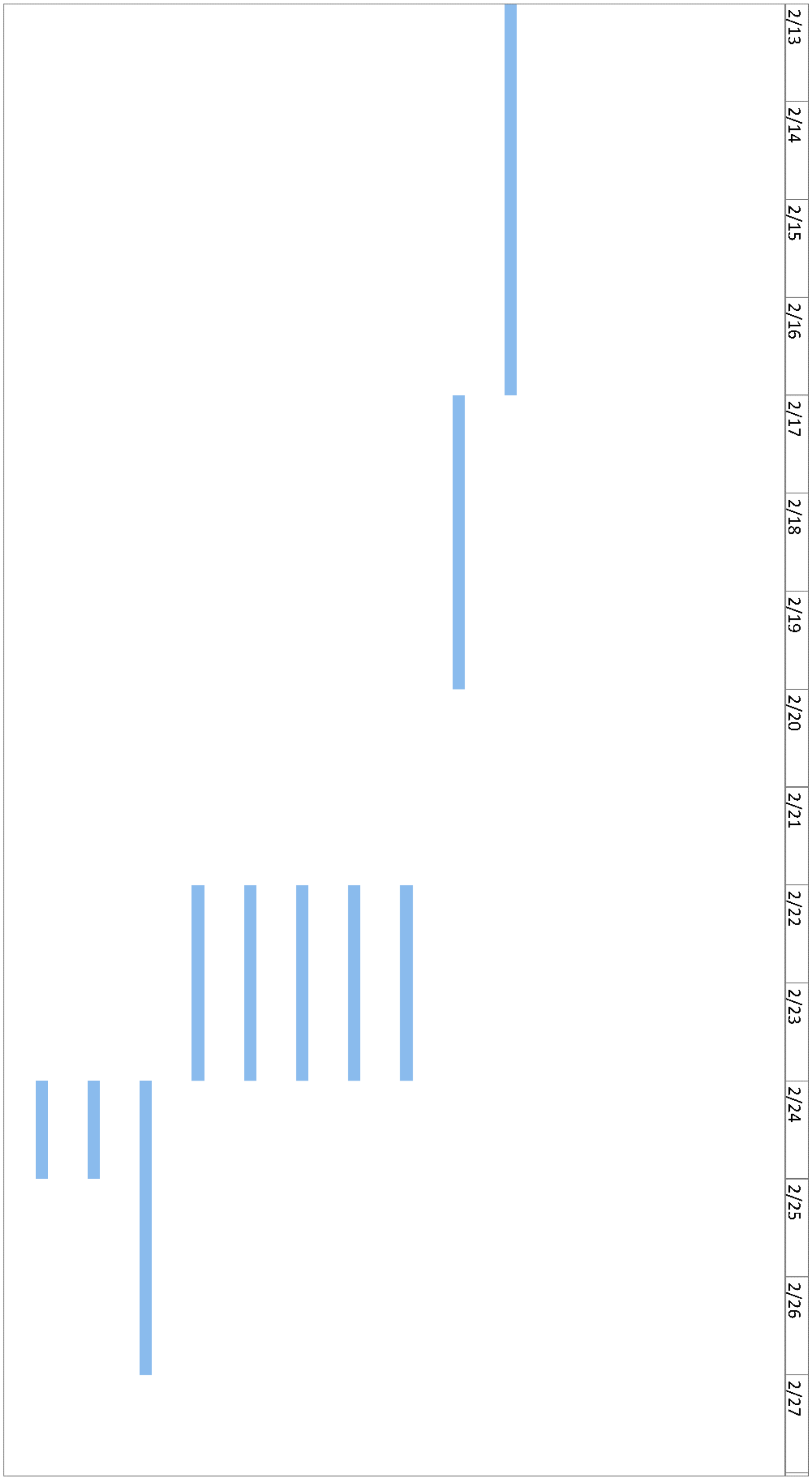


Figure 73: Gantt Chart for the Improve Phase

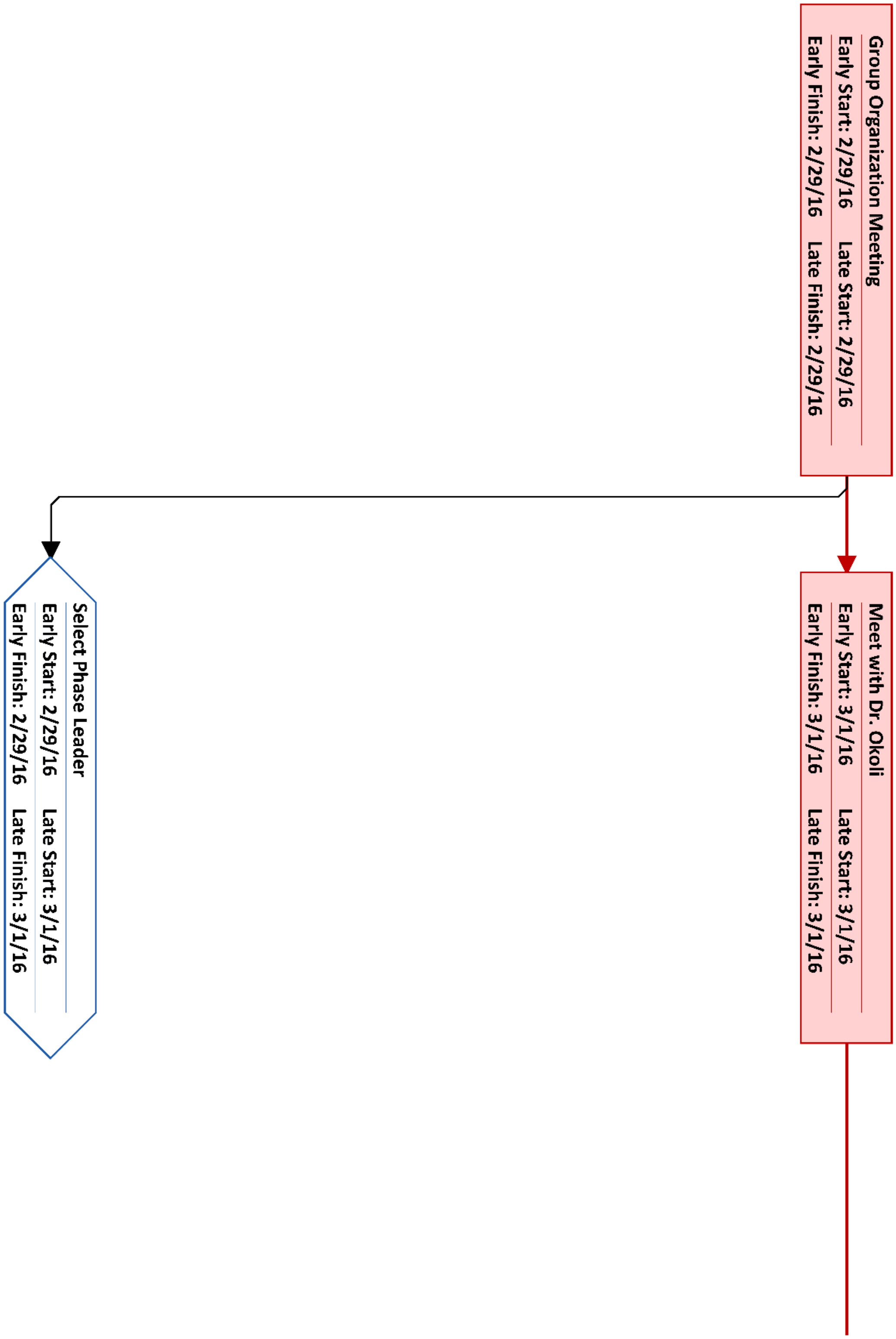
Using Figure 72 and Figure 73, the earliest the Improve Phase can end is 2/26/15. The latest the Improve Phase can end is also 2/26/16.

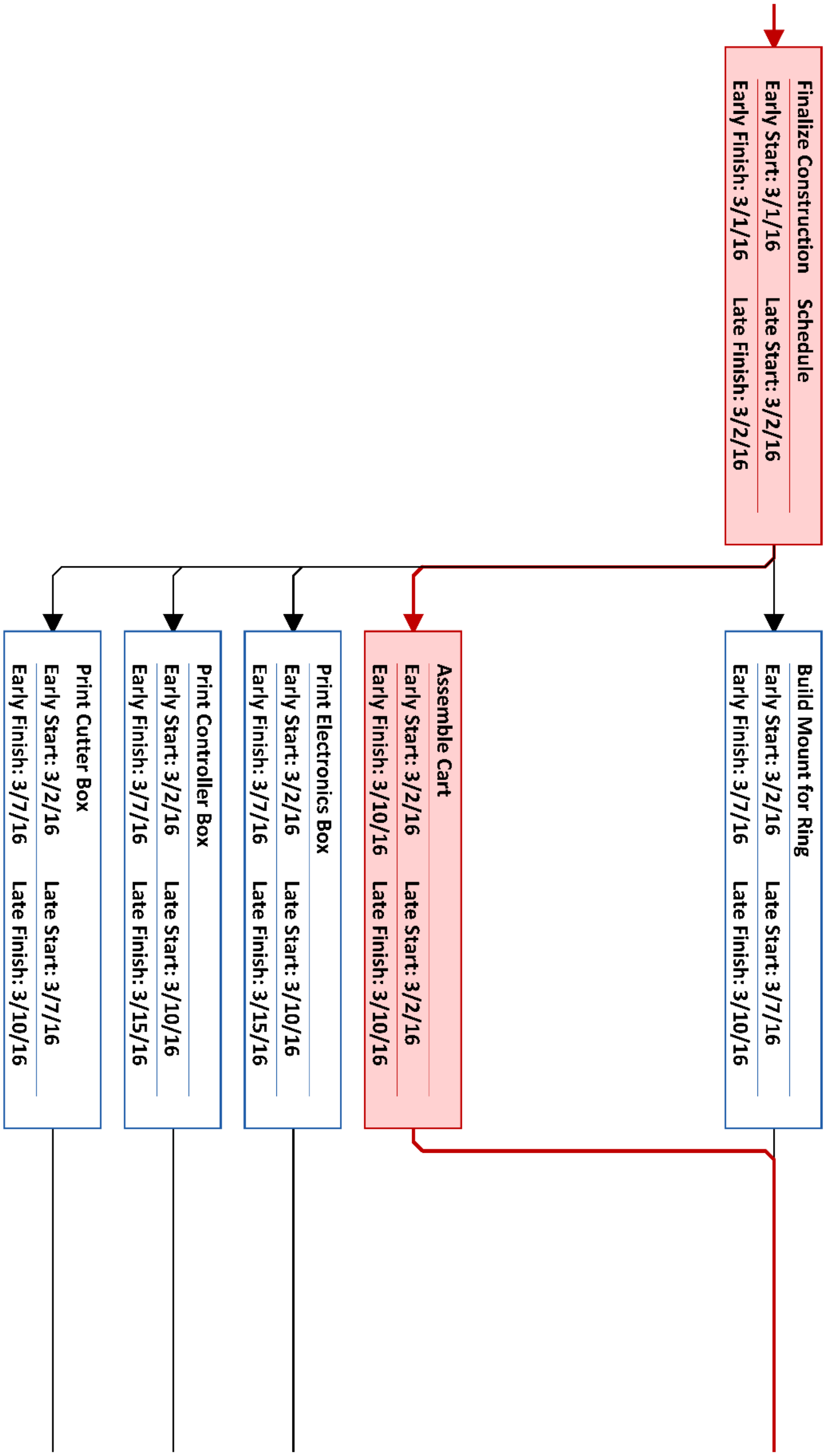
9.1.5 Control Phase Tasks

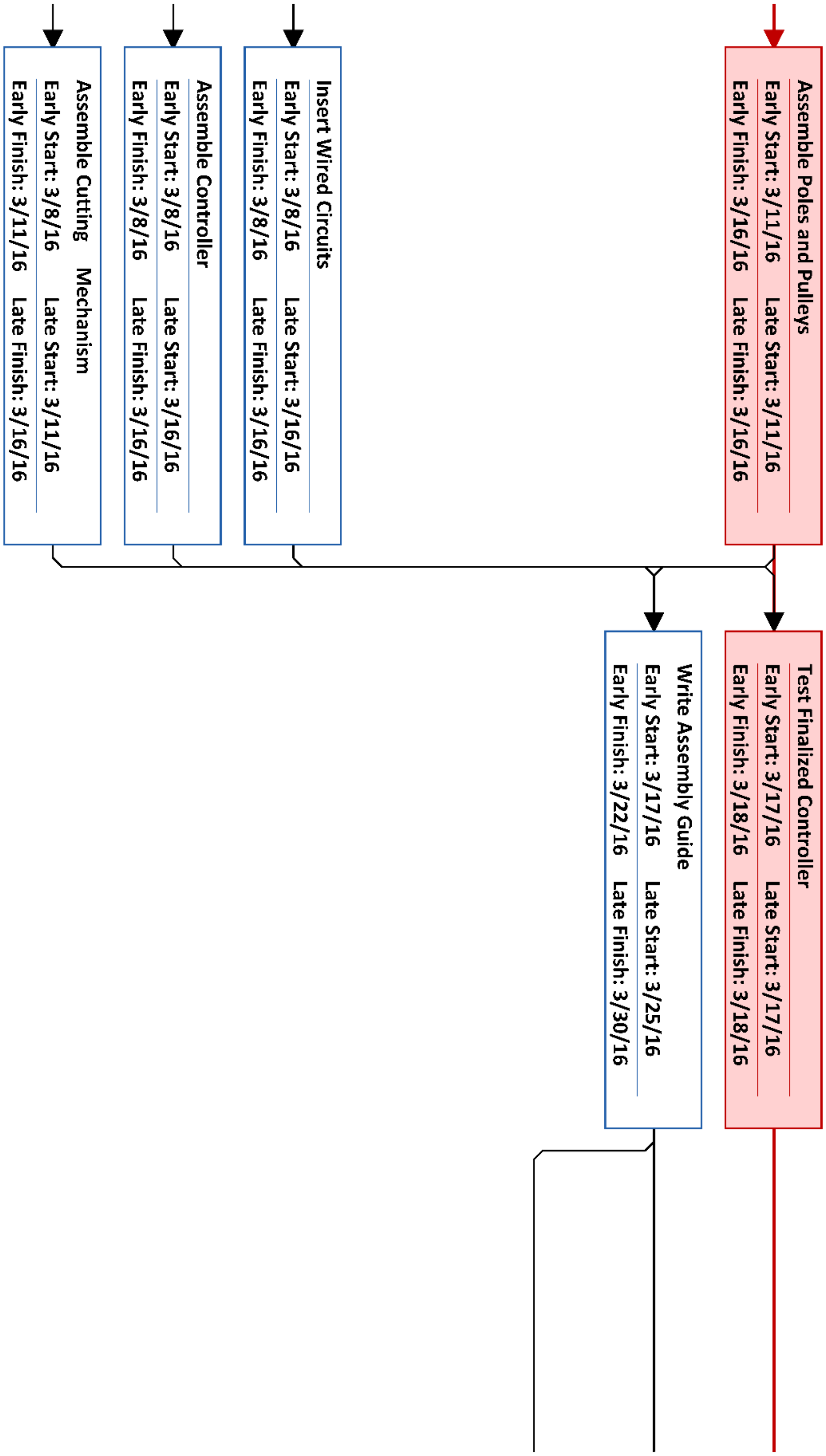
Major tasks that are required to be completed by the end of the Control Phase are discussed in Table 46. Figure 74 depicts the network flow diagram for the Control Phase, which includes a broad outline of the tasks that need to be completed. Quantitative information regarding the tasks in Figure 74 is given in Table 47.

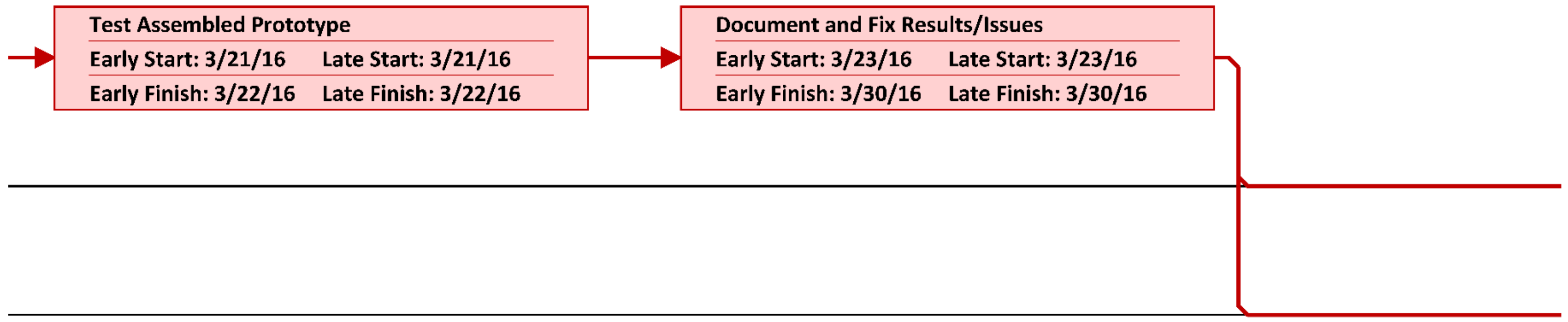
Table 46: Major Tasks for the Control Phase

Task	Explanation
Contacting and meeting with Dr. Okoli.	The sponsor can inform the group of any prototype benchmarks that must be met.
Test final components	Components should be tested prior to assembly to ensure that they are working properly.
Construct cutting mechanism	The cutting mechanism should be constructed before being affixed to the poles.
Construct prototype	The poles and cart should be assembled together.
Finalize controller	The prototype controller should be built and finalized.
Test prototype	The prototype should be tested after it is built to ensure that it meets the sponsor’s requirements.
Document and fix results/issues	Any issues that arise during testing should be documented and fixed.


Group Organization Meeting
Early Start: 2/29/16
Late Start: 2/29/16
Early Finish: 2/29/16
Late Finish: 2/29/16
Meet with Dr. Okoli
Early Start: 3/1/16
Late Start: 3/1/16
Early Finish: 3/1/16
Late Finish: 3/1/16
Select Phase Leader
Early Start: 2/29/16
Late Start: 3/1/16
Early Finish: 2/29/16
Late Finish: 3/1/16


Finalize Construction Schedule
Early Start: 3/1/16
Late Start: 3/2/16
Early Finish: 3/1/16
Late Finish: 3/2/16
Build Mount for Ring
Early Start: 3/2/16
Late Start: 3/7/16
Early Finish: 3/7/16
Late Finish: 3/10/16
Assemble Cart
Early Start: 3/2/16
Late Start: 3/2/16
Early Finish: 3/10/16
Late Finish: 3/10/16
Print Electronics Box
Early Start: 3/2/16
Late Start: 3/10/16
Early Finish: 3/7/16
Late Finish: 3/15/16
Print Controller Box
Early Start: 3/2/16
Late Start: 3/10/16
Early Finish: 3/7/16
Late Finish: 3/15/16
Print Cutter Box
Early Start: 3/2/16
Late Start: 3/7/16
Early Finish: 3/7/16
Late Finish: 3/10/16


Assemble Poles and Pulleys
Early Start: 3/11/16
Late Start: 3/11/16
Early Finish: 3/16/16
Late Finish: 3/16/16
Insert Wired Circuits
Early Start: 3/8/16
Late Start: 3/16/16
Early Finish: 3/8/16
Late Finish: 3/16/16
Assemble Controller
Early Start: 3/8/16
Late Start: 3/16/16
Early Finish: 3/8/16
Late Finish: 3/16/16
Assemble Cutting Mechanism
Early Start: 3/8/16
Late Start: 3/11/16
Early Finish: 3/11/16
Late Finish: 3/16/16
Test Finalized Controller
Early Start: 3/17/16
Late Start: 3/17/16
Early Finish: 3/18/16
Late Finish: 3/18/16
Write Assembly Guide
Early Start: 3/17/16
Late Start: 3/25/16
Early Finish: 3/22/16
Late Finish: 3/30/16


Test Assembled Prototype
Early Start: 3/21/16
Late Start: 3/21/16
Early Finish: 3/22/16
Late Finish: 3/22/16
Document and Fix Results/Issues
Early Start: 3/23/16
Late Start: 3/23/16
Early Finish: 3/30/16
Late Finish: 3/30/16

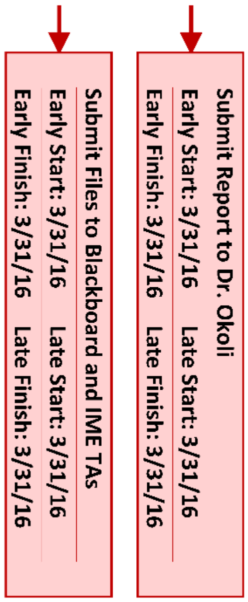


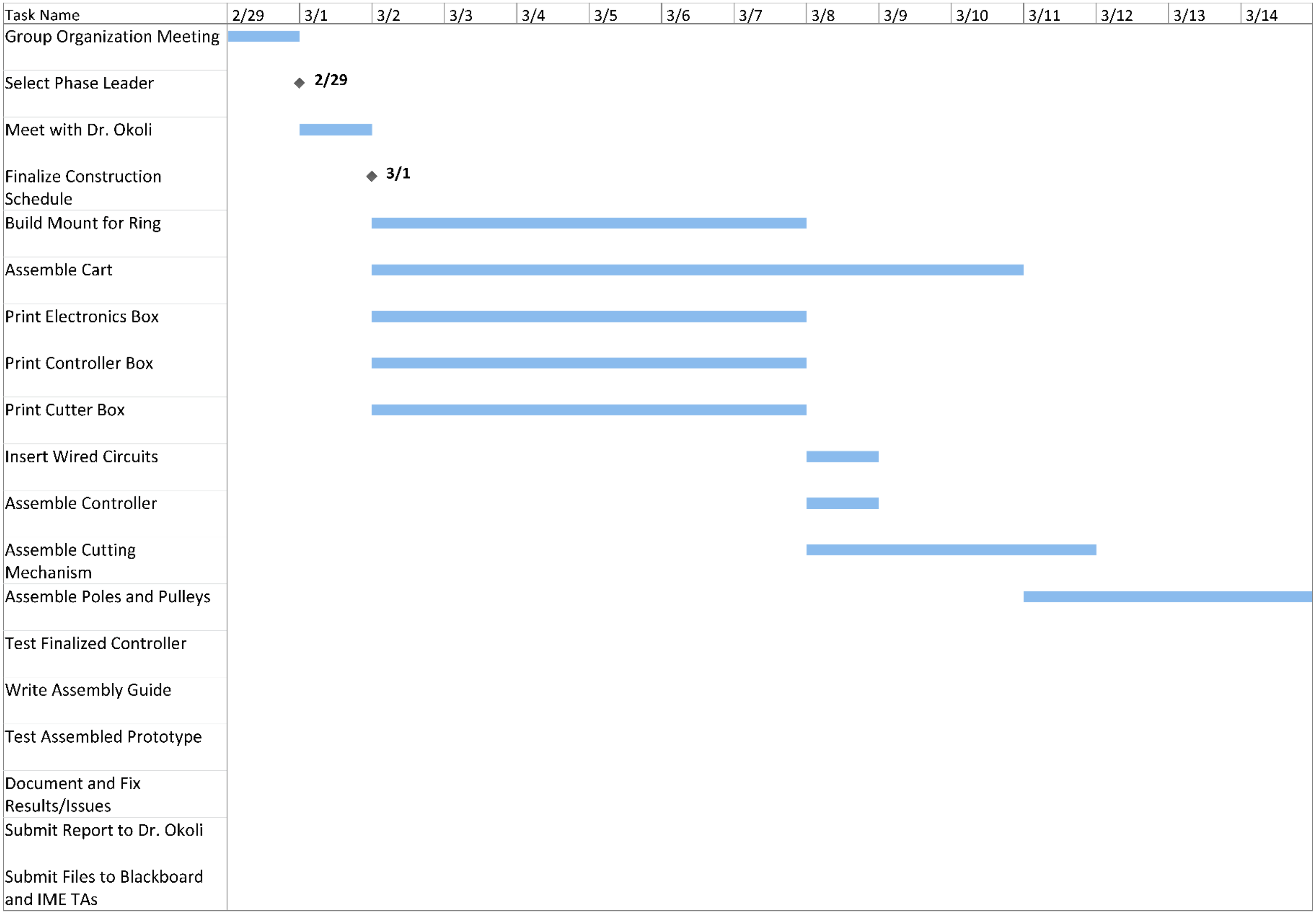
Figure 74: Network Flow Diagram for the Control Phase

Table 47: Detailed Network Flow Diagram Information for Control Phase Tasks

Task Name	Start	Finish	Free Slack	Total Slack	Early Start	Early Finish	Late Start	Late Finish
Group Organization Meeting	2/29/16	2/29/16	0 days	0 days	2/29/16	2/29/16	2/29/16	2/29/16
Select Phase Leader	2/29/16	2/29/16	1 day	1 day	2/29/16	2/29/16	3/1/16	3/1/16
Meet with Dr. Okoli	3/1/16	3/1/16	0 days?	0 days?	3/1/16	3/1/16	3/1/16	3/1/16
Finalize Construction Schedule	3/1/16	3/1/16	0 days	0 days	3/1/16	3/1/16	3/2/16	3/2/16
Build Mount for Ring	3/2/16	3/7/16	3 days	3 days	3/2/16	3/7/16	3/7/16	3/10/16
Assemble Cart	3/2/16	3/10/16	0 days	0 days	3/2/16	3/10/16	3/2/16	3/10/16
Print Electronics Box	3/2/16	3/7/16	0 days	6 days	3/2/16	3/7/16	3/10/16	3/15/16
Print Controller Box	3/2/16	3/7/16	0 days	6 days	3/2/16	3/7/16	3/10/16	3/15/16
Print Cutter Box	3/2/16	3/7/16	0 days	3 days	3/2/16	3/7/16	3/7/16	3/10/16
Insert Wired Circuits	3/8/16	3/8/16	6 days	6 days	3/8/16	3/8/16	3/16/16	3/16/16
Assemble Controller	3/8/16	3/8/16	6 days	6 days	3/8/16	3/8/16	3/16/16	3/16/16
Assemble Cutting Mechanism	3/8/16	3/11/16	3 days	3 days	3/8/16	3/11/16	3/11/16	3/16/16
Assemble Poles and Pulleys	3/11/16	3/16/16	0 days	0 days	3/11/16	3/16/16	3/11/16	3/16/16
Test Finalized Controller	3/17/16	3/18/16	0 days	0 days	3/17/16	3/18/16	3/17/16	3/18/16
Write Assembly Guide	3/17/16	3/22/16	6 days	6 days	3/17/16	3/22/16	3/25/16	3/30/16
Test Assembled Prototype	3/21/16	3/22/16	0 days	0 days	3/21/16	3/22/16	3/21/16	3/22/16
Document and Fix Results/Issues	3/23/16	3/30/16	0 days	0 days	3/23/16	3/30/16	3/23/16	3/30/16
Submit Report to Dr. Okoli	3/31/16	3/31/16	0 days	0 days	3/31/16	3/31/16	3/31/16	3/31/16
Submit Files to Blackboard and IME TAs	3/31/16	3/31/16	0 days	0 days	3/31/16	3/31/16	3/31/16	3/31/16

Free slack and total slack (float) were discussed in Section 9.1.1. All activities with a total slack value of zero (0) in Table 47 are along the Control Phase’s critical path, which is denoted by red boxes and arrows in Figure 74. These critical tasks must be completed by the specified deadline, or the Control Phase will be delayed. Table 47 illustrates that the first part of the Control Phase’s critical path starts on 2/29/16 and ends on 3/31/16. Thus, the critical path of the Control Phase is 31 days.

Gantt charts were discussed in Section 9.1.1. A Gantt chart of the Control Phase’s planned activities was constructed and is depicted in Figure 75.


Task Name
2/29
3/1
3/2
3/3
3/4
3/5
3/6
3/7
3/8
3/9
3/10
3/11
3/12
3/13
3/14
Group Organization Meeting
Select Phase Leader
2/29
Meet with Dr. Okoli
Finalize Construction Schedule
3/1
Build Mount for Ring
Assemble Cart
Print Electronics Box
Print Controller Box
Print Cutter Box
Insert Wired Circuits
Assemble Controller
Assemble Cutting Mechanism
Assemble Poles and Pulleys
Test Finalized Controller
Write Assembly Guide
Test Assembled Prototype
Document and Fix Results/Issues
Submit Report to Dr. Okoli
Submit Files to Blackboard and IME TAs

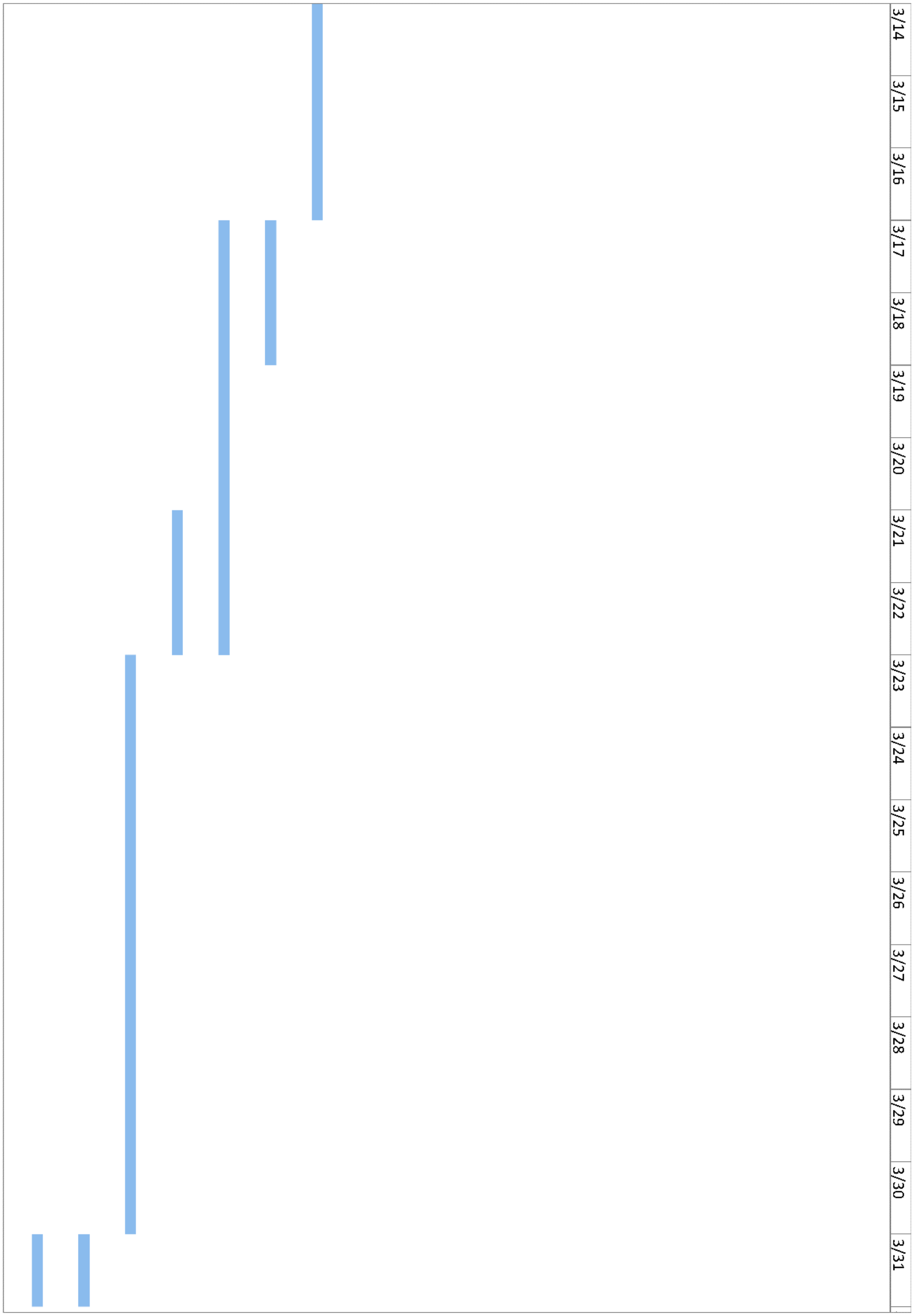


Figure 75: Gantt Chart for the Control Phase

Using Figure 74 and Figure 75, the earliest the Control Phase can end is 3/31/16. The latest the Control Phase can end is also 3/31/16.

9.2 Risk Management

To help identify risks for this project, a Strengths/Weaknesses/Threats/Opportunities (SWOT) matrix was constructed and is depicted in Figure 76.

Strengths

- Machine safer than human workers
- Easy to use joystick
- Strong materials add durability

Weaknesses

- Mechanism is not completely automated.
  - -Assembly from tree to tree
  - -Cutting mechanism pulled upward
- Mechanism is not faster than a worker climbing up the tree.
- Inability to examine oil palm in the field.

Opportunities

- Increase productivity, eliminating human fatigue
- Design a mechanism that is easy to operate
- Less maintenance
- Eliminate risk of death for humans

Threats

- Cutting oil palm fruits could injure the operator or damage the machine or tree
- Exceeding the $2,500 budget.
- Ordered parts do not arrive in a timely manner

Figure 76: SWOT Matrix

In Figure 76, safety has been taken into consideration and the use of the machine will allow workers to harvest fruit bunches without ascending and descending each oil palm tree. Additionally, the team considered that workers might be inexperienced controlling sophisticated electronic equipment. The team solved this issue by utilizing a simple joystick controller.

Finally, aluminum was used to reduce weight and add strength to the design, which makes it very durable.

Although the team has integrated electromechanical components into the prototype, the system is not completely autonomous. The system has to be setup on each tree. Subsequently, the cutting mechanism has to be pushed upward. As a result, the mechanism is not expected to work faster than a human climbing the tree. Since there are no oil palm trees located in the Tallahassee area, the device will have to be tested on a structure similar to a 12-meter tall oil palm tree, such as a light pole.

As humans become fatigued after climbing several trees throughout the day, they gradually become less productive. The prototype, however, will continue to operate at the same level of productivity, ultimately increasing the total oil palm fruit output.

As a potential threat, there exists a possibility that the cutting mechanism could harm the operator if it falls. Exceeding the budget is another potential threat, because the project would not be able to be completed within the sponsor's requirements. In addition, if receipt of the ordered parts is delayed, it could prevent an effective prototype from being completed.

The projected demand increase for palm oil [5] means that new techniques to improve the efficiency of current harvesting methods are needed. Since humans become fatigued after climbing several trees throughout the day [2], there is a limit to a human worker's efficiency. An electromechanical harvesting device would allow workers to remain on the ground and decrease the amount of physical labor during the harvesting process. This will allow laborers to harvest more oil palm fruit in a safer and more efficient manner.

The petiole, depicted in Figure 77 [47], can become a potential threat for the device during the harvesting process. Petioles are sharp and can prevent the device from descending the tree or can possibly damage it. Exceeding the budget is another potential threat, because the project would not be completed within the sponsor's requirements. Since the final design has yet been selected, it is difficult to determine how much (if any) damage may occur when operating prototype. The operator, machine, or tree could be at risk while cutting oil palm fruit. The probability and impact of each of these risks is depicted in Figure 78. In Figure 78, the color green indicates that a "low risk" is deemed acceptable and safe, while the color yellow means that a "moderate risk" is acceptable with proper safety precautions. The colors red and dark red both indicate that the "high risk" or "extreme risk" is dangerous and unacceptable, respectively. The difference between a "high risk" and "extreme risk" is that an "extreme risk" is more likely to occur than a "high risk." These descriptions are also given in Figure 78.

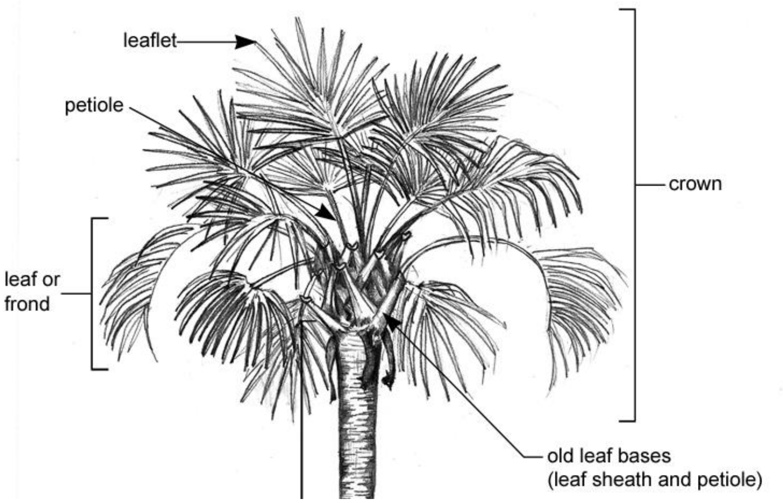
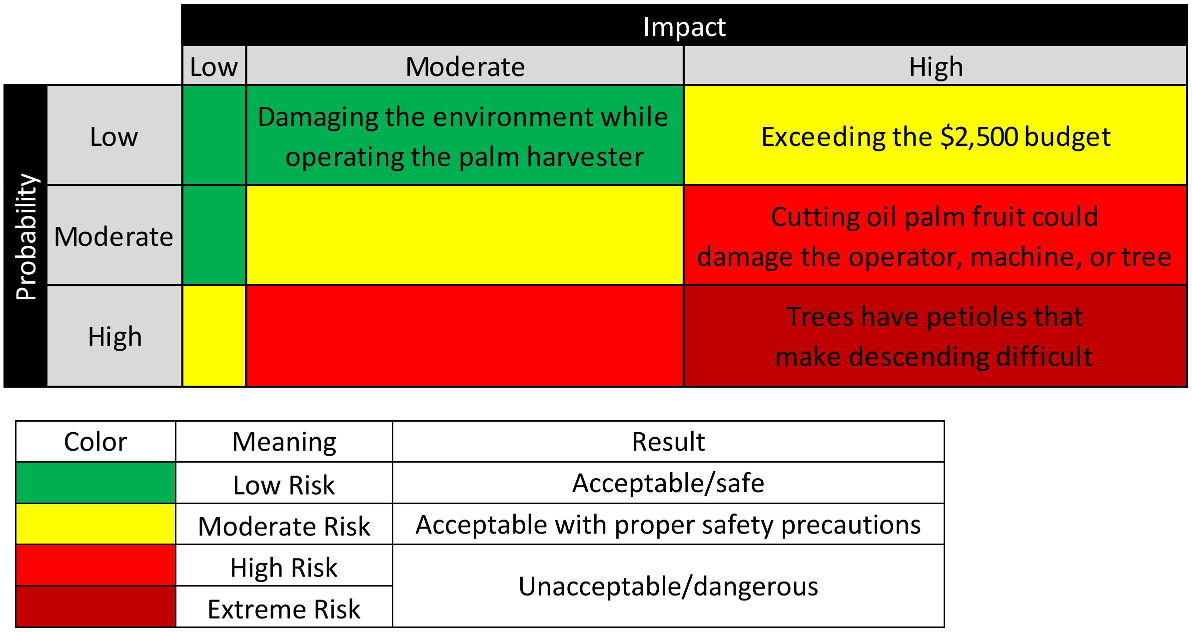


Figure 77: Upper Portion of a Generic Palm Tree [47]



		Impact		
		Low	Moderate	High
Probability	Low	🟩	Damaging the environment while operating the palm harvester	Exceeding the $2,500 budget
	Moderate	🟩	🟨	Cutting oil palm fruit could damage the operator, machine, or tree
	High	🟨	🟥	Trees have petioles that make descending difficult

Color	Meaning	Result
🟩	Low Risk	Acceptable/safe
🟨	Moderate Risk	Acceptable with proper safety precautions
🟥	High Risk	Unacceptable/dangerous
🟥	Extreme Risk	

Figure 78: Risk Matrix

9.3 Budget and Bill of Materials

The sponsor has set a budget of $2,500 for the entire project. Since any design selected will most likely contain several mechanical components and some electrical components, the mechanical parts and materials used in construction of the prototype will likely utilize most of the budget. In order to ensure the project does not exceed its budget, 8% of the budget ($200) is set as the management reserve amount.

9.3.1 Estimated Budget

The "most likely" cost of this project assumes that most parts used in the prototype will be constructed from lightweight aluminum that can easily be machined by team members. Some additional mechanical parts, such as actuators, may also be required. Since most of the electrical components will simply involve the mechanical devices communicating among themselves and to the operator, the cost is not expected to be as significant. Based on the Class of 2015's expenditures [9] the most likely cost of this project is described in Table 48.

Table 48: Budget Based on the Most Likely Cost of the Components

Item	**Most Likely Cost**
Mechanical Components	$500.00
Materials	$1,500.00
Electrical Components	$300.00
Total Cost	**$2,300.00**
Remaining Management Reserve	**$200.00**

Table 48 illustrates that the project would be completed within the most likely cost budget, with the entire management reserve still available. Table 49 shows a more optimistic scenario that assumes that a minimum number of mechanical and electrical parts will be required and that most of the mechanical parts can be fabricated from existing stock material.

Table 49: Budget Based on the Optimistic Cost of the Components

Item	**Optimistic Cost**
Mechanical Components	$200.00
Materials	$1,200.00
Electrical Components	$100.00
Total	**$1,500.00**
Remaining Management Reserve	**$200.00**
Budget Surplus	**$800.00**

Table 49 demonstrates that the optimistic cost budget would result in the project being completed with the entire management reserve still available, as well as a budget surplus of $800. However, a more pessimistic scenario would likely involve some combination of the budgets given in Table 48, Table 49, and Table 49.

This scenario could result from the team members improperly machining parts, which would result in new materials that would need to be ordered and fabricated quickly, in order to not delay the project. The pessimistic cost budget is given in Table 50.

Table 50: Budget Based on the Pessimistic Cost of the Components

Item	**Cost**
Mechanical Components	\$600.00
Materials	\$1,700.00
Electrical Components	\$300.00
Total	**\$2,600.00**
Remaining Management Reserve	**−\$100.00**

Table 50 illustrates the most pessimistic scenario, the entire management reserve would be used, and the project would still exceed the budget by \$100. The team would either have to petition the sponsor for a slight increase in the budget to complete the project or fund the overage using donations from team members.

In order to determine the most plausible budget, a weighted average of the budgets given in **Error! Reference source not found.**Table 48, Table 49, and Table 50 must be computed, using the formula $\boldsymbol{C_e = (C_o + 4C_m + C_p)/6}$, where $\boldsymbol{C_o}$ represents the optimistic budget given in Table 49, $\boldsymbol{C_m}$ represents the most likely budget given in Table 48, and $\boldsymbol{C_p}$ represents the pessimistic budget given in Table 50. This calculation yielded the final budget given in Table 51.

Table 51: Final Budget Based on a Weighted Average of Three Budgets

Item	**Cost**
Mechanical Components	\$466.67
Materials	\$1,483.33
Electrical Components	\$267.67
Total	**\$2,217.67**
Remaining Management Reserve	**\$200.00**
Budget Surplus	**\$82.33**

Table 51 demonstrates that the project would be completed within the budget and results in a budget surplus of \$82.33. The previously estimated budget tables are given in Appendix I.

9.3.2 Actual Expenditures and Bill of Materials

The actual expenditures for the selected design and the bill of materials are given in Table 52.

Table 52: Budget and Bill of Materials

Part	Quantity	Unit Price	Total
9.525 mm x 2438.4 mm x 965.2 mm Aluminum Sheet	1	$529.20	$529.20
1 kilogram of 3D Printing Material	3	$34.00	$102.00
DC Motors	3	$34.00	$102.00
Stepper Motor	1	$199.78	$199.78
Lead Screw Rod	1	$ 9.14	$9.14
Lead Screw Nut	1	$0.50	$0.50
Linear Bearings (6.35 mm x 20.6375 mm x 7.9375 mm)	4	$ 46.20	$184.80
Shaft (6.35 mm x 609.6 mm)	1	$ 20.73	$ 20.73
Robot Mount	1	Used from Aluminum Sheet/PLA material	
12V Winch Battery	1	**	**
Connectors (25 Pack)	1	$14.83	$14.83
Arduino	3	$20.79	$62.37
Joystick Shield	1	$8.00	$8.00
10A 5–25V Dual Channel DC Motor Driver	2	$23.49	$46.98
30A 5–30V Single Brushed DC Motor Driver	1	$37.99	$37.99
L298N MotoMama H-Bridge Motor Driver Shield	1	$9.98	$9.98
Transmitter/Receiver	1	$3.00	$3.00
Bread Board	1	$4.54	$4.54
Battery Holder	3	$1.76	$5.28
AA Cell Batteries (4 Pack)	3	$5.28	$15.84
4400mAH 3.7V Li-Ion Battery	10	$20.00	$199.99
D Cell Batteries (8 Pack)	1	$11.34	$11.34
USB Breakaway Cable	1	$5.39	$5.39
65 x 22 Gauge Assorted Jumper Wires	1	$3.95	$3.95
7620 mm #22 Gauge Black Hook-Up Wire	1	$2.25	$2.25
Miscellaneous Hardware (screws, nuts, et cetera)	As Required	$50.00	$50.00
Winch	1	$104.26	$104.26
Cart	1	$269.99	$269.99
Pulley	1	**	**
Braided Steel Line	1	**	**
Telescoping Square Tubing	1	**	**
Chainsaw Blade	1	**	**
Metric High-Strength Class 10 Steel Thread	2	$ 2.43	$ 4.86
Black- Oxide Steel Flat Rollers with Seal	2	$ 21.00	$ 42.00
Shaft Supports	4	$ 17.40	$ 69.60
Leveling Jacks	1	$ 90.23	$ 90.23
Battery Boxes	1	$ 20.07	$ 20.07
**Used from previous year; mm = millimeter		**TOTAL**	$2,230.89

The analysis of the budget determines that the electrical components total to $753.58 and the mechanical components total to $1,477.31, with a total budget use of $2,230.89. This leaves $269.11 remaining from the total budget of $2,500.00. Since the telescoping tubing from the previous year is used in the current design, it resulted in a saving of about $650.00 in the total budget. With these savings and the large portion of the mechanical materials already in the group's possession, the budget could be used to order the electrical components and remaining mechanical components necessary to complete the design.

In order to keep the costs to a minimum and to be economical with the budget, it was decided to use parts from the Class of 2015's project that also appear in the current design. This included the 12V winch battery, the telescoping aluminum tubing, the winch, the pulleys, and the braided steel line. In total this saved the group about $650.00 [9]. With these parts already available for use, the budget was able to be spent in other areas of the design.

Another major change to the budget with the current design from the last design is the inclusion of the utility cart. This change used $269.99 of the budget, but replaced the bicycle wheels, the axle, and the handles from the last design, all of which totaled about $300.00. Along with this choice being more efficient in terms of time for production and guaranteed functionality, it also is a more cost efficient choice.

Figure 79 depicts an S-curve that shows the target expenditures of the budget over the entire length of the project. Most expenditures occurred midway through the project, due to the process of ordering parts.

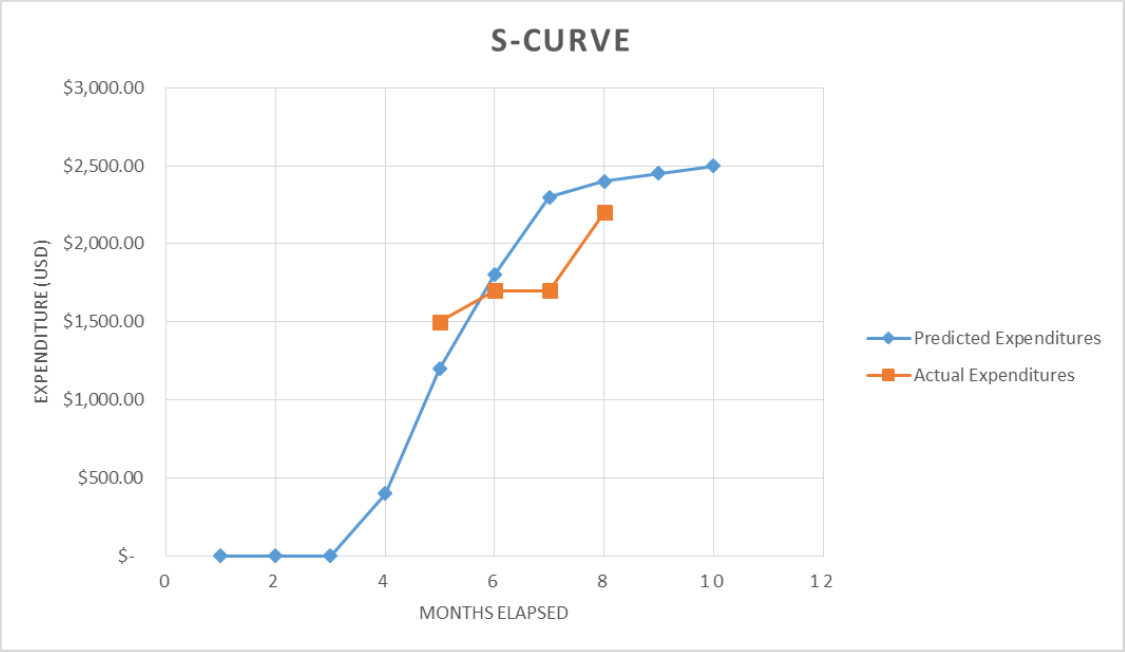


Figure 79: S-Curve

10. Conclusion

There is a large demand for palm oil, all over the world; unfortunately, the current methods used to harvest oil palm fruit are inefficient [2]. Developing a device to improve the efficiency of oil palm fruit harvesting would increase production and improve workers' safety. The current method requires humans to climb 12-meter tall palm trees and manually cut fruit bunches; this is extremely dangerous because a worker has a high probability of falling off the tree [10]. Creating an electromechanical system would eliminate this risky human involvement. To design such a device, the team met with Dr. Okoli, the project's sponsor, researched basic information on oil palm fruit harvesting methods, proposed several design concepts, and became familiar with the limitations that the final design must satisfy.

In the Define Phase, the group constructed a house of quality to determine which technical requirements were the most important to satisfy the customer's requirements; the group found that the electromechanical components was the most important technical requirement, followed by the system weight and modular design. The group also discussed two main approaches to designing a harvesting device. The first approach involved improving one of the previous groups' designs, while the second was to create a new system. The team proposed three distinct design concepts to the project's sponsor that could achieve all customer requirements. The first design proposed making the Class of 2015's existing telescopic poles more portable and improving the cart design's mobility and safety. The second design involved modifying an existing gas-powered pole pruner with an extendable fiberglass shaft to reach a height of 12 meters. This also included mounting a camera at the end of the saw to allow the operator to see the oil palm fruit bunches at the top of the tree; this camera will be connected via Bluetooth to a screen used by a worker on the ground. The final design proposed constructing a semi-autonomous, tree-climbing robot. The robot would have ascended and descended the tree autonomously, but the user would have been required to instruct the robot to begin climbing and manually stop the robot at the top of the tree. Once the robot arrived at the top of the tree, the user would have manually operated the cutting mechanism to harvest the desired oil palm fruit bunches.

In this phase, the previously discussed concepts lead to a selected design containing aspects of all aforementioned designs. The design consists of a large circular track that encircles the palm tree and allows a cutting mechanism to traverse around its circumference. The track is raised to the fruit by using a series of pole sections that are attached together at the base and raised upward. Finite element analyses were then conducted on the components of the design to determine if it could achieve design requirements. The ring was analyzed and it was found that the stresses exhibited from the weight of the cutter and the ring itself required the thickness to be increased from 6.35 millimeters to 9.525 millimeters to produce an acceptable factor of safety of 2.8. The ring's deflection was also analyzed and found to be fewer than 1.50.8 millimeters below the horizontal. It was determined that this still allowed the cutter to operate effectively. Next, the cutter mechanism was discussed and a design for the electrical controls was proposed. Finally, the most vulnerable component of the base, the locking mechanism, was analyzed and it was found that even with a thick and heavy pole weighing 41 kilograms, the lowest possible factor of safety was 3.8.

The group then used finite element analyses to measure the effects of daily use on the proposed design. After making some modifications, such as increasing the thickness of the ring, the stresses experienced by the structure yielded acceptable factors of safety and the deflections experienced by the ring and the pole did not inhibit the overall performance of the mechanism. Next, a budget was devised based on what the team determined would be the necessary components to meet all the sponsor's design requirements. By prioritizing building the top of the design first, the ring and cutter section will likely consume the time available for the completion of this project. In the Measure Phase, the FEA of the pole was completed.

During the Analyze Phase, several milestones were achieved to help accomplish the team's end goal of completing the project by the end of the semester. After the FEA of the aluminum poling was completed, two major conclusions were apparent. First, the initial cross-sectional area of the poling was too small to support the column stress and weight of the ring, due to the density of the ring's material; aluminum was selected for the ring due to budgetary constraints, which resulted in the poling needing to be stronger and have a larger cross-sectional area to provide the required support. This revelation brought the team to their second conclusion—a design change was needed. The team's design needed to be changed because the weight of the entire system would have been too heavy for one individual to lift, which was the initial design implementation. The team then referenced the Class of 2015's design to see if any design concepts or parts could be salvaged to foment the required design modifications. The team discovered that the lifting mechanism from the previous design would be sufficient for the new design's requirements. The square hollow aluminum poling, pulleys, braided steel cable, winch, and battery are all able to be used, which allowed the team to allocate more funds for other parts. After a new modified final design was constructed in modeling software and a bill of materials was completed, all required parts were ordered.

In the Improve Phase, the team conducted a lifting assessment using the NIOSH lifting equation. This assessment allowed the team to shorten the length of the cart's arm from 3.35 meters to 1.22 meters. Next, the team determined that steel L-brackets should be used to affix the telescoping poles to the cart's base. An FEA showed that the L-brackets would support the weight of the poles. The prototype's electrical components were constructed and tested, in preparation for the Control Phase.

In this phase, the completed cart was assembled and tested. The poles were able to extend to the necessary height to cut the palm fruit without threat of structural failure. Additionally, the use of the handles to push the cart produced a low enough moment arm that maneuvering the entire device could be done easily. Finally, the total time to raise and lower the pole was significantly lower than it would have taken a human to do it, and far less dangerous.

A few tasks remain that need to be completed before the prototype is fully functional; these tasks should be completed by April 19, 2016. The assembly of the cart entails mounting the battery box and jack support. Building the cutter robot requires the team to mount the guide shafts with linear bearings, and the electronics box with the batteries and electrical components, as well as the cutter box should be mounted onto the traversing platform. The team has allotted time for prototype testing and for troubleshooting any issues that may arise.

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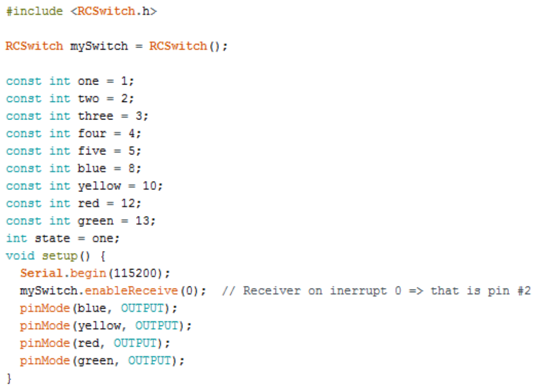
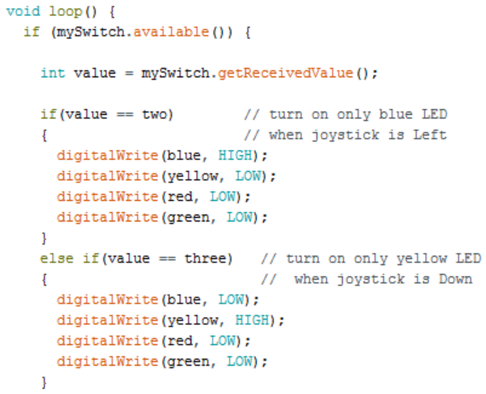
Appendix A: Receiver Circuit Testing Code



```
#include <RCSwitch.h>

RCSwitch mySwitch = RCSwitch();

const int one = 1;
const int two = 2;
const int three = 3;
const int four = 4;
const int five = 5;
const int blue = 8;
const int yellow = 10;
const int red = 12;
const int green = 13;
int state = one;
void setup() {
  Serial.begin(115200);
  mySwitch.enableReceive(0);  // Receiver on inerrupt 0 => that is pin #2
  pinMode(blue, OUTPUT);
  pinMode(yellow, OUTPUT);
  pinMode(red, OUTPUT);
  pinMode(green, OUTPUT);
}
```



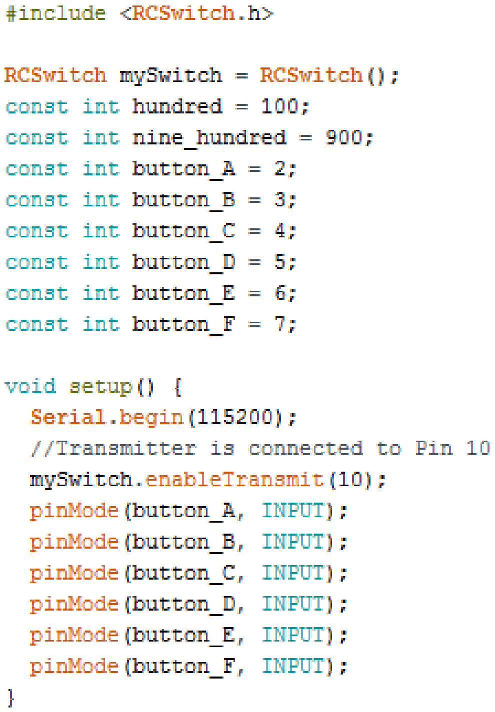
```
void loop() {
  if (mySwitch.available()) {

    int value = mySwitch.getReceivedValue();

    if(value == two)        // turn on only blue LED
    {                       // when joystick is Left
      digitalWrite(blue, HIGH);
      digitalWrite(yellow, LOW);
      digitalWrite(red, LOW);
      digitalWrite(green, LOW);
    }
    else if(value == three)   // turn on only yellow LED
    {                         //  when joystick is Down
      digitalWrite(blue, LOW);
      digitalWrite(yellow, HIGH);
      digitalWrite(red, LOW);
      digitalWrite(green, LOW);
    }
```

```
    else if(value == four)     // turn on only green LED
    {                           //when joystick is Right
      digitalWrite(blue, LOW);
      digitalWrite(yellow, LOW);
      digitalWrite(red, LOW);
      digitalWrite(green, HIGH);
    }
    else if(value == five)    // turn on only red LED
    {                          //  when joystick is Up
      digitalWrite(blue, LOW);
      digitalWrite(yellow, LOW);
      digitalWrite(red, HIGH);
      digitalWrite(green, LOW)
    }
    else   // turn off all leds
    {     //when joystick is in middle position
      digitalWrite(blue, LOW);
      digitalWrite(yellow, LOW);
      digitalWrite(red, LOW);
      digitalWrite(green, LOW);
    }
    mySwitch.resetAvailable();
  }
}
```

Appendix B: Transmitter Circuit Testing Code

```
#include <RCSwitch.h>

RCSwitch mySwitch = RCSwitch();
const int hundred = 100;
const int nine_hundred = 900;
void setup() {


  Serial.begin(115200);

  // Transmitter is connected to Arduino Pin #10
  mySwitch.enableTransmit(10);

}
 void loop() {

   int sensorValx = analogRead(A0);
   int sensorValy = analogRead(A2);

   if(sensorValx < hundred)
   {
   mySwitch.send("000000000000000000000010");
   }
   else if(sensorValy < hundred)
   {
   mySwitch.send("000000000000000000000011");
   }
   else if(sensorValx > nine_hundred)
   {
   mySwitch.send("000000000000000000000100");
   }
   else if(sensorValy > nine_hundred)
   {
   mySwitch.send("000000000000000000000101");
   }
   else
   ▯
   mySwitch.send("000000000000000000000001");
   }
 }
```

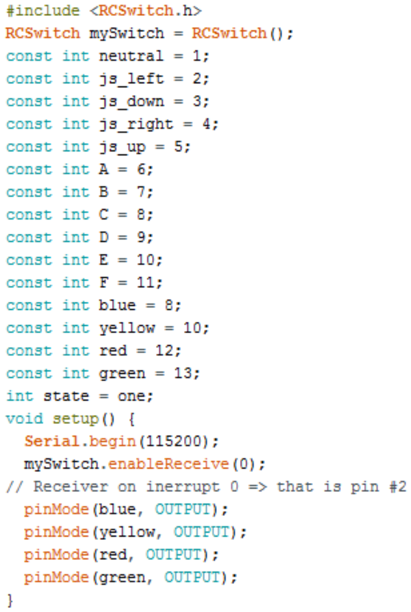
Appendix C: Controller Testing Code for Transmitter



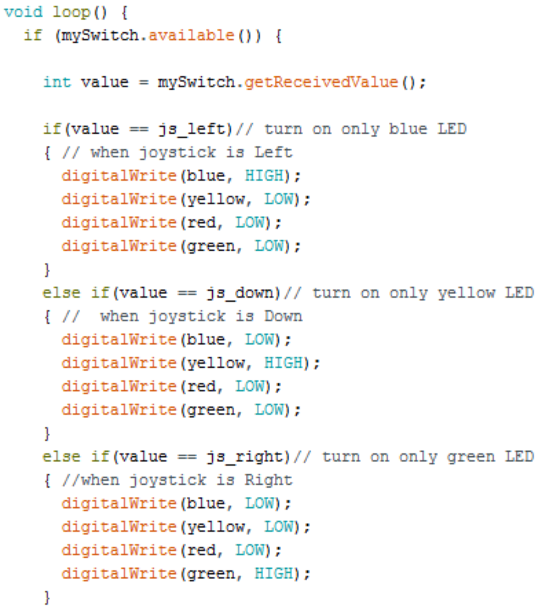
```
#include <RCSwitch.h>

RCSwitch mySwitch = RCSwitch();
const int hundred = 100;
const int nine_hundred = 900;
const int button_A = 2;
const int button_B = 3;
const int button_C = 4;
const int button_D = 5;
const int button_E = 6;
const int button_F = 7;

void setup() {
  Serial.begin(115200);
  //Transmitter is connected to Pin 10
  mySwitch.enableTransmit(10);
  pinMode(button_A, INPUT);
  pinMode(button_B, INPUT);
  pinMode(button_C, INPUT);
  pinMode(button_D, INPUT);
  pinMode(button_E, INPUT);
  pinMode(button_F, INPUT);
}
```

```
void loop() {
  int sensorValx = analogRead(A0);
  int sensorValy = analogRead(A1);

  if(sensorValx < hundred)
    mySwitch.send("000000000000000000000010");
  else if(sensorValy < hundred)
    mySwitch.send("000000000000000000000011");
  else if(sensorValx > nine_hundred)
    mySwitch.send("000000000000000000000100");
  else if(sensorValy > nine_hundred)
    mySwitch.send("000000000000000000000101");
  else if(button_A == HIGH)
    mySwitch.send("000000000000000000000110");
  else if(button_B == HIGH)
    mySwitch.send("000000000000000000000111");
  else if(button_C == HIGH)
    mySwitch.send("000000000000000000001000");
  else if(button_D == HIGH)
    mySwitch.send("000000000000000000001001");
  else if(button_E == HIGH)
    mySwitch.send("000000000000000000001010");
  else if(button_F == HIGH)
    mySwitch.send("000000000000000000001011");
  else
    mySwitch.send("000000000000000000000001");
}
```

Appendix D: Controller Testing Code for Receiver

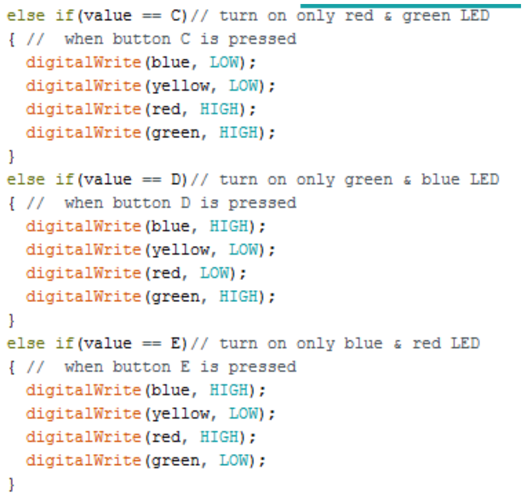


```
#include <RCSwitch.h>
RCSwitch mySwitch = RCSwitch();
const int neutral = 1;
const int js_left = 2;
const int js_down = 3;
const int js_right = 4;
const int js_up = 5;
const int A = 6;
const int B = 7;
const int C = 8;
const int D = 9;
const int E = 10;
const int F = 11;
const int blue = 8;
const int yellow = 10;
const int red = 12;
const int green = 13;
int state = one;
void setup() {
  Serial.begin(115200);
  mySwitch.enableReceive(0);
// Receiver on inerrupt 0 => that is pin #2
  pinMode(blue, OUTPUT);
  pinMode(yellow, OUTPUT);
  pinMode(red, OUTPUT);
  pinMode(green, OUTPUT);
}
```

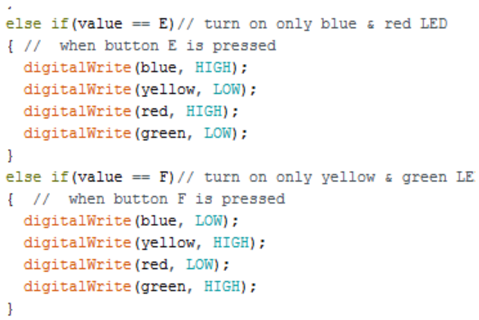


```
void loop() {
  if (mySwitch.available()) {

    int value = mySwitch.getReceivedValue();

    if(value == js_left)// turn on only blue LED
    { // when joystick is Left
      digitalWrite(blue, HIGH);
      digitalWrite(yellow, LOW);
      digitalWrite(red, LOW);
      digitalWrite(green, LOW);
    }
    else if(value == js_down)// turn on only yellow LED
    { //  when joystick is Down
      digitalWrite(blue, LOW);
      digitalWrite(yellow, HIGH);
      digitalWrite(red, LOW);
      digitalWrite(green, LOW);
    }
    else if(value == js_right)// turn on only green LED
    { //when joystick is Right
      digitalWrite(blue, LOW);
      digitalWrite(yellow, LOW);
      digitalWrite(red, LOW);
      digitalWrite(green, HIGH);
    }
```

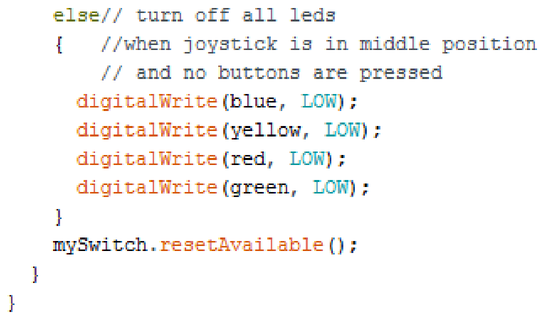
```
else if(value == js_up) // turn on only red LED
{ //  when joystick is Up
  digitalWrite(blue, LOW);
  digitalWrite(yellow, LOW);
  digitalWrite(red, HIGH);
  digitalWrite(green, LOW)
}
else if(value == A)// turn on only blue & yellow LED
{ //  when button A is pressed
  digitalWrite(blue, HIGH);
  digitalWrite(yellow, HIGH);
  digitalWrite(red, LOW);
  digitalWrite(green, LOW);
}
else if(value == B)// turn on only yellow & red LED
{ //  when button B is pressed
  digitalWrite(blue, LOW);
  digitalWrite(yellow, HIGH);
  digitalWrite(red, HIGH);
  digitalWrite(green, LOW);
}
```



```
else if(value == C)// turn on only red & green LED
{ //  when button C is pressed
  digitalWrite(blue, LOW);
  digitalWrite(yellow, LOW);
  digitalWrite(red, HIGH);
  digitalWrite(green, HIGH);
}
else if(value == D)// turn on only green & blue LED
{ //  when button D is pressed
  digitalWrite(blue, HIGH);
  digitalWrite(yellow, LOW);
  digitalWrite(red, LOW);
  digitalWrite(green, HIGH);
}
else if(value == E)// turn on only blue & red LED
{ //  when button E is pressed
  digitalWrite(blue, HIGH);
  digitalWrite(yellow, LOW);
  digitalWrite(red, HIGH);
  digitalWrite(green, LOW);
}
```

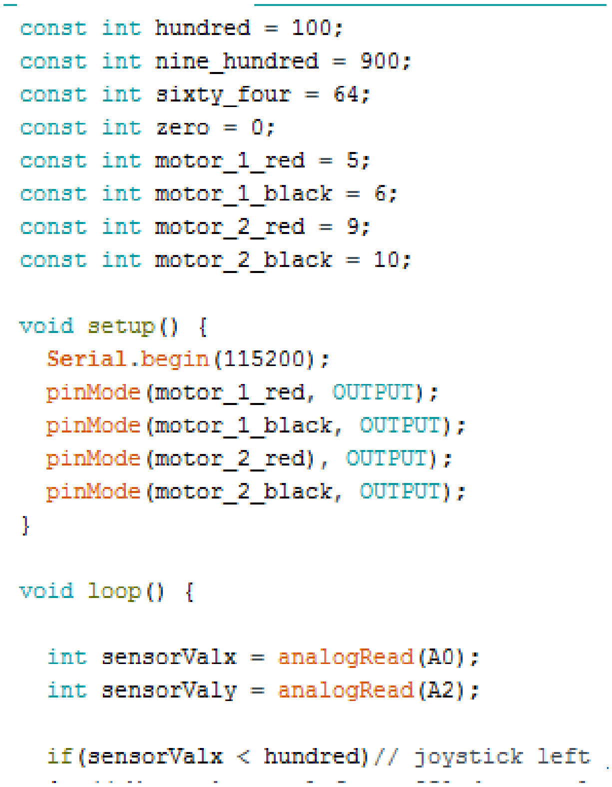


```
else if(value == E)// turn on only blue & red LED
{ //  when button E is pressed
  digitalWrite(blue, HIGH);
  digitalWrite(yellow, LOW);
  digitalWrite(red, HIGH);
  digitalWrite(green, LOW);
}
else if(value == F)// turn on only yellow & green LE
{  //  when button F is pressed
  digitalWrite(blue, LOW);
  digitalWrite(yellow, HIGH);
  digitalWrite(red, LOW);
  digitalWrite(green, HIGH);
}
```

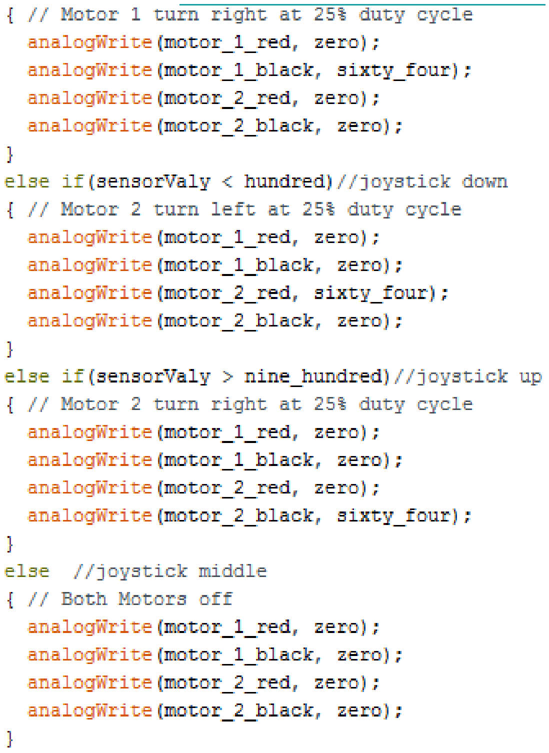


```
    else// turn off all leds
    {   //when joystick is in middle position
        // and no buttons are pressed
      digitalWrite(blue, LOW);
      digitalWrite(yellow, LOW);
      digitalWrite(red, LOW);
      digitalWrite(green, LOW);
    }
    mySwitch.resetAvailable();
  }
}
```

Appendix E: Testing Code for DC Motors and Winch

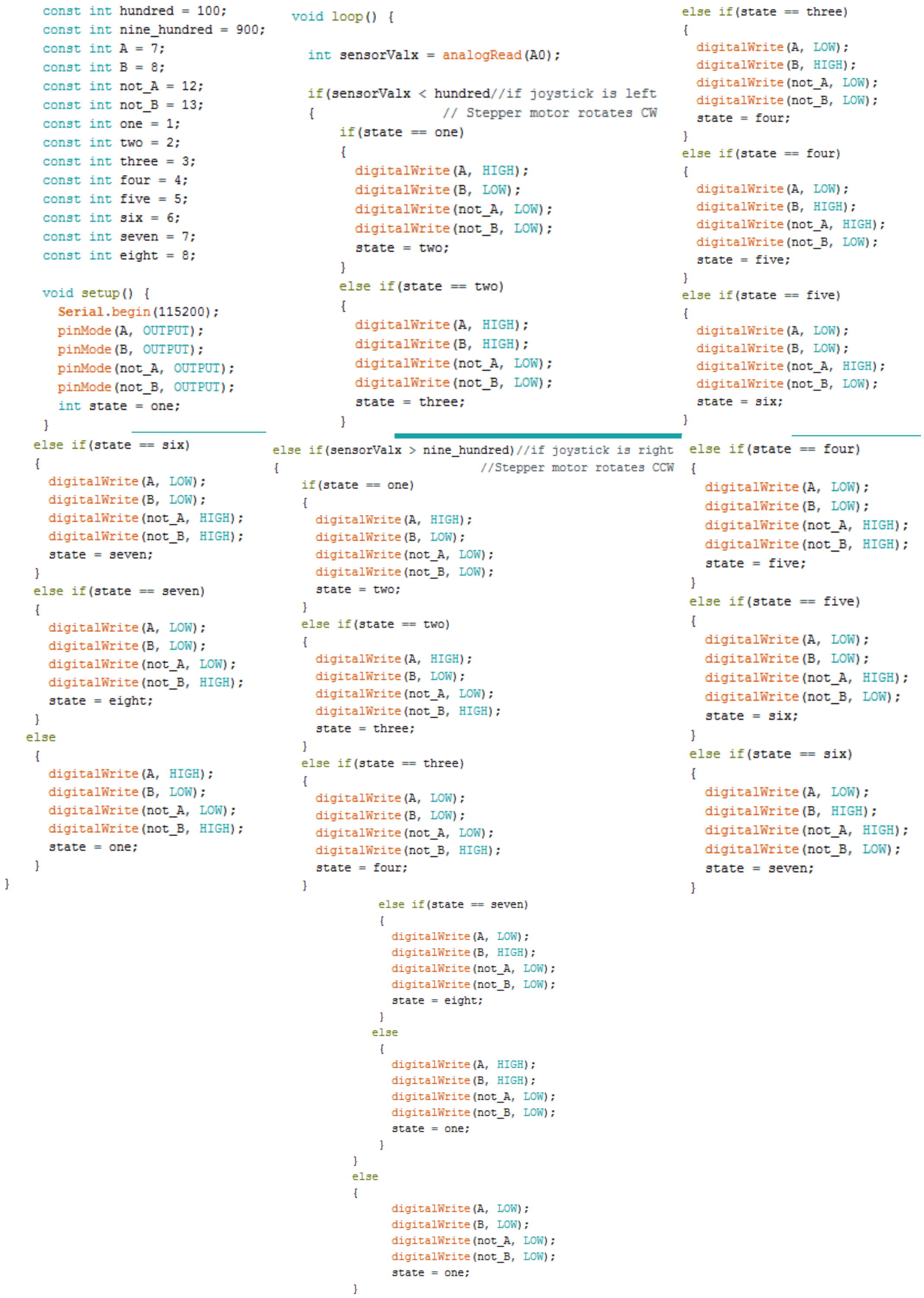


```
const int hundred = 100;
const int nine_hundred = 900;
const int sixty_four = 64;
const int zero = 0;
const int motor_1_red = 5;
const int motor_1_black = 6;
const int motor_2_red = 9;
const int motor_2_black = 10;

void setup() {
  Serial.begin(115200);
  pinMode(motor_1_red, OUTPUT);
  pinMode(motor_1_black, OUTPUT);
  pinMode(motor_2_red), OUTPUT);
  pinMode(motor_2_black, OUTPUT);
}

void loop() {

  int sensorValx = analogRead(A0);
  int sensorValy = analogRead(A2);

  if(sensorValx < hundred)// joystick left
```



```
{ // Motor 1 turn right at 25% duty cycle
  analogWrite(motor_1_red, zero);
  analogWrite(motor_1_black, sixty_four);
  analogWrite(motor_2_red, zero);
  analogWrite(motor_2_black, zero);
}
else if(sensorValy < hundred)//joystick down
{ // Motor 2 turn left at 25% duty cycle
  analogWrite(motor_1_red, zero);
  analogWrite(motor_1_black, zero);
  analogWrite(motor_2_red, sixty_four);
  analogWrite(motor_2_black, zero);
}
else if(sensorValy > nine_hundred)//joystick up
{ // Motor 2 turn right at 25% duty cycle
  analogWrite(motor_1_red, zero);
  analogWrite(motor_1_black, zero);
  analogWrite(motor_2_red, zero);
  analogWrite(motor_2_black, sixty_four);
}
else  //joystick middle
{ // Both Motors off
  analogWrite(motor_1_red, zero);
  analogWrite(motor_1_black, zero);
  analogWrite(motor_2_red, zero);
  analogWrite(motor_2_black, zero);
}
```

Appendix F: Code Used for Testing Stepper Motor



```
const int hundred = 100;
const int nine_hundred = 900;
const int A = 7;
const int B = 8;
const int not_A = 12;
const int not_B = 13;
const int one = 1;
const int two = 2;
const int three = 3;
const int four = 4;
const int five = 5;
const int six = 6;
const int seven = 7;
const int eight = 8;

void setup() {
  Serial.begin(115200);
  pinMode(A, OUTPUT);
  pinMode(B, OUTPUT);
  pinMode(not_A, OUTPUT);
  pinMode(not_B, OUTPUT);
  int state = one;
}
```

```
void loop() {

  int sensorValx = analogRead(A0);

  if(sensorValx < hundred//if joystick is left
  {                        // Stepper motor rotates CW
      if(state == one)
      {
        digitalWrite(A, HIGH);
        digitalWrite(B, LOW);
        digitalWrite(not_A, LOW);
        digitalWrite(not_B, LOW);
        state = two;
      }
      else if(state == two)
      {
        digitalWrite(A, HIGH);
        digitalWrite(B, HIGH);
        digitalWrite(not_A, LOW);
        digitalWrite(not_B, LOW);
        state = three;
      }
```

```
else if(state == three)
{
  digitalWrite(A, LOW);
  digitalWrite(B, HIGH);
  digitalWrite(not_A, LOW);
  digitalWrite(not_B, LOW);
  state = four;
}
else if(state == four)
{
  digitalWrite(A, LOW);
  digitalWrite(B, HIGH);
  digitalWrite(not_A, HIGH);
  digitalWrite(not_B, LOW);
  state = five;
}
else if(state == five)
{
  digitalWrite(A, LOW);
  digitalWrite(B, LOW);
  digitalWrite(not_A, HIGH);
  digitalWrite(not_B, LOW);
  state = six;
}
```

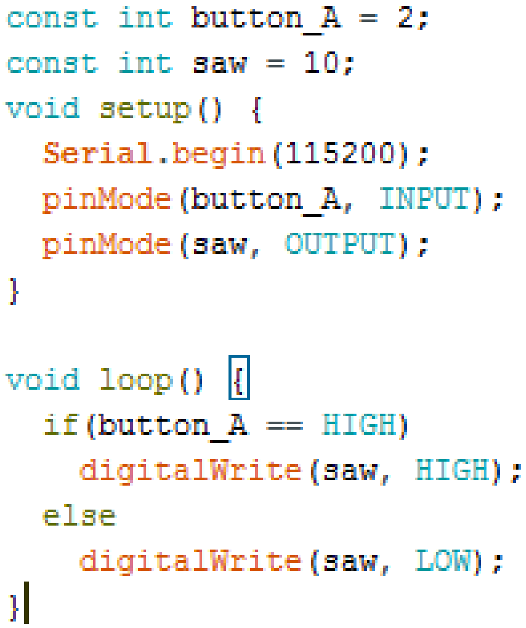
```
  else if(state == six)
  {
    digitalWrite(A, LOW);
    digitalWrite(B, LOW);
    digitalWrite(not_A, HIGH);
    digitalWrite(not_B, HIGH);
    state = seven;
  }
  else if(state == seven)
  {
    digitalWrite(A, LOW);
    digitalWrite(B, LOW);
    digitalWrite(not_A, LOW);
    digitalWrite(not_B, HIGH);
    state = eight;
  }
 else
  {
    digitalWrite(A, HIGH);
    digitalWrite(B, LOW);
    digitalWrite(not_A, LOW);
    digitalWrite(not_B, HIGH);
    state = one;
  }
}
```

```
else if(sensorValx > nine_hundred)//if joystick is right
{                                  //Stepper motor rotates CCW
    if(state == one)
    {
      digitalWrite(A, HIGH);
      digitalWrite(B, LOW);
      digitalWrite(not_A, LOW);
      digitalWrite(not_B, LOW);
      state = two;
    }
    else if(state == two)
    {
      digitalWrite(A, HIGH);
      digitalWrite(B, LOW);
      digitalWrite(not_A, LOW);
      digitalWrite(not_B, HIGH);
      state = three;
    }
    else if(state == three)
    {
      digitalWrite(A, LOW);
      digitalWrite(B, LOW);
      digitalWrite(not_A, LOW);
      digitalWrite(not_B, HIGH);
      state = four;
    }
```

```
else if(state == four)
{
  digitalWrite(A, LOW);
  digitalWrite(B, LOW);
  digitalWrite(not_A, HIGH);
  digitalWrite(not_B, HIGH);
  state = five;
}
else if(state == five)
{
  digitalWrite(A, LOW);
  digitalWrite(B, LOW);
  digitalWrite(not_A, HIGH);
  digitalWrite(not_B, LOW);
  state = six;
}
else if(state == six)
{
  digitalWrite(A, LOW);
  digitalWrite(B, HIGH);
  digitalWrite(not_A, HIGH);
  digitalWrite(not_B, LOW);
  state = seven;
}
```

```
      else if(state == seven)
      {
        digitalWrite(A, LOW);
        digitalWrite(B, HIGH);
        digitalWrite(not_A, LOW);
        digitalWrite(not_B, LOW);
        state = eight;
      }
     else
      {
        digitalWrite(A, HIGH);
        digitalWrite(B, HIGH);
        digitalWrite(not_A, LOW);
        digitalWrite(not_B, LOW);
        state = one;
      }
  }
  else
  {
        digitalWrite(A, LOW);
        digitalWrite(B, LOW);
        digitalWrite(not_A, LOW);
        digitalWrite(not_B, LOW);
        state = one;
  }
```

Appendix G: Code Used for Testing the Saw



```
const int button_A = 2;
const int saw = 10;
void setup() {
  Serial.begin(115200);
  pinMode(button_A, INPUT);
  pinMode(saw, OUTPUT);
}

void loop() {
  if(button_A == HIGH)
    digitalWrite(saw, HIGH);
  else
    digitalWrite(saw, LOW);
}
```

Appendix H: Return on Investment Calculations

Wage assumptions and return on investment calculations for Malaysian oil palm fruit harvesters.

Assumptions

Malaysian workers earn $297 per month.

Each oil palm plantation contains hundreds of trees.

Oil palms are harvested for eight (8) hours daily.

A worker earns a simple salary of $\$297/\text{month} \times 12\text{ months} = \$3{,}564/\text{year}$

The return on investment (ROI) formula is:

$$\text{ROI} = \frac{(\text{Gain from Investment} - \text{Cost of Investment}}{\text{Cost of Investment}}$$

Computing the ROI:

$$\text{ROI} = \frac{(\$3{,}564 - \$2{,}000)}{\$2{,}000} = 0.7820$$

$$\text{ROI}_{\text{percent}} = \text{ROI} \times 100\% = 0.7820 \times 100\% = 78.20\%$$

Appendix I: Estimated Budget Tables

Table 53: Estimated Budget for the Ring and Cutter Mechanism

Part	Cost ($)	Source
Ring	1,050	[48]
3D Printing Material	100	[49]
DC Motors	150	Estimated
DC Motors	150	Estimated
Stepper Motor	130	[50]
Lead Screw Rod	27	[51]
Lead Screw Nut	12	[52]
Electrical Components	115	Estimated
Linear Bearings	30	[53]
Shaft	38	[54]
Shaft Housing	20	[55]
Robot Mount	30	[48]
Battery	150	Estimated
Total	**2,002**	

*3D printing refers to additive manufacturing

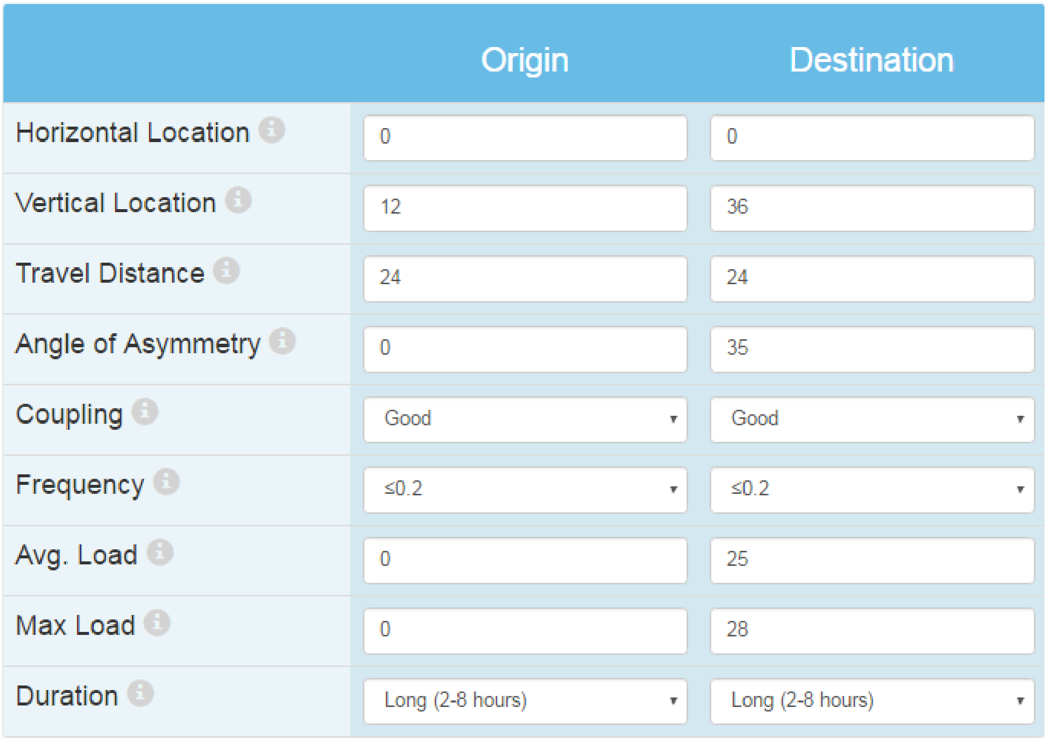
The budget given in Table 53 lists the price of each part. Each entry contains the estimated cost of each respective part and the source where it was obtained. The team is using a top-to-bottom approach because of the complexity of the ring and cutter. The ring will be made out of a 2438.4-millimeter by 965.2-millimeter sheet of aluminum that will cost $1,050. Other mechanical components will be obtained from this sheet, such as the platform on which the robot stands, as well as the mount housings. $100 will be allocated to 3D printer materials. Even though the price per 1 kilogram of 3D printing materials is $50, an extra set will be ordered in case of any issues during fabrication. Some electrical components and motors are yet to be chosen, because Dr. Gupta is currently advising the team on motors that will meet the design requirements. Lightweight motors that the team has found cost around $150. All electrical components that will control the motors are not expected to cost more than $150. The robot mount will be machined or made from a water jet from one solid block of aluminum that will cost $30. A battery has not been selected but it is estimated to cost $150. As shown in Table 53, total cost of the preliminary ring design is expected to be around $2,000. After researching material costs from a variety of different vendors, it was found that the aluminum polling and base could not be completed with only $500 remaining in the budget. Additionally, there is a possibility that once this design is analyzed further, the initial $2,000 estimate could increase and restrict the budget for the rest of the design further. These estimates were used to construct the bill of materials given in Table 54.

Table 54: Bill of Materials for the Ring and Cutter Mechanism

Bill of Materials	
Part	**QTY.**
0.375" x 96" x 38" Aluminum Sheet	1
1 kilogram of 3D Printing Material	2
Hinge	1
DC Motors	3
Stepper Motor	1
Track Wheel	1
Lead Screw Rod	1
Lead Screw Nut	1
Linear Bearings	4
Shaft	2
Shaft Housing	4
Robot Mount	1
Battery	1
Connectors	15
Arduino	2
Joystick Shield	1
Motor Drivers	3
Transmitter/Receiver	1
Bread Board	1
Battery Holder	2
AA Cell Batteries	8
D Cell Batteries	8
USB Breakaway Cable	1
Miscellaneous Hardware (screws, nuts, et cetera)	As Required

Appendix J: NIOSH and LI Calculations

This appendix shows the calculation of the RWL and LI for the lifting of the cart's handles. The horizontal location, vertical location, and travel distance were all measured in inches, because the NIOSH system utilizes United States customary units. The team directly measured the angle of asymmetry and determined that there was good coupling. The team estimated that the operator would lift the device once every 15 minutes. Finally, the effective average load lifted was determined to be 25 pounds (11.34 kilograms) from the handle, with a maximum of 28 pounds (12.70 kilograms). Lastly, the team assumed that operators will work eight-hour shifts. These values were then inputted into a NIOSH equation calculator, as shown in Figure 80.



	Origin	Destination
Horizontal Location	0	0
Vertical Location	12	36
Travel Distance	24	24
Angle of Asymmetry	0	35
Coupling	Good	Good
Frequency	≤0.2	≤0.2
Avg. Load	0	25
Max Load	0	28
Duration	Long (2-8 hours)	Long (2-8 hours)

Figure 80: NIOSH Calculator

The RWL and LI were computed and are given in Table 55.

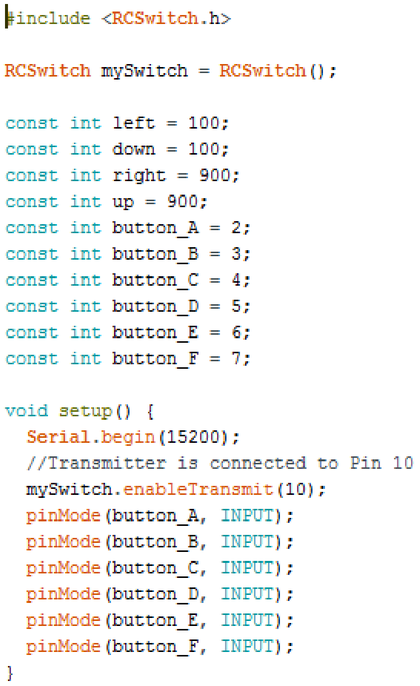
Table 55: RWL and LI

	Origin	Destination
RWL	33.18 pounds (15.05 kilograms)	32.62 pounds (14.80 kilograms)
LI	0.77	

Since the destination RWL is smaller, the RWL for the lifting task is 32.62 pounds (14.80 kilograms).

Appendix K: Testing Code

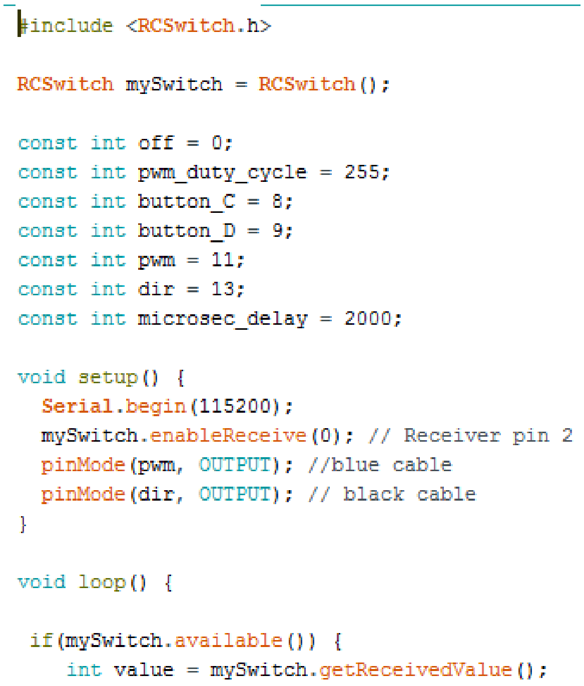
Testing code for the controller electronics:



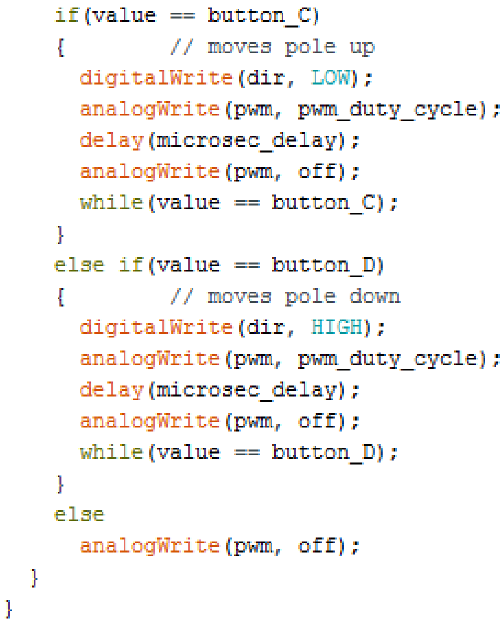
```
#include <RCSwitch.h>

RCSwitch mySwitch = RCSwitch();

const int left = 100;
const int down = 100;
const int right = 900;
const int up = 900;
const int button_A = 2;
const int button_B = 3;
const int button_C = 4;
const int button_D = 5;
const int button_E = 6;
const int button_F = 7;

void setup() {
  Serial.begin(15200);
  //Transmitter is connected to Pin 10
  mySwitch.enableTransmit(10);
  pinMode(button_A, INPUT);
  pinMode(button_B, INPUT);
  pinMode(button_C, INPUT);
  pinMode(button_D, INPUT);
  pinMode(button_E, INPUT);
  pinMode(button_F, INPUT);
}
```

```
void loop() {
  int sensorValx = analogRead(A0);
  int sensorValy = analogRead(A1);

  if(sensorValx < left)
    mySwitch.send("000000000000000000000010");
  else if(sensorValy < down)
    mySwitch.send("000000000000000000000011");
  else if(sensorValx > right)
    mySwitch.send("000000000000000000000100");
  else if(sensorValy > up)
    mySwitch.send("000000000000000000000101");
  else if(digitalRead(button_A) == LOW)
    mySwitch.send("000000000000000000000110");
  else if(digitalRead(button_B) == LOW)
    mySwitch.send("000000000000000000000111");
  else if(digitalRead(button_C) == LOW)
    mySwitch.send("000000000000000000001000");
  else if(digitalRead(button_D) == LOW)
    mySwitch.send("000000000000000000001001");
  else if(digitalRead(button_E) == LOW)
    mySwitch.send("000000000000000000001010");
  else if(digitalRead(button_F) == LOW)
    mySwitch.send("000000000000000000001011");
  else
    mySwitch.send("000000000000000000000001");
}
```

Testing code for the cart electronics:

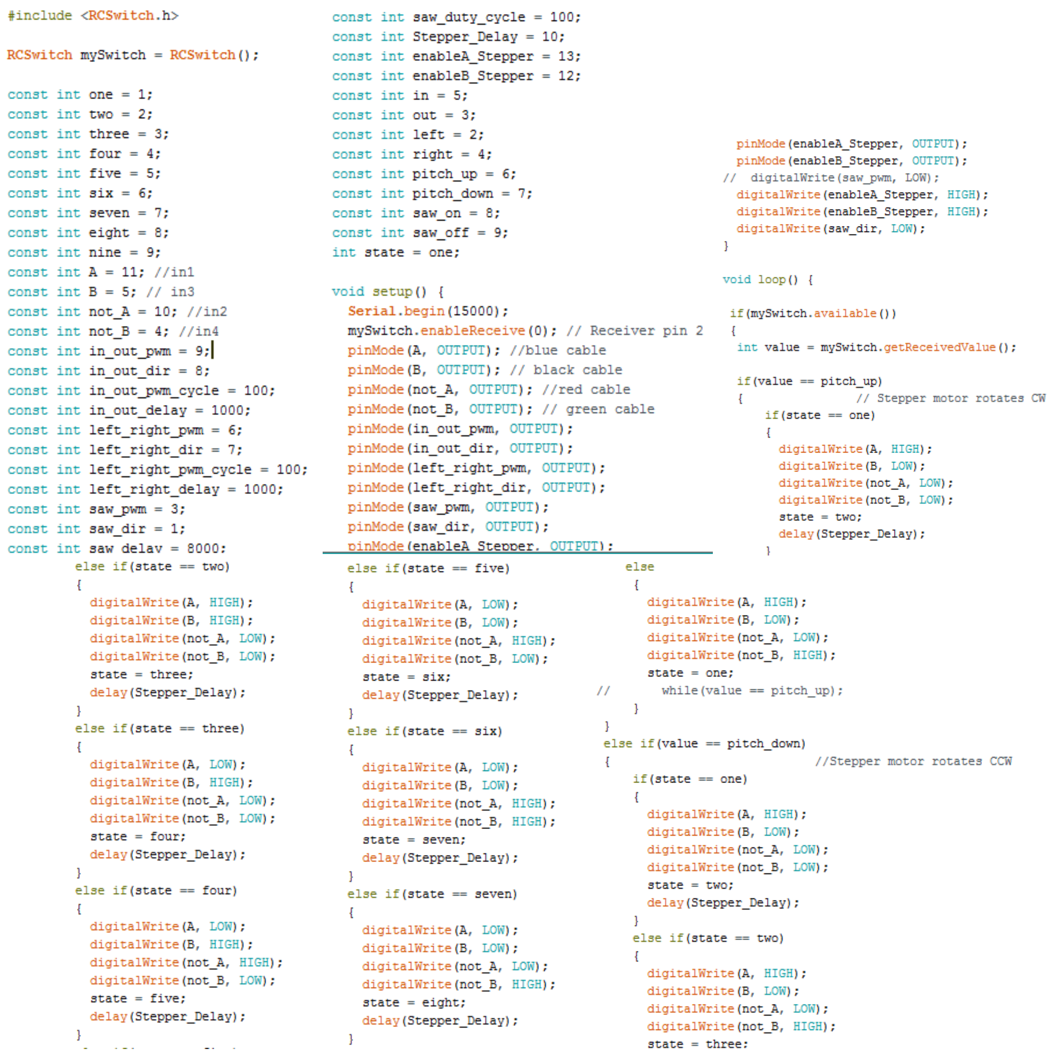


```
#include <RCSwitch.h>

RCSwitch mySwitch = RCSwitch();

const int off = 0;
const int pwm_duty_cycle = 255;
const int button_C = 8;
const int button_D = 9;
const int pwm = 11;
const int dir = 13;
const int microsec_delay = 2000;

void setup() {
  Serial.begin(115200);
  mySwitch.enableReceive(0); // Receiver pin 2
  pinMode(pwm, OUTPUT); //blue cable
  pinMode(dir, OUTPUT); // black cable
}

void loop() {

 if(mySwitch.available()) {
    int value = mySwitch.getReceivedValue();
```



```
  if(value == button_C)
  {         // moves pole up
    digitalWrite(dir, LOW);
    analogWrite(pwm, pwm_duty_cycle);
    delay(microsec_delay);
    analogWrite(pwm, off);
    while(value == button_C);
  }
  else if(value == button_D)
  {         // moves pole down
    digitalWrite(dir, HIGH);
    analogWrite(pwm, pwm_duty_cycle);
    delay(microsec_delay);
    analogWrite(pwm, off);
    while(value == button_D);
  }
  else
    analogWrite(pwm, off);
 }
}
```

Testing code for the cutting mechanism:



```
#include <RCSwitch.h>

RCSwitch mySwitch = RCSwitch();

const int one = 1;
const int two = 2;
const int three = 3;
const int four = 4;
const int five = 5;
const int six = 6;
const int seven = 7;
const int eight = 8;
const int nine = 9;
const int A = 11; //in1
const int B = 5; // in3
const int not_A = 10; //in2
const int not_B = 4; //in4
const int in_out_pwm = 9;
const int in_out_dir = 8;
const int in_out_pwm_cycle = 100;
const int in_out_delay = 1000;
const int left_right_pwm = 6;
const int left_right_dir = 7;
const int left_right_pwm_cycle = 100;
const int left_right_delay = 1000;
const int saw_pwm = 3;
const int saw_dir = 1;
const int saw delay = 8000;
```

```
const int saw_duty_cycle = 100;
const int Stepper_Delay = 10;
const int enableA_Stepper = 13;
const int enableB_Stepper = 12;
const int in = 5;
const int out = 3;
const int left = 2;
const int right = 4;
const int pitch_up = 6;
const int pitch_down = 7;
const int saw_on = 8;
const int saw_off = 9;
int state = one;

void setup() {
  Serial.begin(15000);
  mySwitch.enableReceive(0); // Receiver pin 2
  pinMode(A, OUTPUT); //blue cable
  pinMode(B, OUTPUT); // black cable
  pinMode(not_A, OUTPUT); //red cable
  pinMode(not_B, OUTPUT); // green cable
  pinMode(in_out_pwm, OUTPUT);
  pinMode(in_out_dir, OUTPUT);
  pinMode(left_right_pwm, OUTPUT);
  pinMode(left_right_dir, OUTPUT);
  pinMode(saw_pwm, OUTPUT);
  pinMode(saw_dir, OUTPUT);
  pinMode(enableA Stepper, OUTPUT);
```

```
  pinMode(enableA_Stepper, OUTPUT);
  pinMode(enableB_Stepper, OUTPUT);
//  digitalWrite(saw_pwm, LOW);
  digitalWrite(enableA_Stepper, HIGH);
  digitalWrite(enableB_Stepper, HIGH);
  digitalWrite(saw_dir, LOW);
}

void loop() {

 if(mySwitch.available())
 {
  int value = mySwitch.getReceivedValue();

  if(value == pitch_up)
  {                   // Stepper motor rotates CW
      if(state == one)
      {
        digitalWrite(A, HIGH);
        digitalWrite(B, LOW);
        digitalWrite(not_A, LOW);
        digitalWrite(not_B, LOW);
        state = two;
        delay(Stepper_Delay);
      }
```

```
      else if(state == two)
      {
        digitalWrite(A, HIGH);
        digitalWrite(B, HIGH);
        digitalWrite(not_A, LOW);
        digitalWrite(not_B, LOW);
        state = three;
        delay(Stepper_Delay);
      }
      else if(state == three)
      {
        digitalWrite(A, LOW);
        digitalWrite(B, HIGH);
        digitalWrite(not_A, LOW);
        digitalWrite(not_B, LOW);
        state = four;
        delay(Stepper_Delay);
      }
      else if(state == four)
      {
        digitalWrite(A, LOW);
        digitalWrite(B, HIGH);
        digitalWrite(not_A, HIGH);
        digitalWrite(not_B, LOW);
        state = five;
        delay(Stepper_Delay);
      }
```

```
      else if(state == five)
      {
        digitalWrite(A, LOW);
        digitalWrite(B, LOW);
        digitalWrite(not_A, HIGH);
        digitalWrite(not_B, LOW);
        state = six;
        delay(Stepper_Delay);
      }
      else if(state == six)
      {
        digitalWrite(A, LOW);
        digitalWrite(B, LOW);
        digitalWrite(not_A, HIGH);
        digitalWrite(not_B, HIGH);
        state = seven;
        delay(Stepper_Delay);
      }
      else if(state == seven)
      {
        digitalWrite(A, LOW);
        digitalWrite(B, LOW);
        digitalWrite(not_A, LOW);
        digitalWrite(not_B, HIGH);
        state = eight;
        delay(Stepper_Delay);
      }
```

```
      else
      {
        digitalWrite(A, HIGH);
        digitalWrite(B, LOW);
        digitalWrite(not_A, LOW);
        digitalWrite(not_B, HIGH);
        state = one;
//        while(value == pitch_up);
      }
  }
  else if(value == pitch_down)
  {                    //Stepper motor rotates CCW
      if(state == one)
      {
        digitalWrite(A, HIGH);
        digitalWrite(B, LOW);
        digitalWrite(not_A, LOW);
        digitalWrite(not_B, LOW);
        state = two;
        delay(Stepper_Delay);
      }
      else if(state == two)
      {
        digitalWrite(A, HIGH);
        digitalWrite(B, LOW);
        digitalWrite(not_A, LOW);
        digitalWrite(not_B, HIGH);
        state = three;
```

```
        delay(Stepper_Delay);
      }
      else if(state == three)
      {
        digitalWrite(A, LOW);
        digitalWrite(B, LOW);
        digitalWrite(not_A, LOW);
        digitalWrite(not_B, HIGH);
        state = four;
        delay(Stepper_Delay);
      }
      else if(state == four)
      {
        digitalWrite(A, LOW);
        digitalWrite(B, LOW);
        digitalWrite(not_A, HIGH);
        digitalWrite(not_B, HIGH);
        state = five;
        delay(Stepper_Delay);
      }
      else if(state == five)
      {
        digitalWrite(A, LOW);
        digitalWrite(B, LOW);
        digitalWrite(not_A, HIGH);
        digitalWrite(not_B, LOW);
        state = six;
        delay(Stepper Delay);
```

```
      }
      else if(state == six)
      {
        digitalWrite(A, LOW);
        digitalWrite(B, HIGH);
        digitalWrite(not_A, HIGH);
        digitalWrite(not_B, LOW);
        state = seven;
        delay(Stepper_Delay);
      }
      else if(state == seven)
      {
        digitalWrite(A, LOW);
        digitalWrite(B, HIGH);
        digitalWrite(not_A, LOW);
        digitalWrite(not_B, LOW);
        state = eight;
        delay(Stepper_Delay);
      }
     else
      {
        digitalWrite(A, HIGH);
        digitalWrite(B, HIGH);
        digitalWrite(not_A, LOW);
        digitalWrite(not_B, LOW);
        state = one;
//        while(value == pitch_down);
      }
```

```
      }
  }
  else if(value == in)
  {
    digitalWrite(in_out_dir, HIGH);
    analogWrite(in_out_pwm, in_out_pwm_cycle);
//    delay(in_out_delay);
//    while(value == in);
  }
  else if(value == out)
  {
    digitalWrite(in_out_dir, LOW);
    analogWrite(in_out_pwm, in_out_pwm_cycle);
//    delay(in_out_delay);
//    while(value == in);
  }
  else if(value == left)
  {
    digitalWrite(left_right_dir, HIGH);
    analogWrite(left_right_pwm, left_right_pwm_cycle);
 //   delay(left_right_delay);
 //   while(value == left);
  }
  else if(value == right)
  {
    digitalWrite(left_right_dir, LOW);
    analogWrite(left_right_pwm, left_right_pwm_cycle);
   // delay(left right delay);
```

```
      digitalWrite(left_right_dir, LOW);
      analogWrite(left_right_pwm, left_right_pwm_cycle);
     // delay(left_right_delay);
     // while(value == right);
    }
    else if(value == saw_on)
    {
      analogWrite(saw_pwm, saw_duty_cycle);
     // delay(saw_delay);
     // digitalWrite(saw_pwm, LOW);
     // while(value == saw_on);
    }
    else if(value == saw_off)
    {
      analogWrite(saw_pwm, 0);
    }
    else
    {
      digitalWrite(A, LOW);
      digitalWrite(B, LOW);
      digitalWrite(not_A, LOW);
      digitalWrite(not_B, LOW);
      analogWrite(in_out_pwm, 0);
      analogWrite(left_right_pwm, 0);
      state = one;
     }
  }
}
```