FAMU-FSU COLLEGE OF ENGINEERING

Development of a Semi-Autonomous Oil Palm Fruit Harvesting Device

IME Group 10: Business Analysis

A report submitted to Dr. Okenwa Okoli
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This report summarizes the technical progress made in the five phases of this project. Also included is a detailed business analysis.

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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 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. Finally, the prototype was assembled and its performance was measured. Future improvements were then specified.

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 telescoping poles to push the cutting tool upward. A design was selected that uses the poling system from the Class of 2015’s design and makes it more transportable, in addition to adding a new ring design to improve the cutting mechanism. The telescoping poles are mounted to a wheelbarrow platform that is moved utilizing handles extending from it. The length of the handles was selected to conform to the United States’ Occupational Safety and Health (OSHA) requirements.

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, the poles will be able to be modular and easily detachable for servicing. Additionally, the prototype’s controller was assembled and tested. Next, the entire prototype was assembled and tested.

An assembly guide was written that details how the cart and cutting mechanism should be constructed. Furthermore, detailed operating instructions and a bill of materials 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 constraints of the project are discussed. Subsequently, the project’s technical achievements are discussed. Additionally, the final design is described in detail, including an assembly guide and an operation manual. A detailed business analysis is also provided. Finally, recommendations are provided that should be completed before the device is mass-produced.

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 and allow the operator to 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].

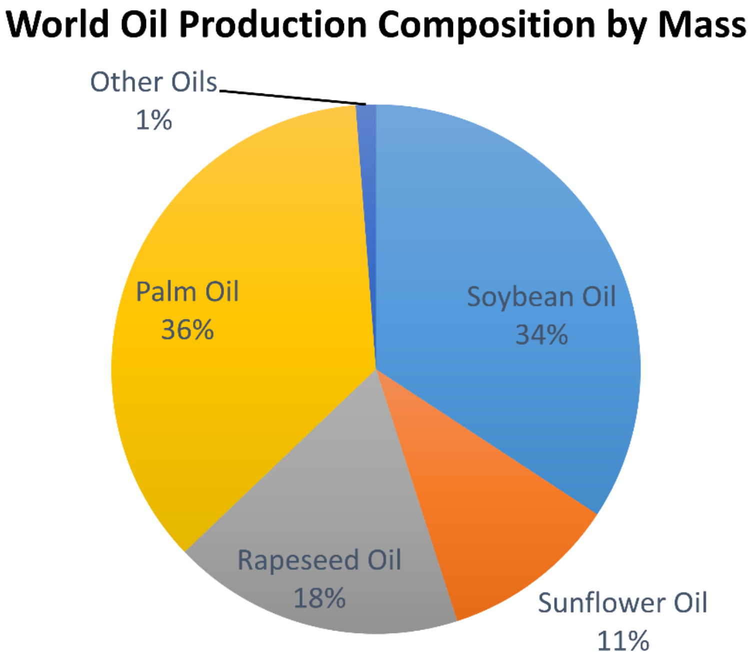


Figure 1: Composition of World Oil Production by Mass [1]

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].

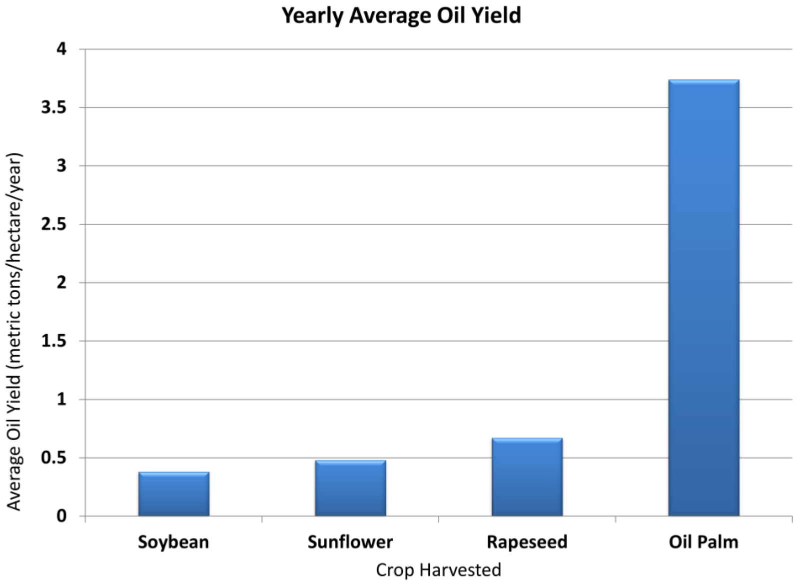


Figure 2: Average Oil Yield in metric tons per hectare of the Top Four Oil Sources [1]

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].

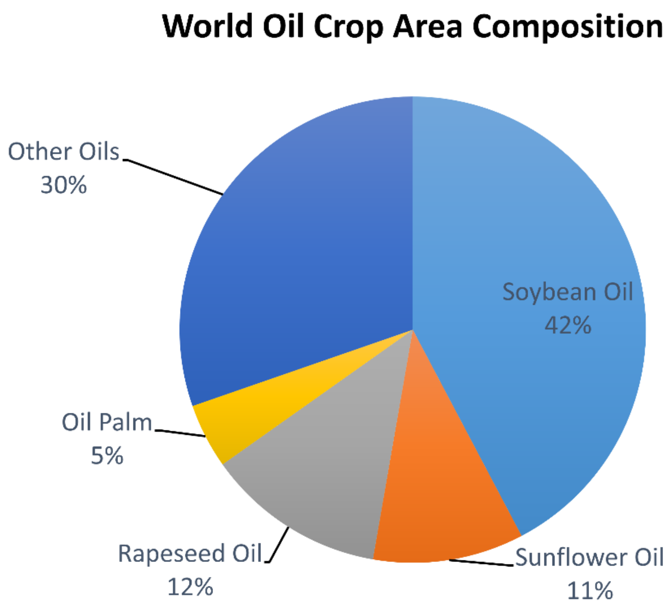


Figure 3: Composition of World Oil Crop Area [1]

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.

2.1.2.1 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.

2.1.3 Stakeholders and Team Organization

The project's sponsor was Dr. Okenwa Okoli, who is the Chair of the IME department at the FAMU-FSU College of Engineering. The IME department provided the funding for this project. Dr. Okoli informed the team of the prototype's functional requirements and was the project's main stakeholder. The team had weekly meetings with Dr. Okoli that discussed the project's progress. Since this project also involved 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, were also project stakeholders. Furthermore, Ms. Margaret Scheiner and Mr. Ryan Adams, the IME senior design Teaching Assistants, were also stakeholders in this project. The FAMU-FSU College of Engineering, IME, ME, and ECE departments were also stakeholders in this project. Finally, the team was 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 reported to Dr. Okoli, the project's sponsor. Enrique Gonzalez was elected as the team's current Phase Leader and 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. 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. Patrick Howard was elected the team's Material Analyst, because he has experience with automobiles and is currently taking a graduate technical elective on vehicle design. Alberto Machado 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 Morin was elected as the group's webmaster, because he is a computer engineering major with HTML, CSS, and JavaScript experience. 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.

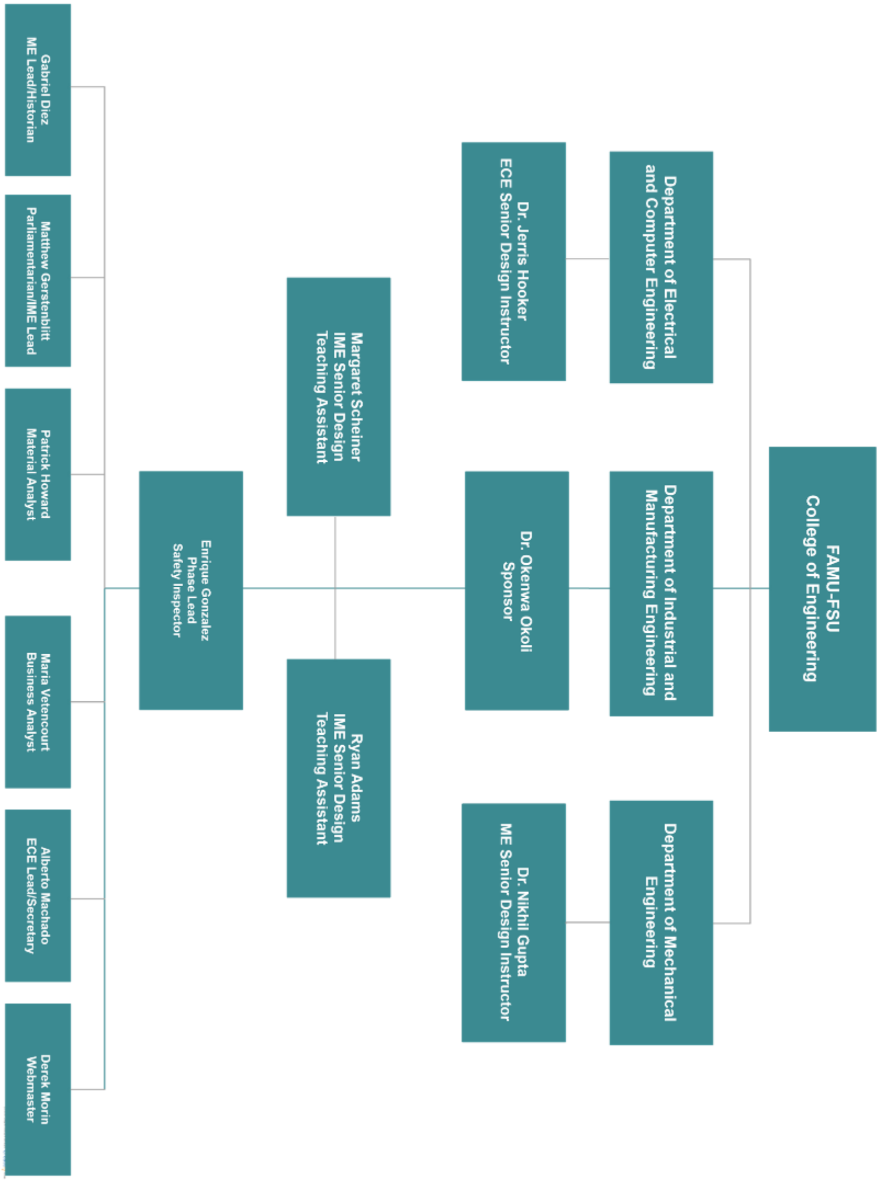


Figure 4: Team Organization Diagram

2.2 Approach

2.2.1 Scope

The scope of this project focused mainly on developing an electromechanical device to harvest oil palm fruit. Before the design of the device began, the group researched oil palm trees and fruit, as well as current oil palm fruit harvesting methods. Once this research was completed, the team brainstormed electromechanical design ideas that were consistent with the sponsor's requirements. Once a design was selected that met all of the sponsor's criteria, the group designed the prototype utilizing PTC Creo Parametric software and analyzed its functionality. Based on the results of the team's analysis, the prototype was optimized to harvest fruit in the shortest possible amount of time. Finally, documentation was created that instructs workers how to operate the device. However, several items were outside the scope of this project. The team was 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 was outside the scope of this project. Finally, the team was not required to obtain feedback from harvesters using the device, because the team was 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 and the telescoping aluminum poling remained from the device. Since the team is still able to access the Class of 2015's reports and documentation, their failures were 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], and meeting with Dr. Okoli, the team determined that the best approach to designing a new prototype was to improve the Class of 2015's ground-based design and make it more portable and safer.

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, many assumptions were made regarding the trees. These assumptions inevitably constrained how the harvesting mechanism was designed. These constraints provided the project with the direction and necessary standards that needed to be met before it could 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 Milestones

There were several major tasks that needed to be completed per phase that are given in Table 7. The tasks from Table 7 are depicted graphically utilizing a Gantt chart, which is depicted in Figure 5.

Table 7: Major Tasks Listed by Phase

Major Task	Explanation
Define Phase	
Research Harvesting Methods	This task 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.
Risk Assessment	This task ensures the safety of all group members during the construction and testing of any prototype design.
Determine Customer Requirements	This task verifies that all of the customer's requirements were successfully understood.
Measure Phase	
Develop Design Concepts	Team members discuss which palm harvesting ideas are feasible, given the time constraints of the project.
Initial CAD Renderings	This task allows the group to visualize how the palm harvesting prototype will appear after it is built and allows for any design issues to be identified before construction begins.
Initial Mechanical Analysis	This task allows the team to ensure the selected design concept will be able to be constructed without failing.
Order Parts	Ensures materials arrive to complete a prototype by the end of the project.
Analyze Phase	
Conduct FEA* on Pole	FEA on the pole must be conducted to determine if the design is feasible.
Final Bill of Materials	Allows the group to show the sponsor what parts are being used to build the prototype.
Test Available Electrical Components	Electrical components must be tested to ensure that they will work in the prototype.

Improve Phase	
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.
Test All Electrical Components	All electrical components must be tested together before they can be installed in the prototype.
Control Phase	
Assemble Mechanical Components	The poles and cart should be assembled together. The cutting mechanism should be assembled separately and not be attached until it is tested.
Assemble Electrical Components	The prototype controller should be built and finalized. The electrical control circuits should also be connected to the Arduino.
Post-Control Phase	
Test Prototype	The mechanical and electrical components should be assembled together and tested for functionality.
Troubleshoot Prototype	Any issues that result in the prototype not performing as designed should be documented and rectified.
Test Improved Prototype	The prototype should be tested again, after any adjustments are made.

*FEA refers to finite element analysis

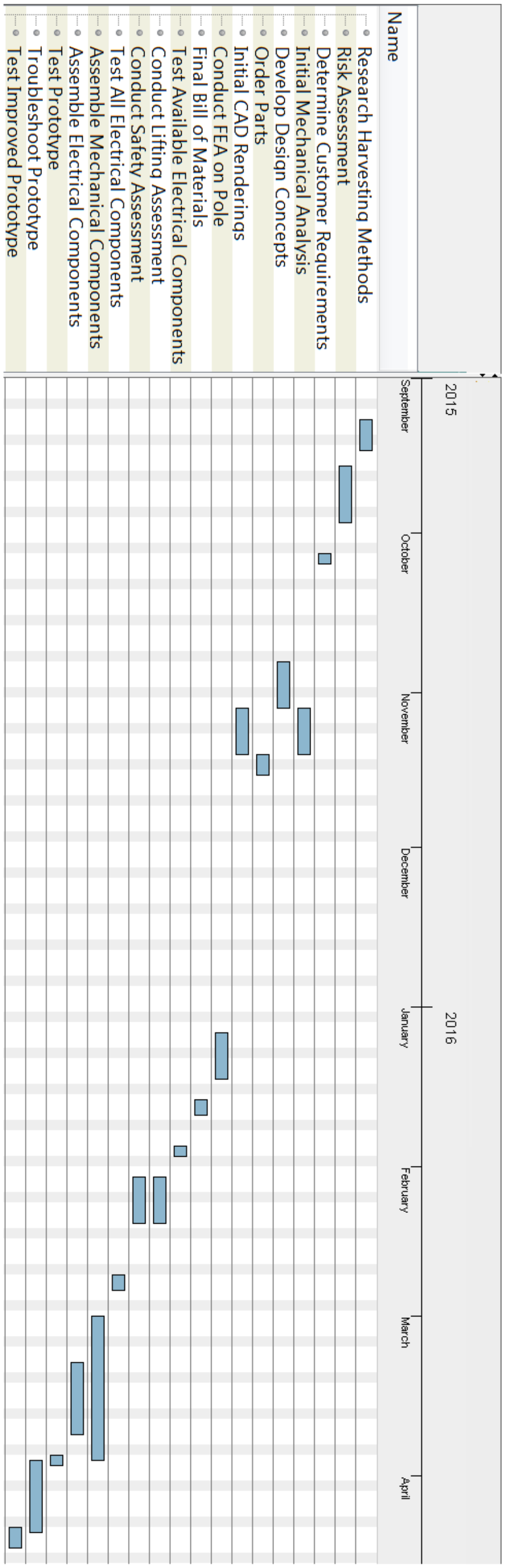


Figure 5: Gantt Chart of Major Tasks

Figure 5 also shows the project's critical path. For example, parts could not be ordered until the design was selected and a finite element analysis (FEA) showed that it would be safe to construct. Similarly, the prototype could not be tested until the mechanical and electrical components were assembled, tested, and then attached to one another. The only major delay that occurred during this project was the ordering process. Once the project's sponsor signed a purchase order form, it had to be approved by the Dean of the FAMU-FSU College of Engineering, which resulted in a delay out of the team's control. Furthermore, since purchase orders could not be placed for items under $100, team members had to spend personal funds to purchase some of the smaller parts needed, such as nuts and bolts, to allow the project to be completed on time.

2.2.5 Budget/Bill of Materials

The sponsor has set a budget of $2,500 for the entire project. The actual expenditures for the selected design and the bill of materials are given in Table 8.

Table 8: 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.

To minimize costs 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 12 V 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.

3. Technical Achievements

3.1 Defining Customer and Technical Requirements

3.1.1 Customer Requirements

According to the sponsor, the purpose of this project was 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 wanted to improve the productivity and safety of this process by using an electromechanical device. Descriptions of each requirement are given in Table 16 in Appendix A. This information was converted into the voice of the customer diagram that is depicted in Figure 45 in Appendix A. The voice of the customer diagram helped the team visualize the customer's requirements and assign corresponding technical requirements to them.

3.1.2 Technical Requirements

The technical requirements needed to meet the customer's requirements are described in Table 9.

Table 9: 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.

3.1.3 Current Harvesting Process

After determine the customer's requirements and technical requirements, the team then analyzed the current oil palm fruit harvesting process. When workers first arrive at the palm tree 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 46 [2] in Appendix A. The goal of this project was to allow workers to use an electromechanical device to harvest the fruit, from the ground.

3.1.4 Ishikawa Diagram

The team constructed an Ishikawa diagram that helped determine why the current harvesting process is ineffective. This diagram is depicted in Figure 47 [2] in Appendix A. The Ishikawa diagram helped direct the project by highlighting important aspects of the current harvesting methods. The team learned that oil palm trees can easily be damaged, grow to a maximum of approximately 12 meters, and require four to six years to bear fruit. Therefore, the team needed to design a system that was able to reach 12 meters and not cause harm to the trees.

Furthermore, since the personnel operating any assembled device will be used to manually ascending and descending oil palm trees, the team decided that the device must be easy to use.

3.1.5 House of Quality

A house of quality was created to assist with this project and is depicted in Figure 48 in Appendix A. The house of quality was important because it allowed the customer's requirements to be converted into technical requirements and helped determine the team's prioritization of tasks [16]. A more detailed explanation of each correlation and relationship is given in the Control Phase report. From Figure 48 in Appendix A, the two most important requirement were the electromechanical components and the system's weight. Thus, the team focused on the two aforementioned requirements during this project.

3.2 Design Process

3.2.1 Design Background

The team created and analyzed several possible designs during the course of this project. Several analyses, including FEA, were conducted and are detailed completely in the Control Phase report. These analyses led to the completion of the team's final design.

3.2.1 Final Design

3.2.1.1 Ring

To minimize the weight of the ring, a semicircular ring with a diameter of 762 millimeters (30 inches) was used. The ring is attached to the pole from its bottom, rather than its side, to further relieve the stresses acting upon it. Without the support of a fully circular ring, the deflection of the ring becomes a serious concern. A deflection analysis was conducted and is depicted in Figure 6.

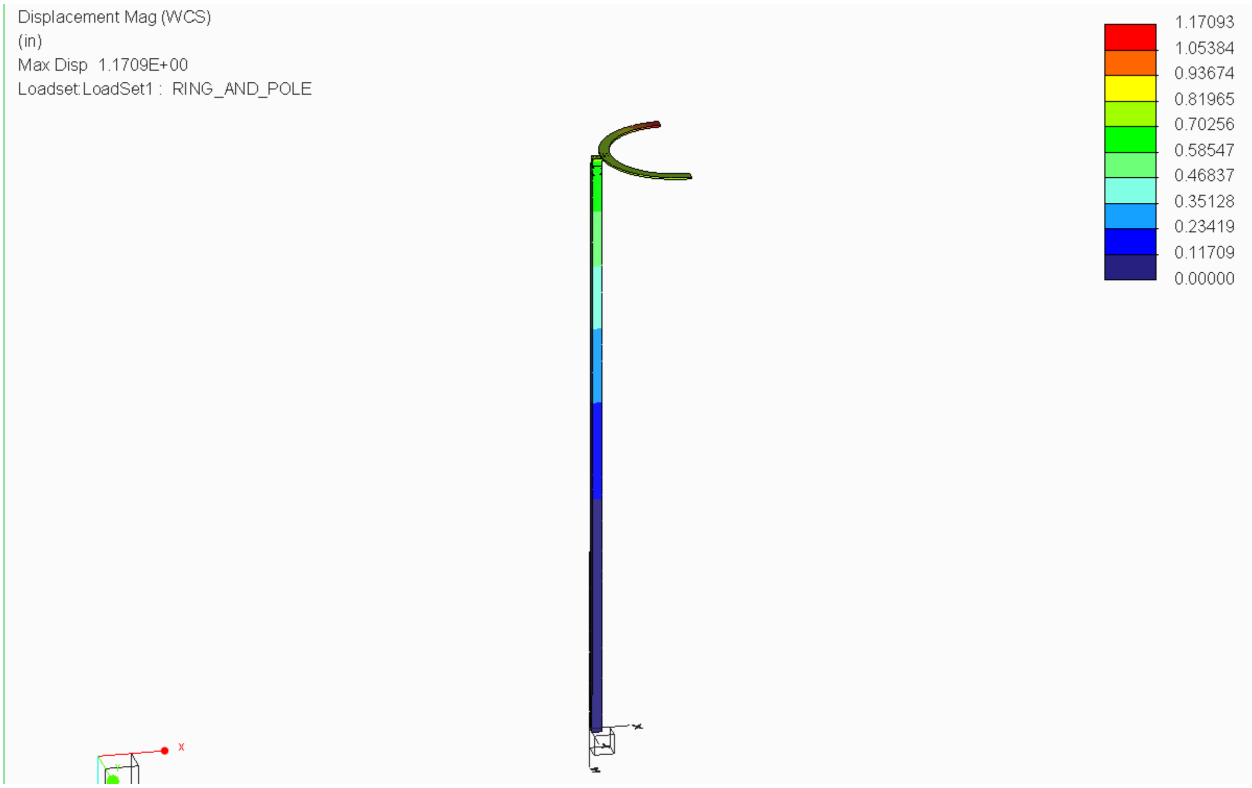


Figure 6: Deflection Analysis of Modified Ring

Figure 6 shows that with the expected weight of the cutter, the 9.525-millimeter thick ring did not experience more than 29.72 millimeters (1.17 inches) of deflection. Since the cutter is able to adjust its position, it will be able to compensate for this small deflection. An FEA was also conducted for the ring and is depicted in Figure 7.

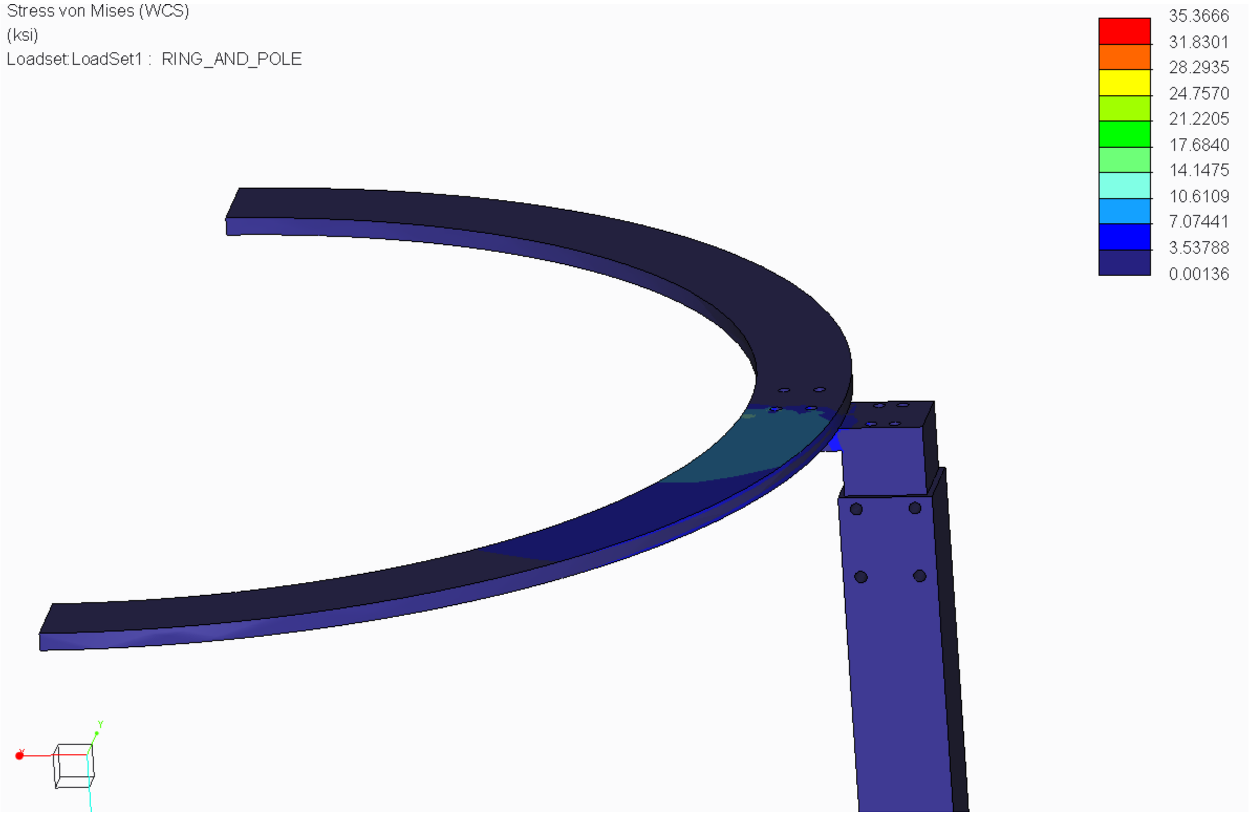


Figure 7: Stress Analysis of Modified Ring

Figure 7 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) [17], 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.

3.2.1.2 Cutter

3.2.1.2.1 Mechanical Components

The cutting mechanism will be set on an aluminum platform that will traverse around the circumference of the ring by utilizing a rack and pinion system with a direct current (DC) motor, to reduce the likelihood of slippage. 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 the cutting housing box that contains a DC motor that controls the saw and the stepper motor that controls its pitch. 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. 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. The electronics box is 101.6 millimeters by 101.6 millimeters by 127 millimeters (length by width by height) and will contain the electronics necessary to control the prototype. The cutting mechanism is depicted in Figure 8.

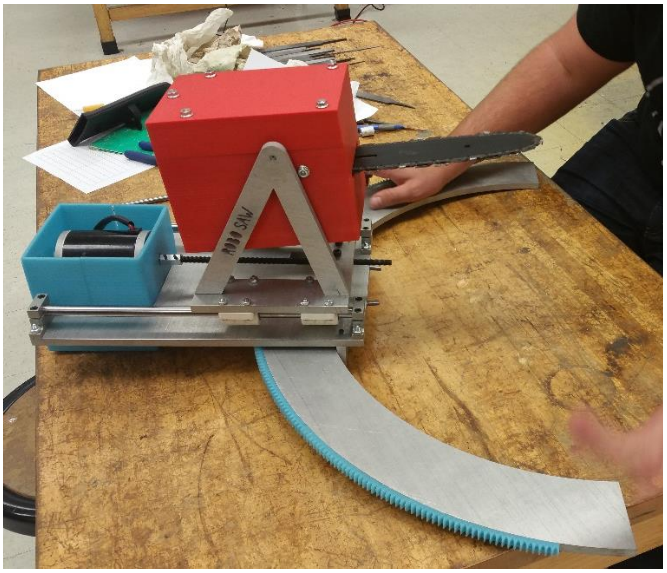


Figure 8: Cutting Mechanism

3.2.1.2.2 Electrical Components

The cutting mechanism will be controlled using an Arduino UNO microcontroller similar to the one depicted in Figure 9 [18]. 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 controller will operate three DC motors with the use of two 10 A 5–25 V Dual Channel DC Motor Drivers, depicted in Figure 10 [19]. A depiction of the configuration of two DC motors with this driver is given by the manufacturer in Figure 11 [19]. The five pins allocated for operation of the driver are given in Table 10 [19]. A truth table for the control logic of both motors is provided in Table 11 [19]. Two motor drivers are necessary to control all three DC motors utilized in the cutting mechanism. Since the stepper motor has a lower current draw, the team selected a smaller motor driver and shown in Figure 12 [19]. The four connections of the stepper connected to this motor driver on Output A and Output B. The four connections from the Control Inputs of the board to the microcontroller will power each connection from the stepper, respectively.

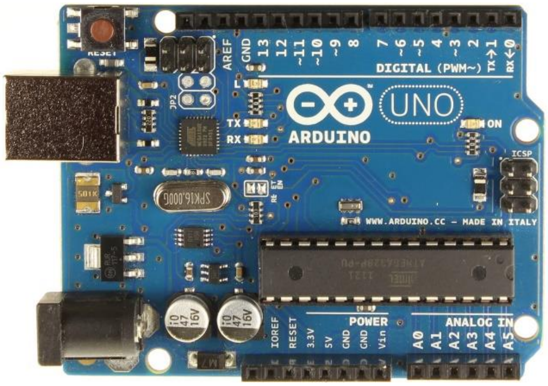


Figure 9: Arduino UNO Microcontroller [18]

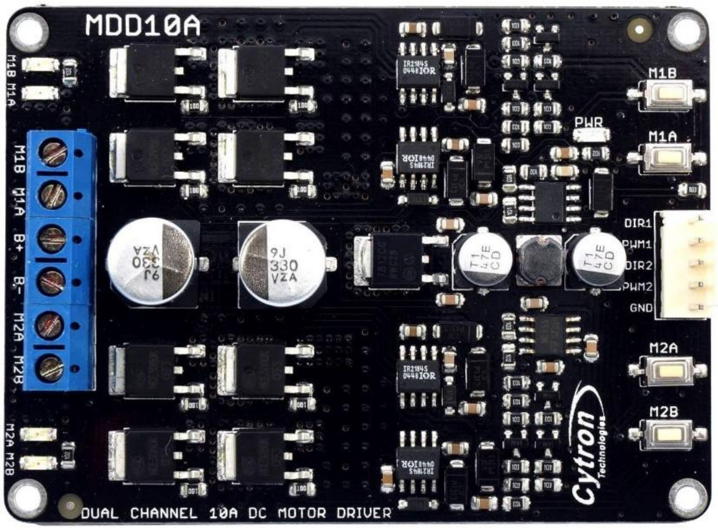


Figure 10: 10A 5-25V Dual Channel DC Motor Driver [19]

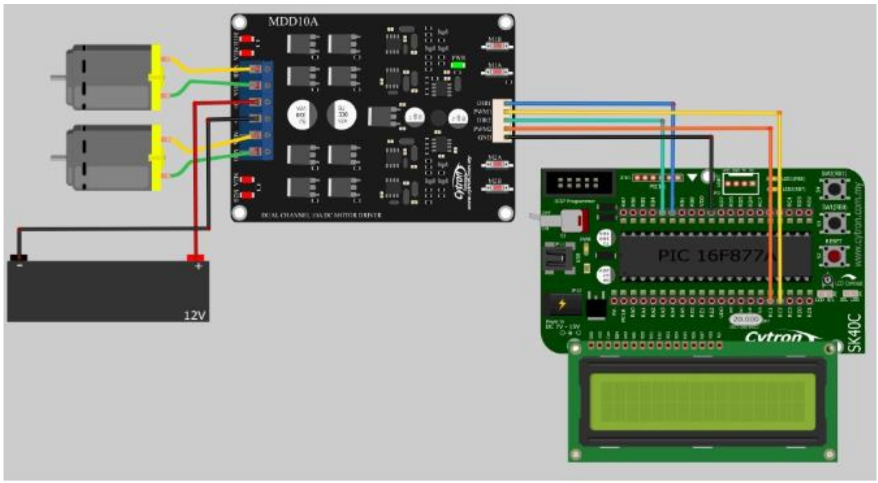


Figure 11: Sample Layout of Motor Driver [19]

Table 10: Motor Driver Pin Operation Descriptions [19]

Pin Name	**Description**
GND	Ground
PWM2	PWM input for speed control (Motor 2)
DIR2	Direction input (Motor 2)
PWM1	PWM input for speed control (Motor 1)
DIR1	Direction input (Motor 1)

Table 11: Control Logic Truth Table [19]

PWM	DIR	Output A	Output B
Low	X(“Don’t care”*)	Low	Low
High	Low	High	Low
High	High	Low	High

*Means that the value in this column does not matter, because PWM has a higher priority

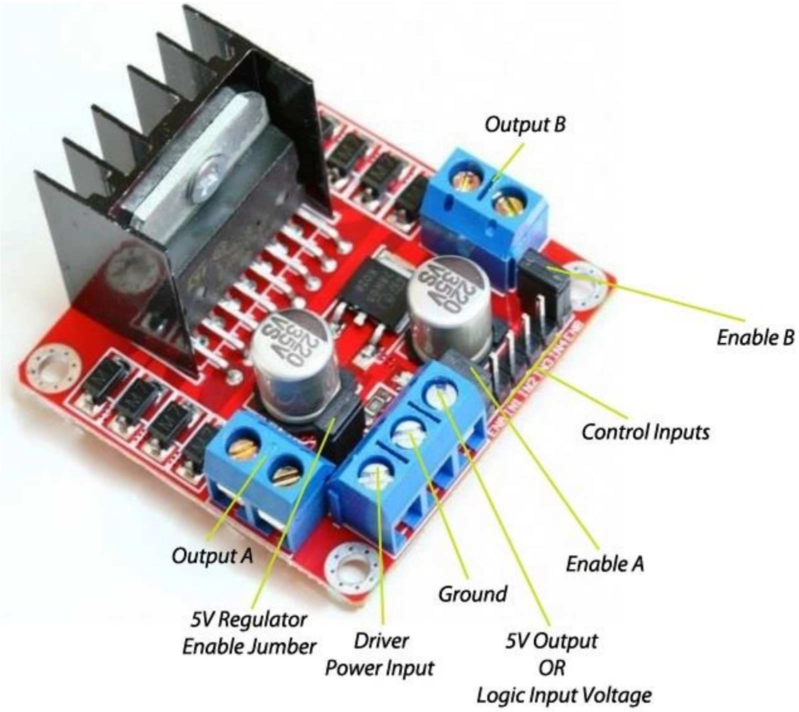


Figure 12: Stepper Motor Driver [19]

For the DC motors to have the ability to rotate in either direction, a positive lead will connect to one of the driver’s output pins and the negative lead to a different output pin. To rotate in one direction, one of the input pins must be set high, while the other remains low. For the reverse direction, simply reverse the input pins. The stepper motor uses internal electromagnetic fields to rotate the magnet inside of the motor. When current is applied to either of the two coils inside of the stepper motor, an electromagnetic field is created. The direction of the electromagnetic field depends on the direction of the current. 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 13 [20].

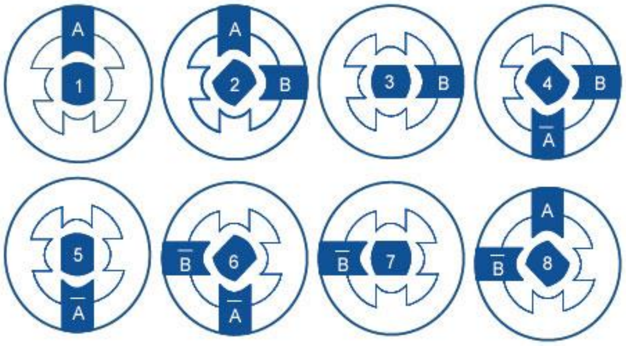


Figure 13: Stepper Motor Forward Sequence [20]

Two of the three DC motors that will be used are depicted in Figure 14 [21]. The stepper motor that will be used is depicted in Figure 15 [22].

Figure 14: DC Motor [21]

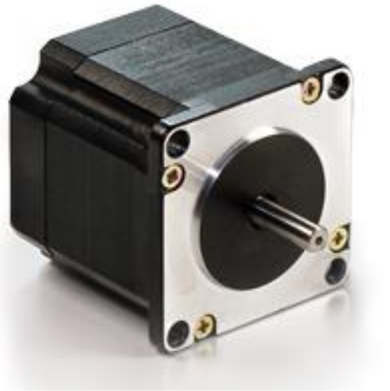


Figure 15: Stepper Motor [22]

For movement of the cutting mechanism, two DC motors and a stepper motor were used. One DC motor will traverse the track and the secondary motor will provide forward and backward translation of the saw. The two DC motors have a power of 150 watts, operate at 3,800 revolutions per minute (RPM), and run from 12–24 V. The third DC motor, acquired from the Black and Decker saw that remains from the Class of 2015's design, operates at 18–24 V. The other specifications of the motor are unknown; the manufacturer would not disclose the motor's specifications, however the motor is intended to be used with the saw, guaranteeing smooth operation. The stepper motor depicted in Figure 15 [23] operates at 18.5 V, has an output torque of 4.237 newton-meters, and requires 1 ampere (A) per phase.

Eleven input/output pins have been utilized thus far, which leaves three extra pins in case more are necessary. The cutting mechanism will operate wirelessly via radio frequency. The receiver and transmitter selected is shown in Figure 16 [24]. 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 [25]. The receiver will operate the cutting mechanism and the transmitter will be inside the wireless controller. The transmitter will operate when powered with 9 V and an antenna of at least 152 millimeters. The controller will also be operated using an Arduino UNO microcontroller, powered using 6 AA cell batteries. An Arduino Joystick Shield will be used for user input and is depicted in Figure 17 [26]. This shield is made specifically for the Arduino UNO. The schematic for the Joystick Shield connected to the Arduino UNO is shown in Figure 18 [27]. The transmitter will utilize any of the unused pins.

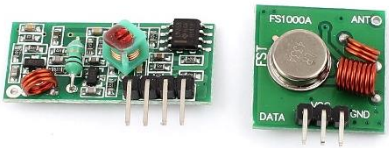


Figure 16: Receiver (left) and Transmitter (right) [24]

Figure 17: Arduino Joystick Shield [26]

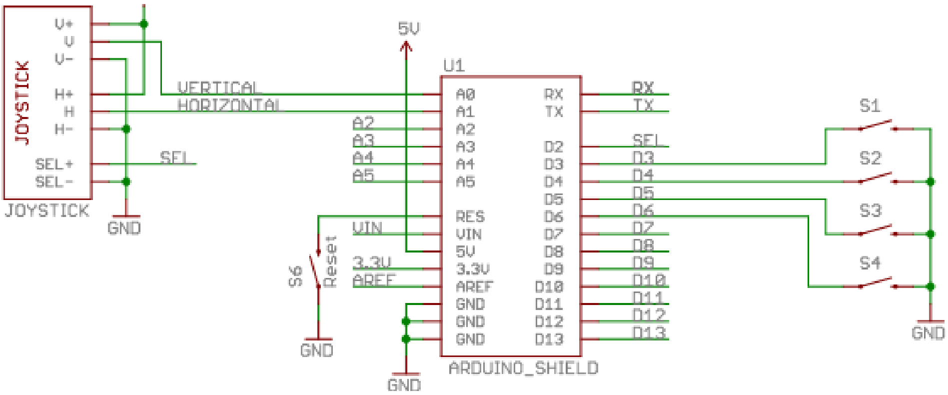


Figure 18: Joystick Shield Schematic [27]

The electronics for the cutting mechanisms required 10 lithium ion batteries that have a voltage of 3.7 V each and a capacity of 4.4 amp-hours. One such battery is depicted in Figure 19 [28].

Figure 19: Selected Battery for Cutter Mechanism [28]

Figure 20 depicts the batteries' layout.

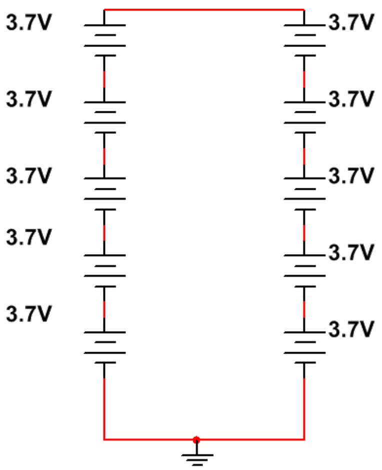


Figure 20: Layout of Cutter Mechanism Batteries

The ten batteries were split into groups of five; each set of five batteries connected in series to output 18.5 V. The two sets were connected in parallel to increase capacity from 4.4 amp-hours to 8.8 amp-hours. The terminals of the batteries were soldered together, covered by heat shrink tubing, to connect them in series. The two sets were secured using zip ties. These batteries are shown in Figure 21. The total weight of these batteries is approximately 0.68 kilograms. Using these batteries, the cutting mechanism will be able to run continuously for a minimum of 3.5 hours (assuming that the mechanism is operating in a 10-hour workday). However, the cutting mechanism will not be operated for this extensive period. Assembly, disassembly, and operating time should be 5 minutes each, so the cutting mechanism will have sufficient power to last the entire period.

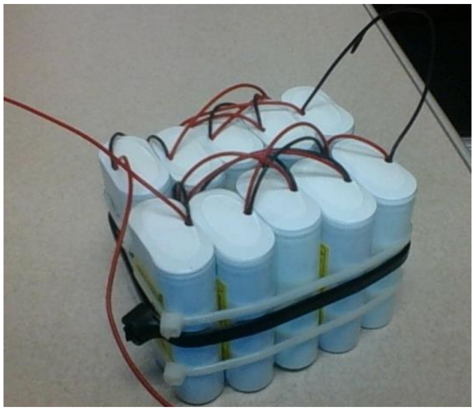


Figure 21: Battery Pack for the Cutting Mechanism

3.2.1.3 Pole

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 uses the Class of 2015's telescoping poles. The telescoping poles are elevated using a system of pulleys shown in Figure 22 [9].

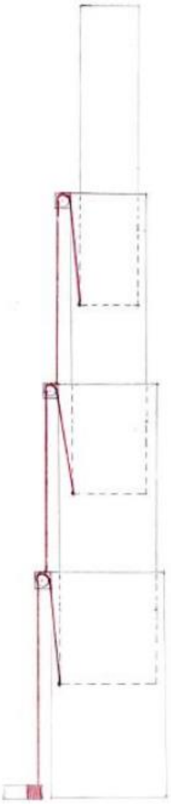


Figure 22: Class of 2015's Pulley Mechanism [9]

As shown in Figure 22, 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.

An FEA was conducted on the full polling structure and the highest stresses produced were found in the brackets (discussed in Section 3.2.1.4). A deflection analysis was also conducted and its results are shown in Figure 23.

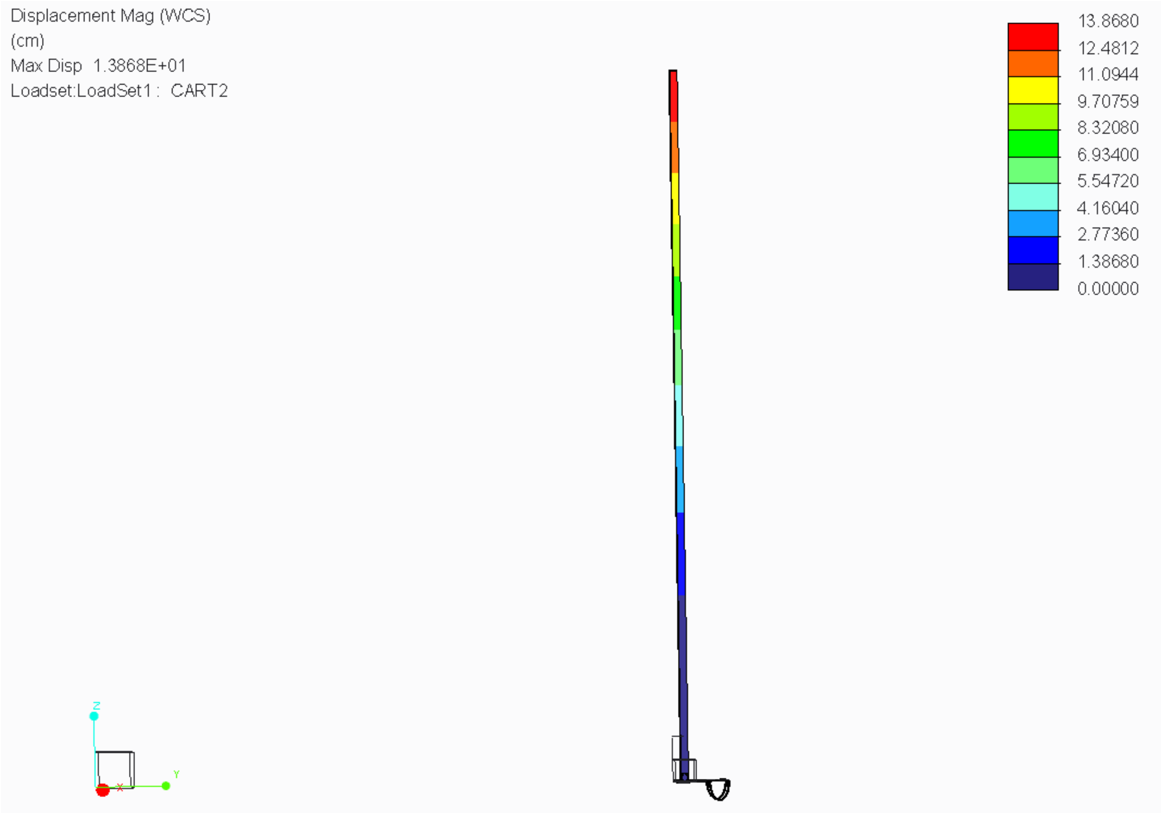


Figure 23: Deflection Analysis (in centimeters) of the Pole Design

The analysis in Figure 23 indicated that with an applied load of 130 newtons the top of the design would not move more than 13 centimeters. This displacement is within the traversing range of mobility of the cutter. While such a high force is unlikely, the device would still be compensate for this deflection and harvest the fruit.

3.2.1.4 Cart

The mobility platform design that was selected is depicted in Figure 24.

Figure 24: Cart

The length of the cart handles depicted in Figure 24 is 1.22 meters. This length was chosen to conform to the United States Occupational Safety and Health Administration's guidelines; these guidelines are discussed in detail in the Control Phase Report.

The cart's design is similar to 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. Unlike the Class of 2015's design, which utilized a four-wheeled cart, the mobility platform uses only two wheels, which makes it easier to maneuver on rough terrain. The cart's chassis was modified from an existing 2-wheel wheelbarrow, to ensure that it was capable of withstanding the weight of the entire poling system.

The pole is mounted using screws and nuts in a way that makes it easy to disassemble without sacrificing strength. An FEA of the mounting system is depicted in Figure 25.

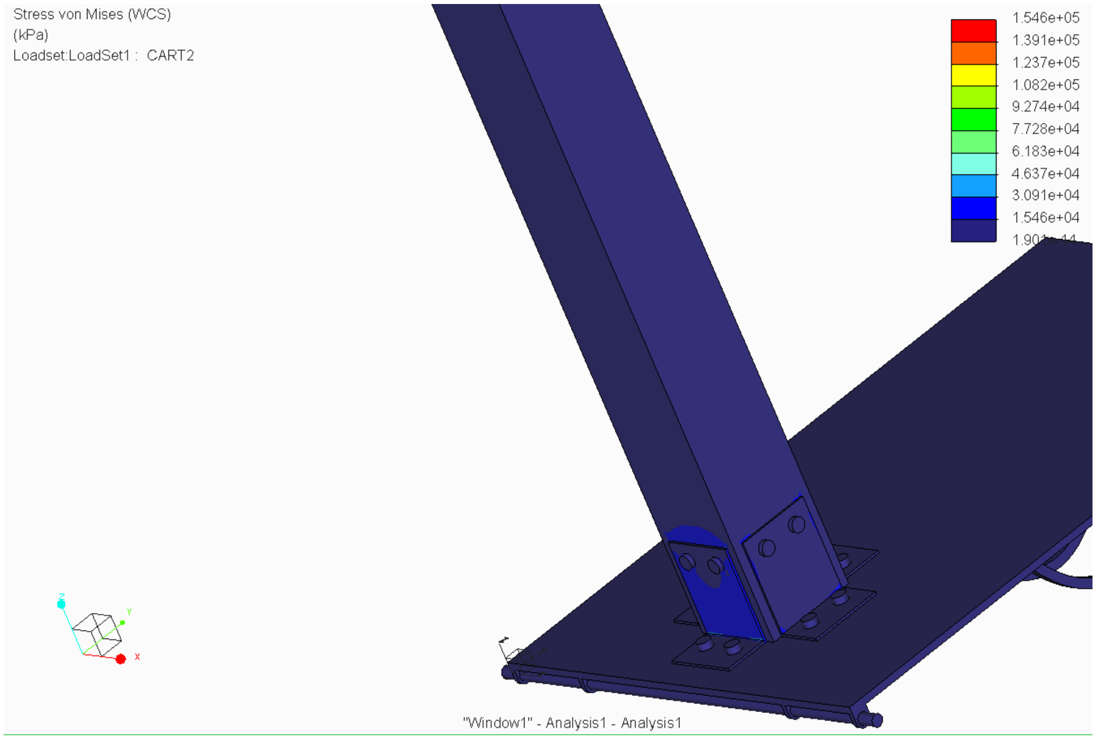


Figure 25: Bracket FEA

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 [29], 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.

3.2.1.4.1 Cart Electronics

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 26 [30]. 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 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 27 [31]. 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 26: Winch Motor [30]

Figure 27: 12V Super Start Marine Deep Cycle Battery [31]

The addition of the components depicted in Figure 26 and Figure 27 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 28 [32], 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.

Figure 28: Motor Driver for Winch Motor [32]

3.3 Component Testing

3.3.1 Electrical Component Testing

3.3.1.1 Wireless Components

To test the functionality of the wireless 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 this 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 9 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 29 and Figure 30.

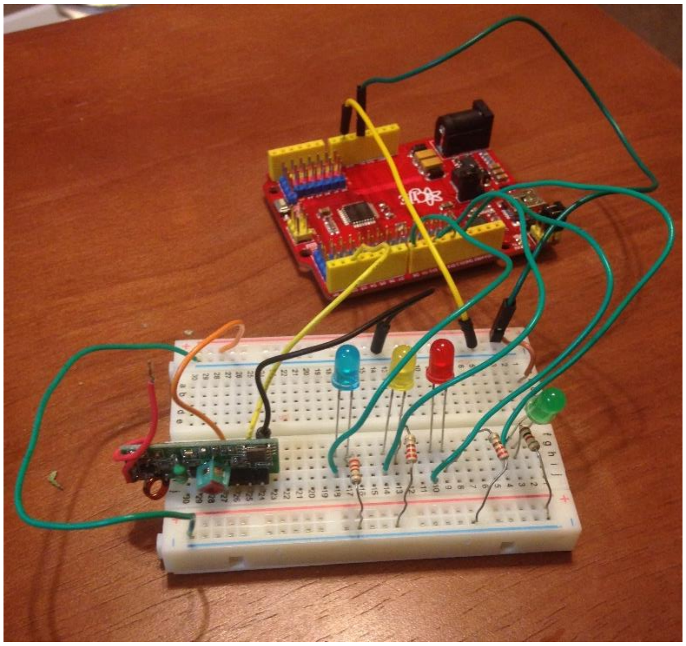


Figure 29: Receiver Testing Circuit

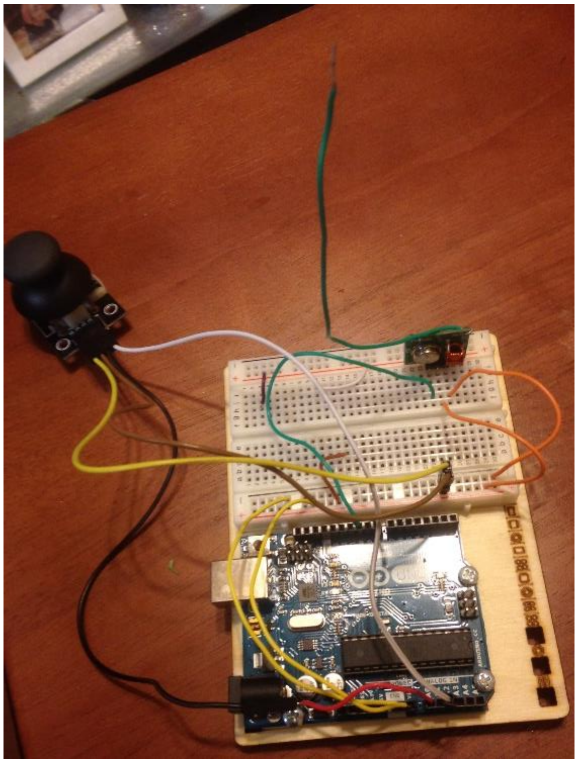


Figure 30: Transmitter Testing Circuit

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 31. The schematic of this controller is shown in Figure 32.

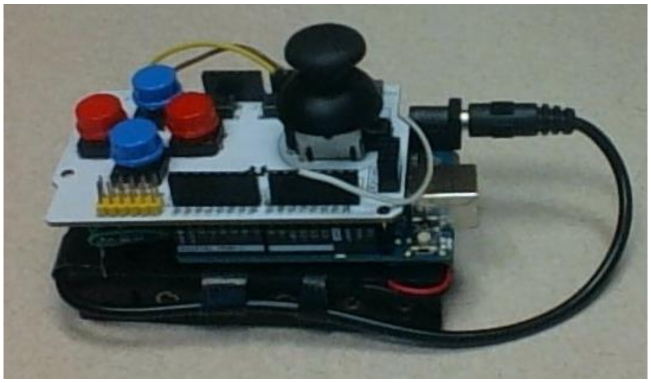


Figure 31: Controller

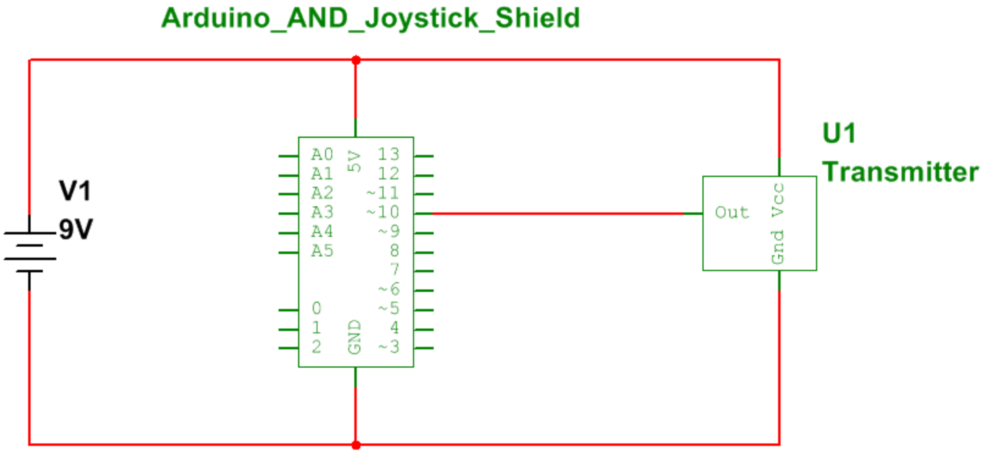


Figure 32: Controller Schematic

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 33.

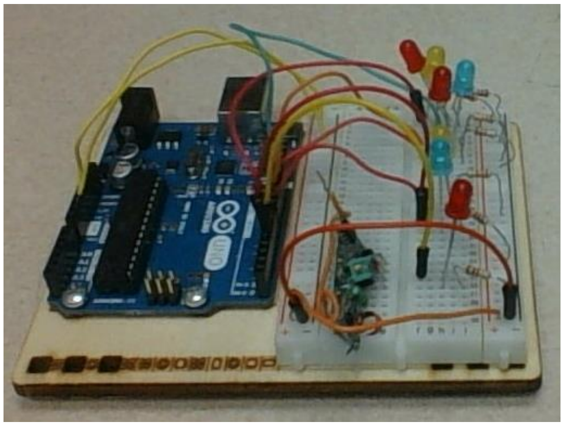


Figure 33: Receiver LED Testing Circuit

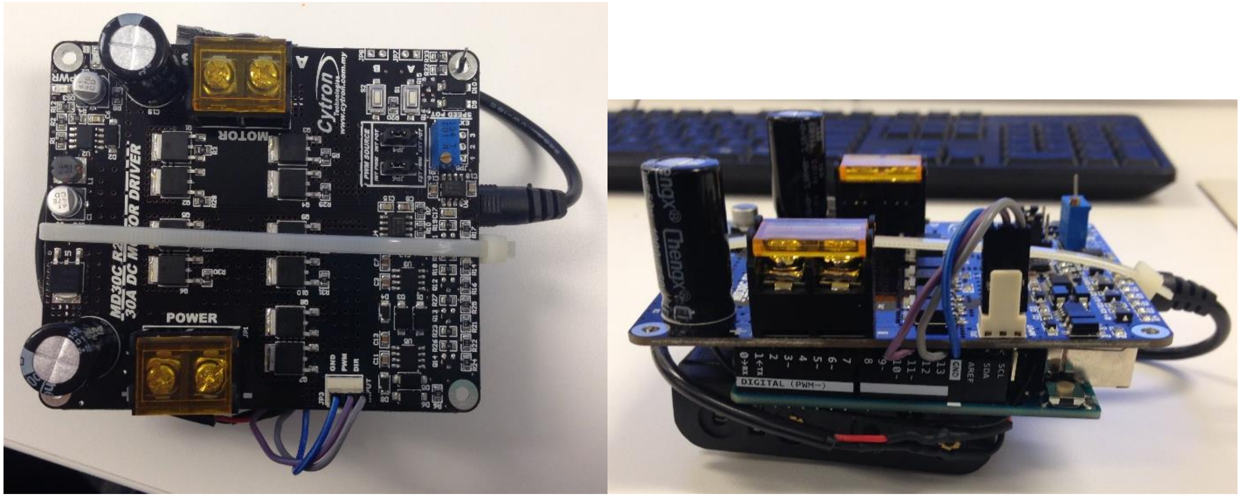
This test confirms that the controller is successfully transmitting a signal and the receiver is successfully receiving it. The LEDs in this test also simulate the toggling of motor drivers in the cutting mechanism. Using the same circuits, the team tested the distance from which a signal could be successfully 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 12 shows the outputs that correspond with each input from the controller. The final code for the controller is given in Appendix B.

Table 12: 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

3.3.1.2 Cart Electronics

The electronics for the cart have been assembled and are depicted in Figure 34. 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 35.



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

Figure 34: Cart Electronics

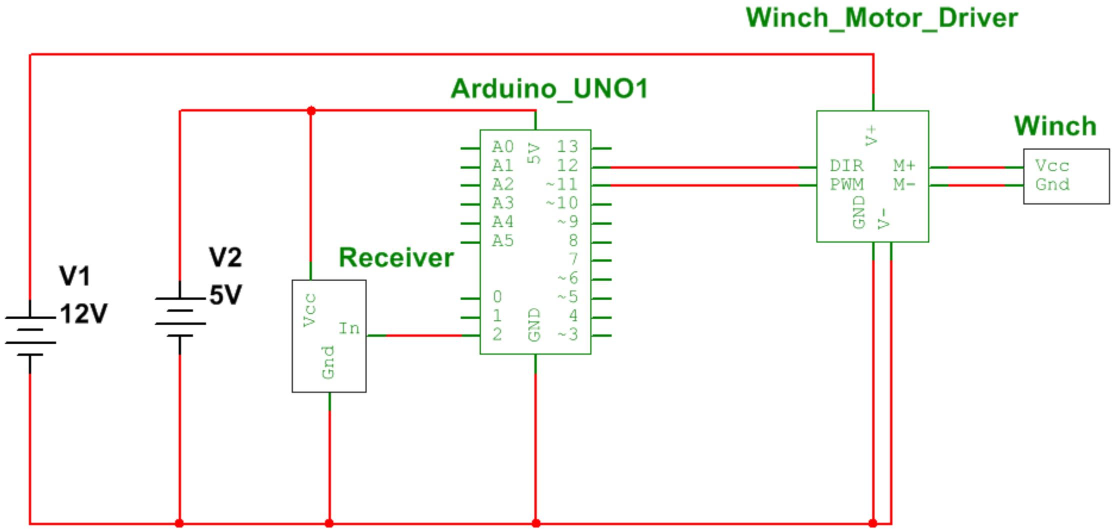


Figure 35: Schematic of Cart Electronics

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 36. This test simply rotated the winch in one direction and then in the other direction. The same test has been done to test the pole's upward and downward movement; the only difference is that the winch will be connected to the pole. The winch has been marked as functional since it can successfully manipulate the telescoping pole upward and downward. The final code for the cart electronics is given in Appendix B.

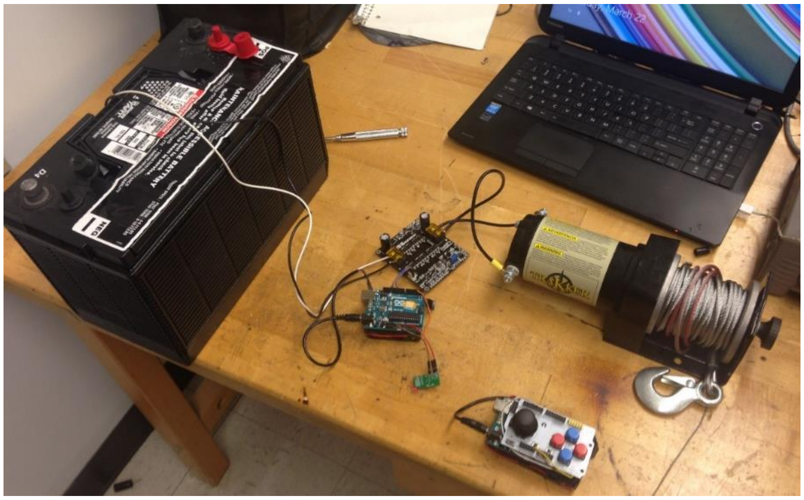


Figure 36: Functionality Test for Cart Electronics

3.3.1.3 Cutting Mechanism Electronics

The DC motors will be operated using PWM signals. The way a PWM signal works is shown in Figure 37 [33]. 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

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.

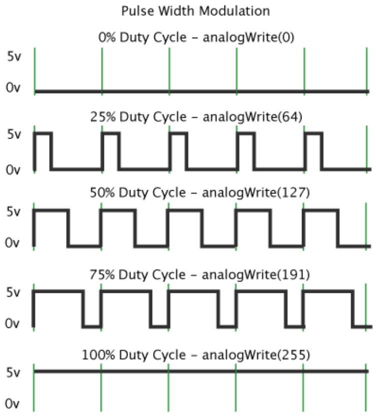


Figure 37: Graph Definition of PWM [33]

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 38. 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 18.5 volts. The stepper motor passes its testing once it can successfully pitch the saw up and down.

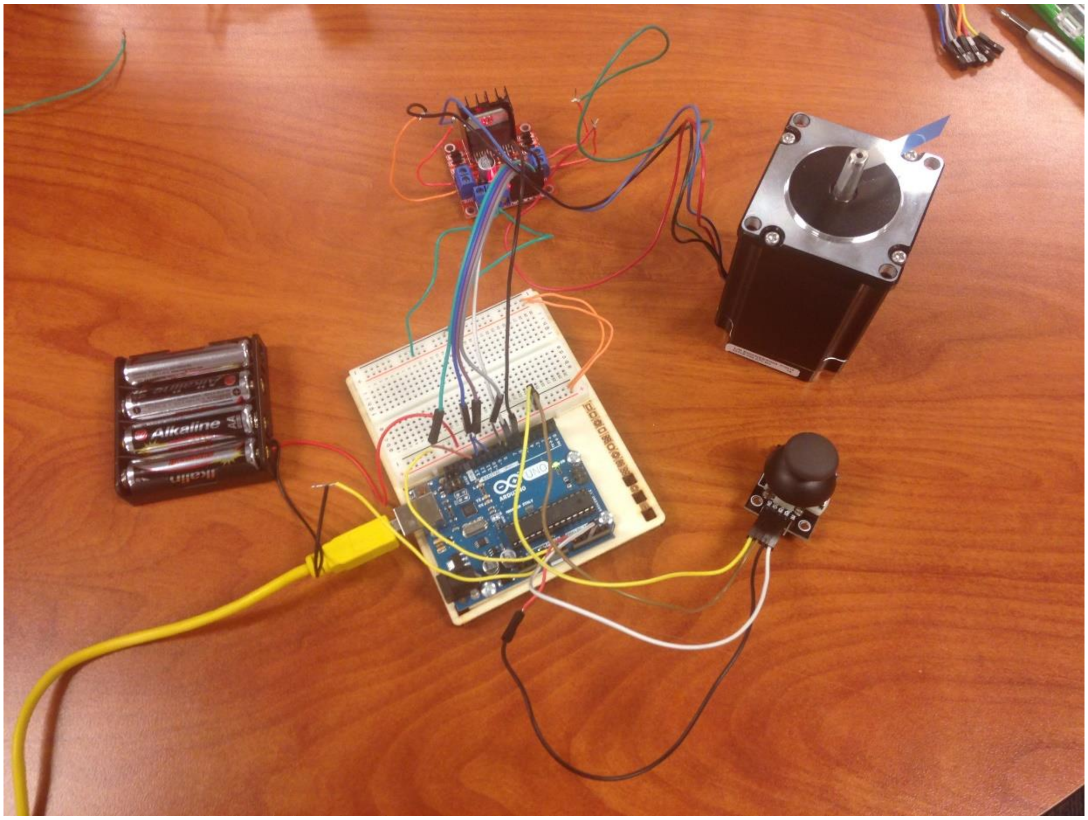


Figure 38: Stepper Motor Testing Circuit

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 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.

Since every individual component has passed their tests, the full system of motors was assembled and tested. Figure 39 depicts the no-load testing circuit.

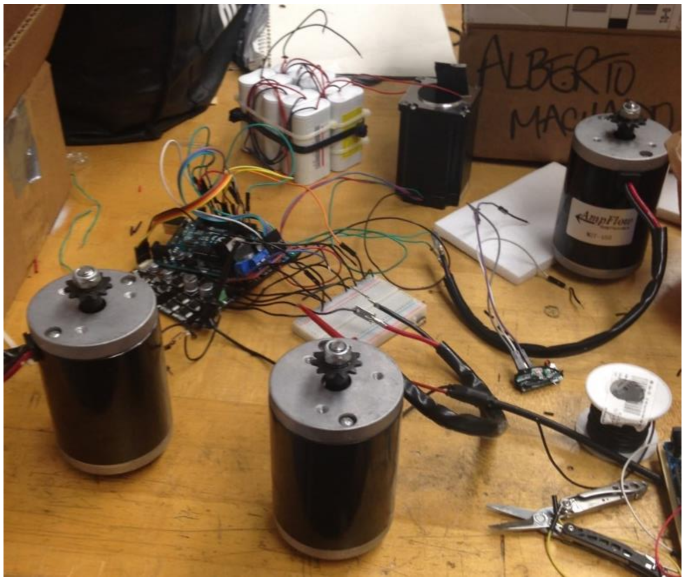


Figure 39: Functionality Test for Motor Drivers and Motors

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 40.

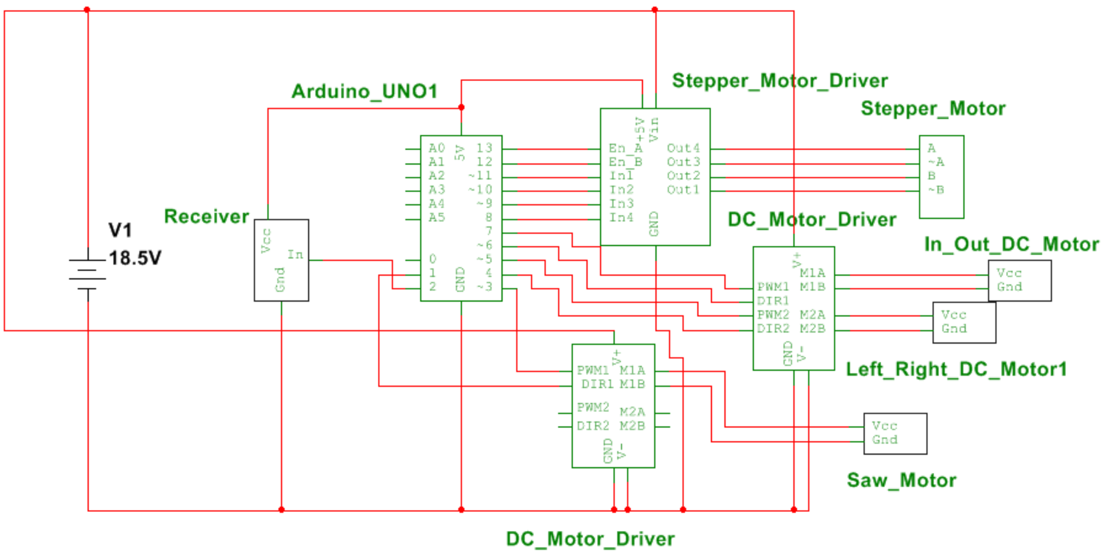


Figure 40: Final Cutting Mechanism Schematic

The final cutter mechanism is depicted in Figure 41 and Figure 42. The entire system was tested and all components functioned properly. A video of the functionality of the cutter mechanism was recorded. 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 final code for the cutter mechanism is given in Appendix B.

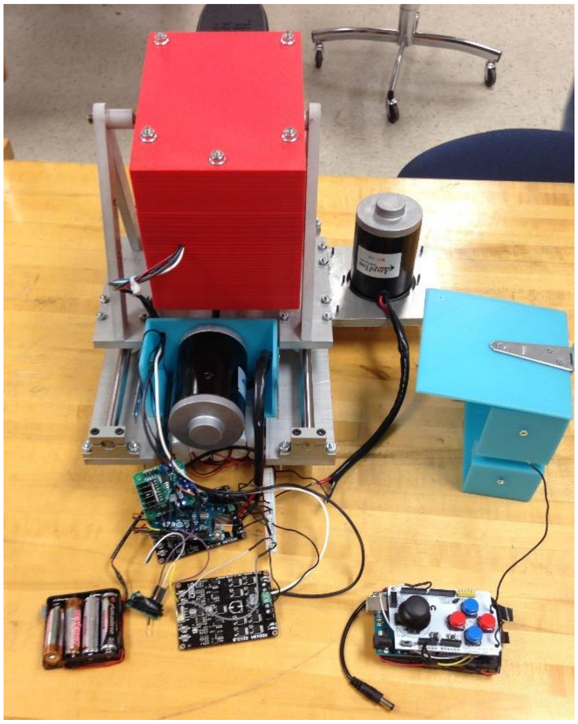


Figure 41: Back View of Final Cutting Mechanism

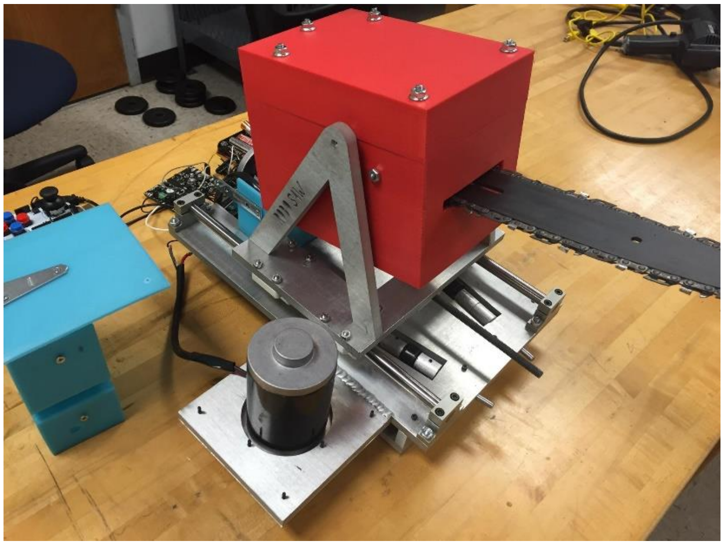


Figure 42: Front View of Final Cutting Mechanism

3.4 Manufacturing Techniques

3.4.1 Safety Considerations

The team developed a safety plan prior to assembly, to determine the protective measures required to avoid any injuries. Table 13 explains dangerous tasks and the actions that should be taken to minimize any risks.

Table 13: 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

3.4.2 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 43.

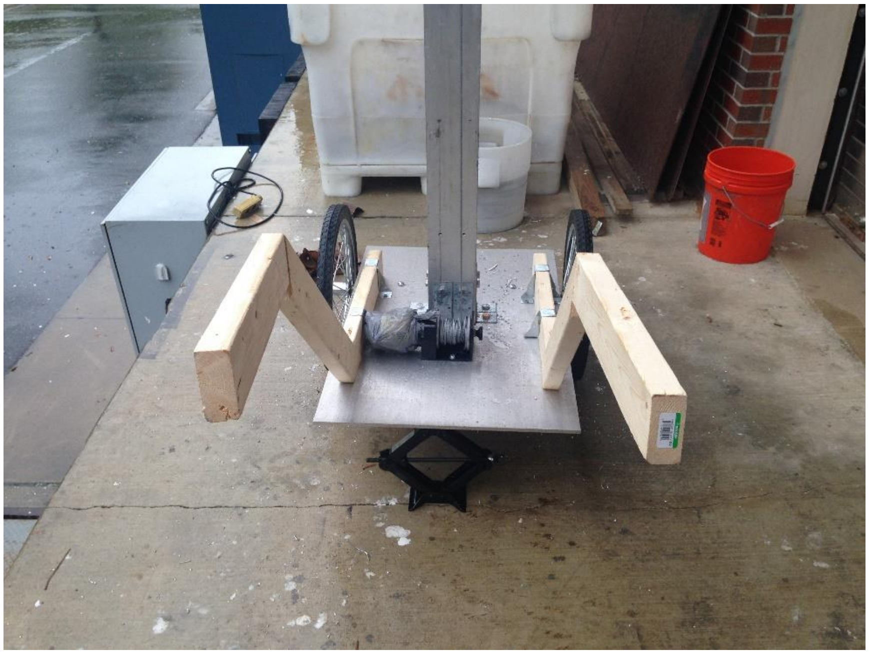


Figure 43: Completed Cart

3.4.3 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. The completed cutter was depicted in Figure 41 and Figure 42.

3.5 Standard Operating Procedure

3.5.1 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.

3.5.2 Specifications

The sponsor’s requirements were discussed in the voice of the customer diagram depicted in Figure 45 and in the house of quality depicted in Figure 48. Table 14 shows how the prototype meets each of the sponsor’s requirements.

Table 14: 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.

4. Business Analysis

4.1 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].

4.2 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.

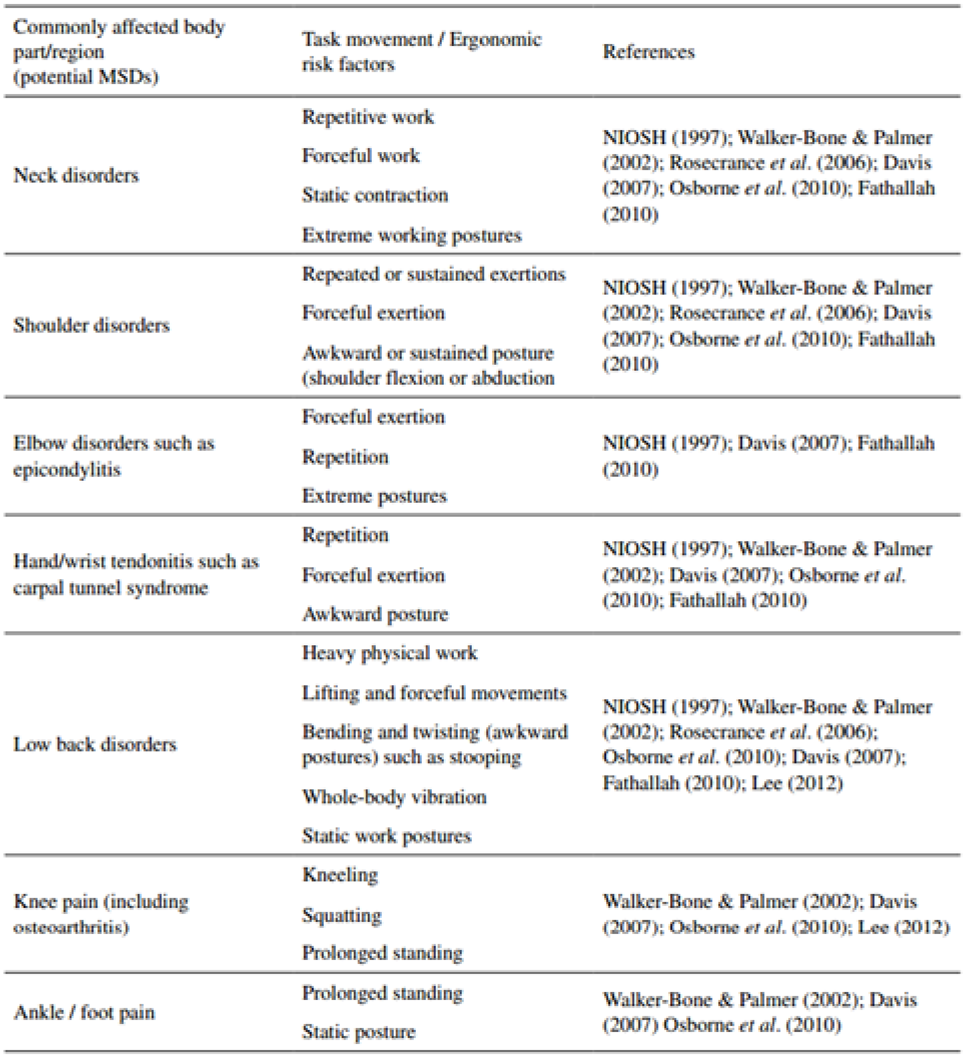
4.3 Ethical Considerations

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.

4.4 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 15 depicts ergonomic risk factors for workers on oil palm plantations [34].

Table 15: Ergonomic Risk Factors on Oil Palm Plantations [34]



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. Currently, the cart’s arms consist of wooden handles, which should be improved in the future to allow the operator to have a better grip of the device. The team recommends materials such as aluminum or steel for this improvement.

4.5 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 [35], 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 [36]. 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.

4.6 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.

5. Project Success

Overall, the project was successful. The completed prototype improves the safety and effectiveness of the Class of 2015's design.

The team’s design allows workers to be safer by not climbing the trees and the wireless controller allows them to stand far away from any potential hazards. Fundamentally, the prototype is functional and meets all of the sponsor’s requirements. However, small improvements must be made before it can be considered a final product.

First, the poles should be improved. Instead of using poles with square cross sections, circular ones should be used. Circular cross sections provide greater column stress resistance and would be less expensive to manufacture. Additionally, the length of each pole section should be decreased. Shorter lengths provide greater deflection resistance, which means that the thickness of each pole could be decreased. Additionally, the shorter lengths provide a smaller moment when the poles are not extended, which would make the device easier to transport.

All of the machined aluminum used in the cutter came from the 9.525-millimeter (3/8-inch) thick aluminum plate. Most of the stresses acting on the cutter would not necessitate such a high thickness. Therefore, an improvement would be to analyze the stresses acting on the cutter during operation and determine the appropriate thickness of material, which would then reduce the weight. An additional way to reduce the weight of the cutter would be to use smaller motors that use a system of gears to improve their torque and angular velocity. These smaller motors would require fewer batteries to operate. Lastly, the cart should have a jack mounted on both sides, to further increase stability.

The handles for the pole were intended to determine if the minimized length of the handles based on OSHA’s guidelines would still allow the operator to lift the cart. In this respect, the handles were successful. Despite its heavy weight, the cart was easy to lift. However, in rough terrain, while the cart was not difficult to lift, it was difficult to push, because the handles were too thick. Additionally, the cart had a tendency to tip forward if raised too high, due to the weight of the long aluminum poles used. While the 25-centimeter height needed to tip the poles forward would be too high for normal, comfortable operation, a mechanism to prevent tipping has to be implemented. This modification can be made by extending the length of the front of the cart with a bracing system. The bracing system would involve a tradeoff between forward distance and ground clearance. For example, under the current design, if the battery is moved closest to the user, the bracing system would either have to extend up to 1.524 meters (5 feet) forward if it is mounted horizontally or 20.32 centimeters (8 inches) downward if it is mounted vertically. To modify the limits for ground clearance and horizontal length, future improvements must involve lowering the weight or height of the poles in order to lower the center of gravity. This suggested modification is depicted in Figure 44.

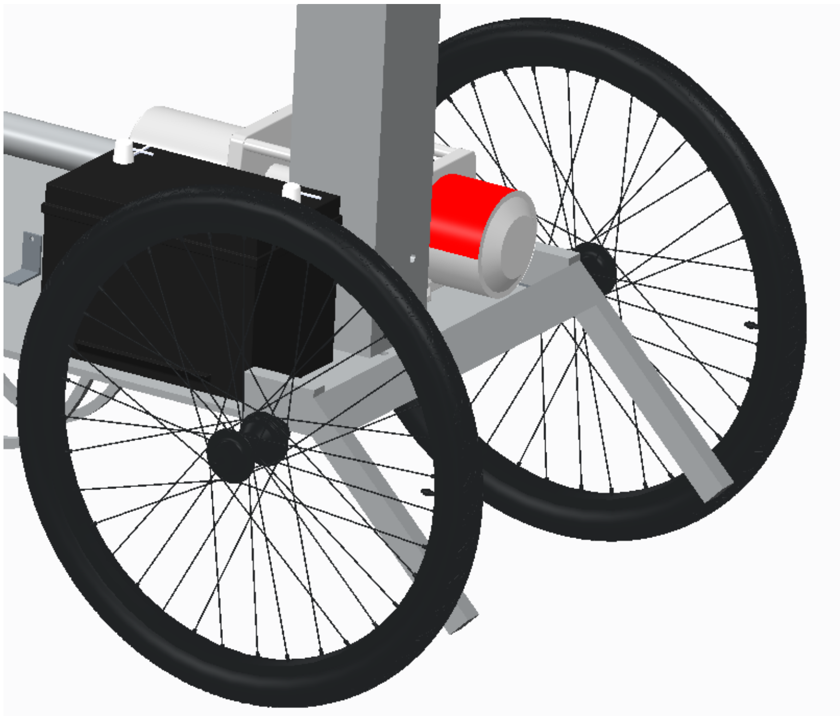


Figure 44: Suggested Cart Improvement

Furthermore, it was difficult for the user to obtain a good grip on the handles. Future work should focus on improving the size and shape of the handles, providing low diameter, circular handles, rather than large, rectangular ones. The smaller diameter handles could be constructed out of steel or aluminum, because of their reduced size.

The controller used was for testing purposes. The current controller is rectangular and does not a housing. In the future, the controller will have a more ergonomic, rounded shape, as well as a plastic waterproof case.

There are a few additional electrical improvements that could also be made. LEDs could also be added to each electrical component for troubleshooting purposes. The LED would allow the user to determine if a component is failing. Furthermore, the electronics should be placed in the box in a way that allows each component to be easily accessed. For space saving purposes, smaller Arduinos could be used. Given that the price of the telescoping poles could be reduced, a camera could be added to the top of the device that would allow the user to see where the cutter is facing via a screen on the controller. Additional sensors should also be added for improved control of the cutting mechanism. The current design utilizes two motor drivers that allow two connections each. Since there are only three motors in the cutter, a motor driver that allows three connections should be used.

Finally, the device was tested in an area where no oil palm trees grow. To verify the functionality of the completed prototype, it should be tested by actually cutting an oil palm fruit bunch.

6. 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.

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 selected design consists of a semi-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 telescoping pole sections that are attached 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. After making some modifications, 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.

The completed cart was then 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. Overall, the team was successful in achieving the design requirements specified by the sponsor. Minor modifications must still be made before a final product can be mass-produced, but as a proof-of-concept prototype, the device was deemed acceptable.

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Appendix A: Defining Customer and Technical Requirements Figures

This appendix provides several figures that were used in defining the customer and technical requirements of this project. Brief descriptions of the figures are provided as needed.

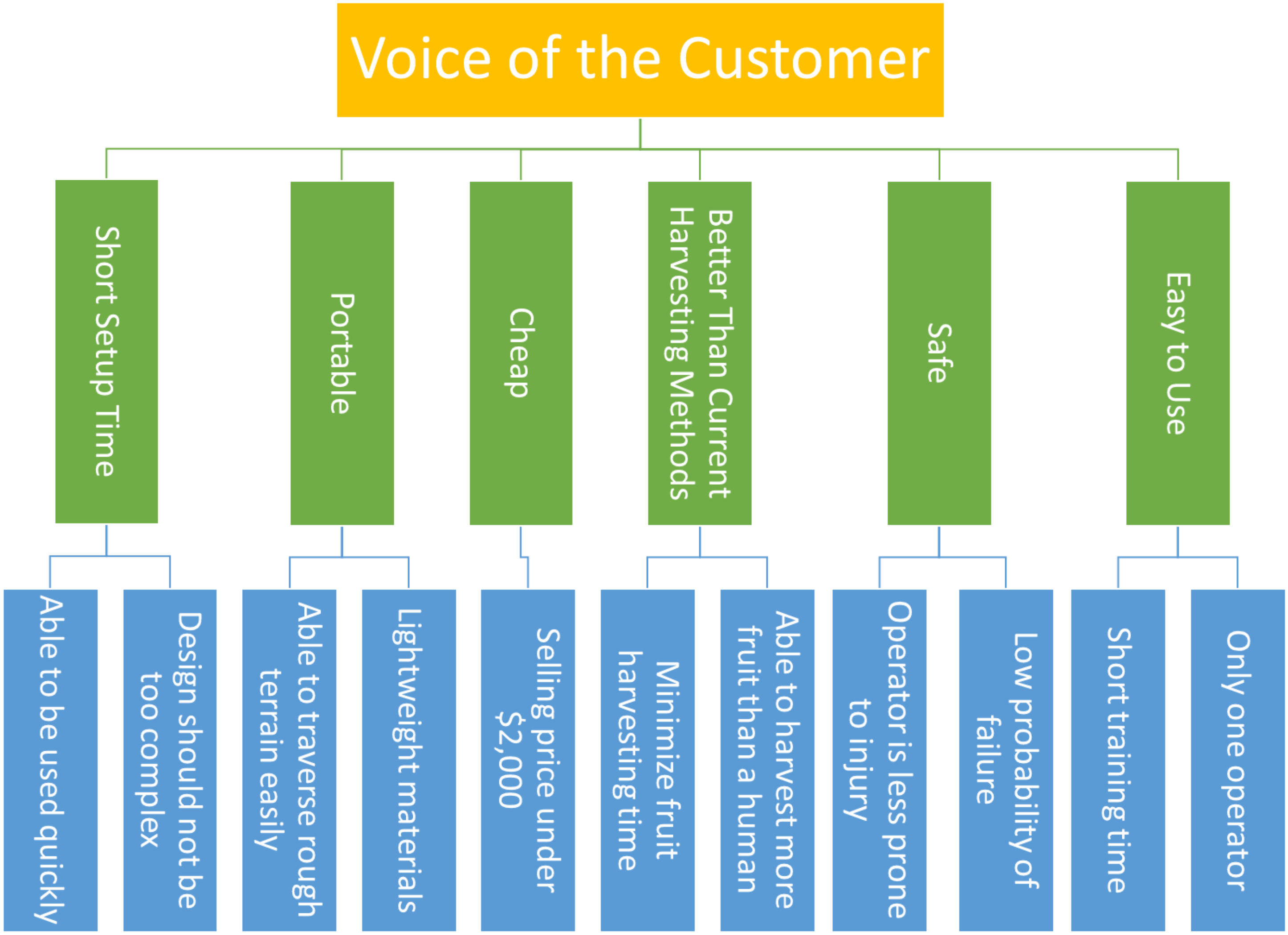


Figure 45: Voice of the Customer Diagram

Table 16: 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.

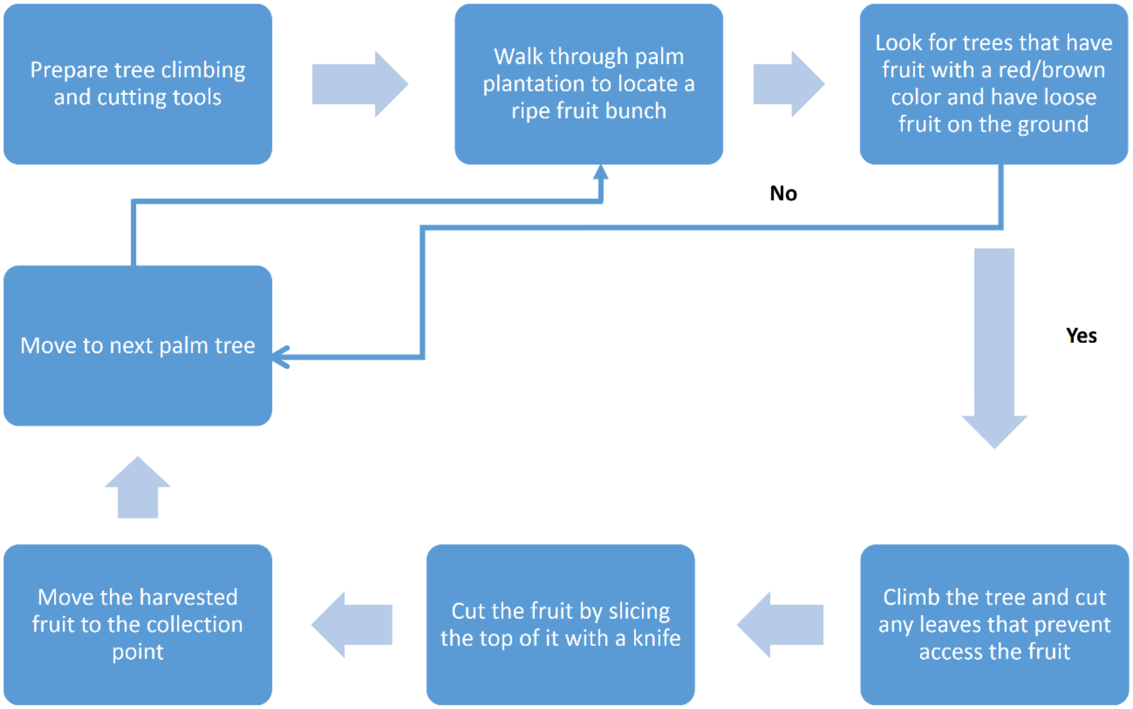


Figure 46: Current Oil Palm Fruit Harvesting Method for Tall Trees [2]

The process depicted in Figure 46 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.

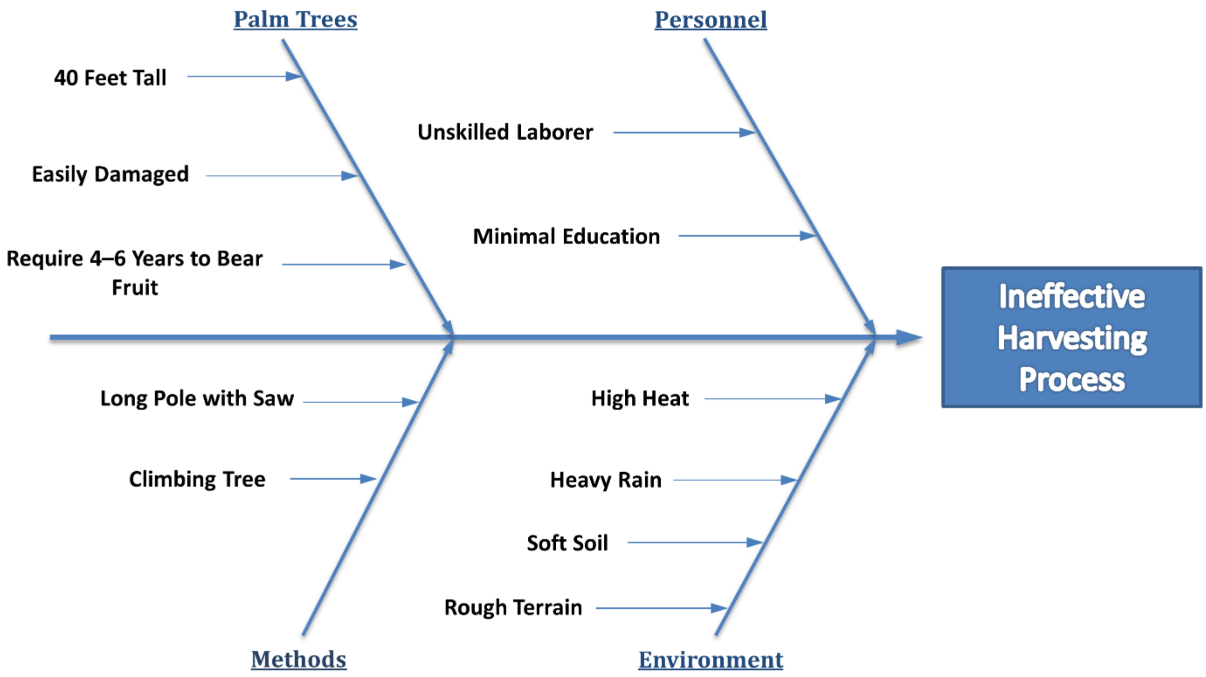
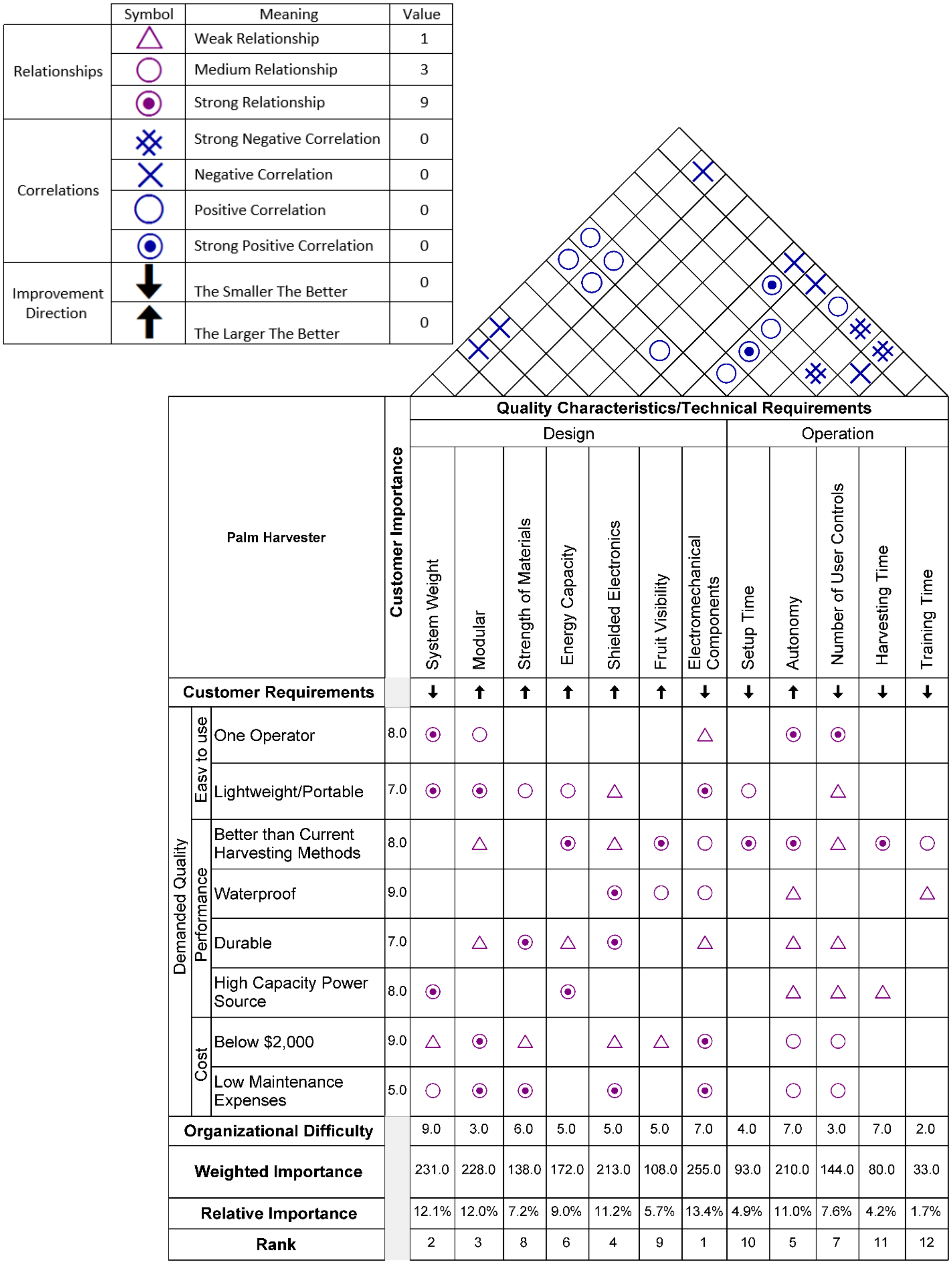


Figure 47: Ishikawa Diagram of the Palm Harvesting Process [2]

Figure 47 shows the causes of the ineffective oil palm fruit harvesting process.



	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	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
				Quality Characteristics/Technical Requirements											
				Design							Operation				
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 48: House of Quality

The purpose of the house of quality was to determine the correlations and relationships between each customer requirement and technical requirement. Customer requirements (also known as the demanded qualities) are listed on the left side of Figure 48. 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 48. 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 48 utilizes the same numerical scale, but denotes the difficulty of the team accomplishing each of the technical requirements.

There are several values that were calculated from Figure 48. The Weighted Importance was 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 17.

Table 17: 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 17, 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 48:

Table 18: 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 12.

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

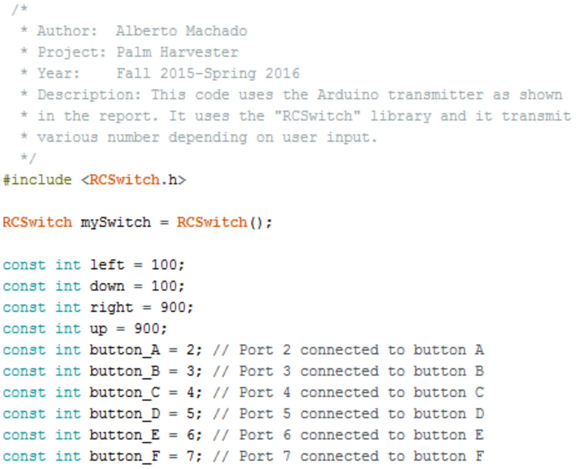
$$Relative\ Importance_{"Training\ Time"} = \frac{33.0}{1905.0} \times 100\% = 1.7\%$$

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.

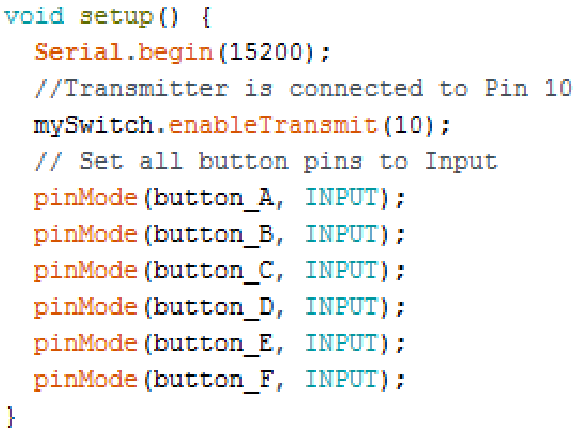
Appendix B: Final Arduino Code

This section provides the Arduino code used for each part of the prototype.

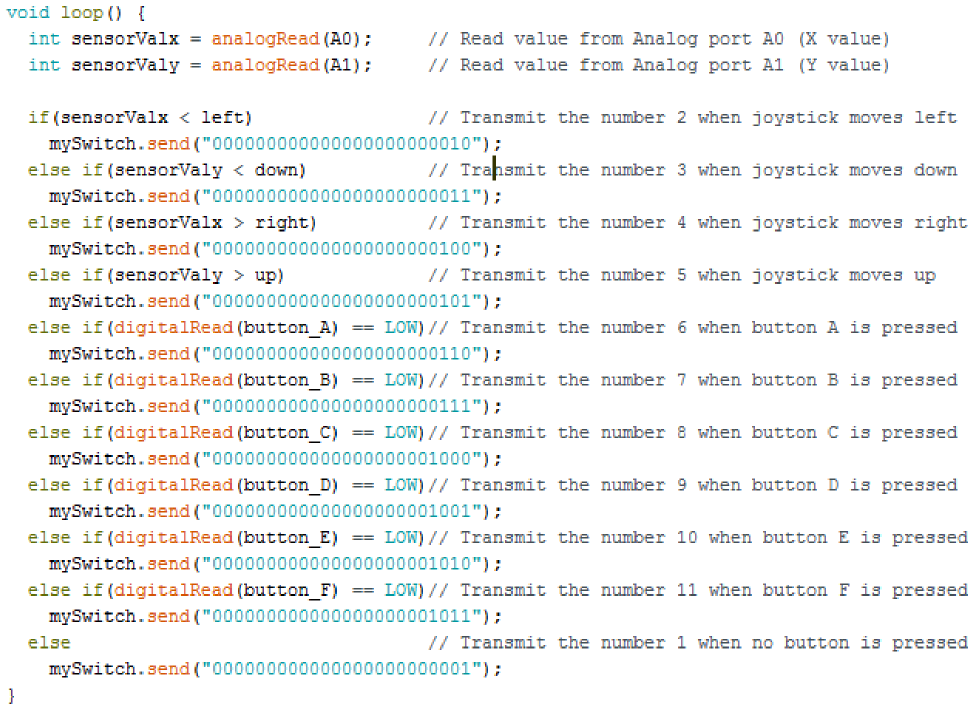
Controller:



```
 /*
  * Author:  Alberto Machado
  * Project: Palm Harvester
  * Year:    Fall 2015-Spring 2016
  * Description: This code uses the Arduino transmitter as shown
  * in the report. It uses the "RCSwitch" library and it transmit
  * various number depending on user input.
  */
#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; // Port 2 connected to button A
const int button_B = 3; // Port 3 connected to button B
const int button_C = 4; // Port 4 connected to button C
const int button_D = 5; // Port 5 connected to button D
const int button_E = 6; // Port 6 connected to button E
const int button_F = 7; // Port 7 connected to button F
```

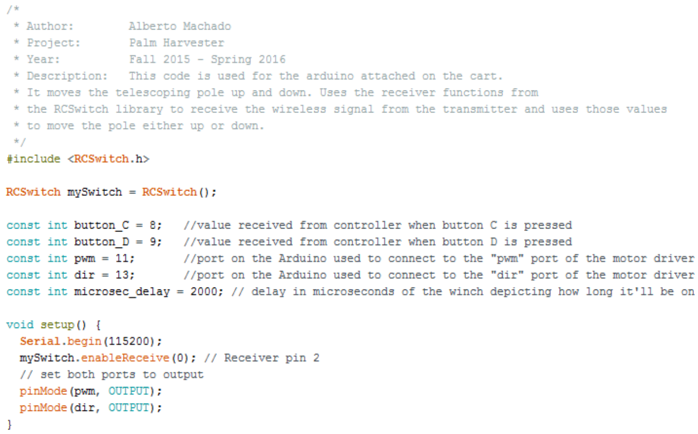


```
void setup() {
  Serial.begin(15200);
  //Transmitter is connected to Pin 10
  mySwitch.enableTransmit(10);
  // Set all button pins to Input
  pinMode(button_A, INPUT);
  pinMode(button_B, INPUT);
  pinMode(button_C, INPUT);
  pinMode(button_D, INPUT);
  pinMode(button_E, INPUT);
  pinMode(button_F,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

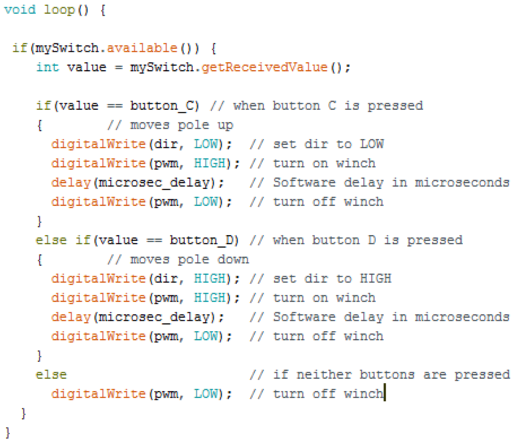


```
void loop() {
  int sensorValx = analogRead(A0);     // Read value from Analog port A0 (X value)
  int sensorValy = analogRead(A1);     // Read value from Analog port A1 (Y value)

  if(sensorValx < left)                // Transmit the number 2 when joystick moves left
    mySwitch.send("000000000000000000000010");
  else if(sensorValy < down)           // Transmit the number 3 when joystick moves down
    mySwitch.send("000000000000000000000011");
  else if(sensorValx > right)          // Transmit the number 4 when joystick moves right
    mySwitch.send("000000000000000000000100");
  else if(sensorValy > up)             // Transmit the number 5 when joystick moves up
    mySwitch.send("000000000000000000000101");
  else if(digitalRead(button_A) == LOW)// Transmit the number 6 when button A is pressed
    mySwitch.send("000000000000000000000110");
  else if(digitalRead(button_B) == LOW)// Transmit the number 7 when button B is pressed
    mySwitch.send("000000000000000000000111");
  else if(digitalRead(button_C) == LOW)// Transmit the number 8 when button C is pressed
    mySwitch.send("000000000000000000001000");
  else if(digitalRead(button_D) == LOW)// Transmit the number 9 when button D is pressed
    mySwitch.send("000000000000000000001001");
  else if(digitalRead(button_E) == LOW)// Transmit the number 10 when button E is pressed
    mySwitch.send("000000000000000000001010");
  else if(digitalRead(button_F) == LOW)// Transmit the number 11 when button F is pressed
    mySwitch.send("000000000000000000001011");
  else                                 // Transmit the number 1 when no button is pressed
    mySwitch.send("000000000000000000000001");
}
```

Cart:

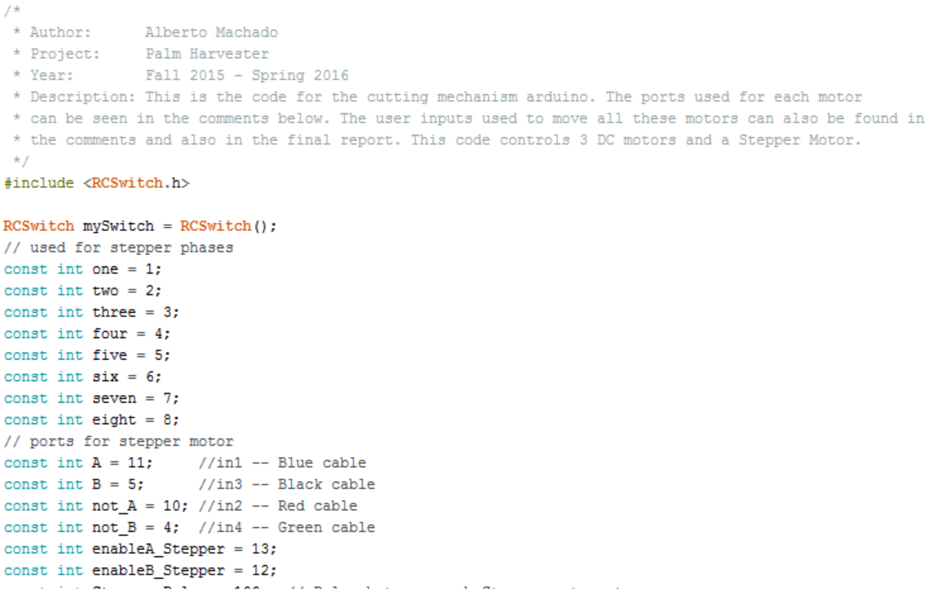


```
/*
 * Author:        Alberto Machado
 * Project:       Palm Harvester
 * Year:          Fall 2015 - Spring 2016
 * Description:   This code is used for the arduino attached on the cart.
 * It moves the telescoping pole up and down. Uses the receiver functions from
 * the RCSwitch library to receive the wireless signal from the transmitter and uses those values
 * to move the pole either up or down.
 */
#include <RCSwitch.h>

RCSwitch mySwitch = RCSwitch();

const int button_C = 8;   //value received from controller when button C is pressed
const int button_D = 9;   //value received from controller when button D is pressed
const int pwm = 11;       //port on the Arduino used to connect to the "pwm" port of the motor driver
const int dir = 13;       //port on the Arduino used to connect to the "dir" port of the motor driver
const int microsec_delay = 2000; // delay in microseconds of the winch depicting how long it'll be on

void setup() {
  Serial.begin(115200);
  mySwitch.enableReceive(0); // Receiver pin 2
  // set both ports to output
  pinMode(pwm, OUTPUT);
  pinMode(dir, OUTPUT);
}
```

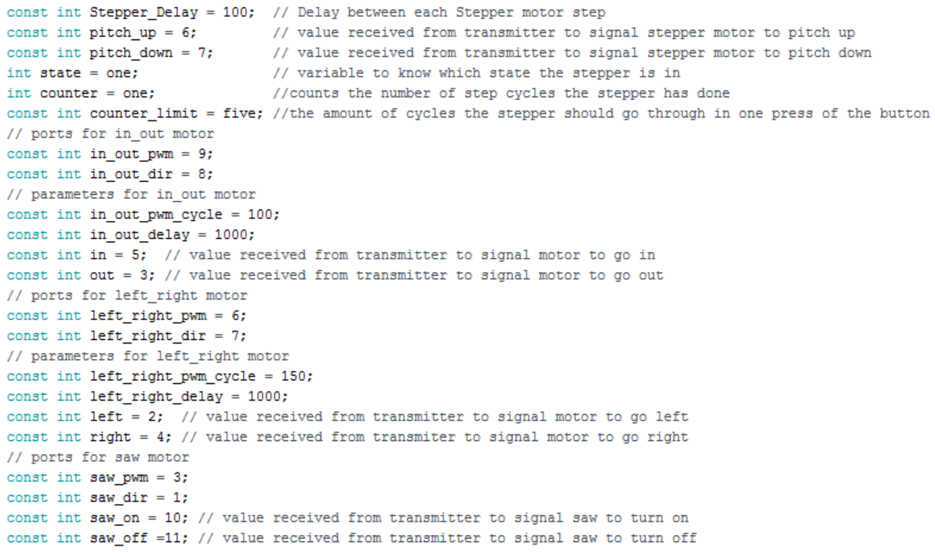


```
void loop() {

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

    if(value == button_C) // when button C is pressed
    {         // moves pole up
      digitalWrite(dir, LOW);  // set dir to LOW
      digitalWrite(pwm, HIGH); // turn on winch
      delay(microsec_delay);   // Software delay in microseconds
      digitalWrite(pwm, LOW);  // turn off winch
    }
    else if(value == button_D) // when button D is pressed
    {         // moves pole down
      digitalWrite(dir, HIGH); // set dir to HIGH
      digitalWrite(pwm, HIGH); // turn on winch
      delay(microsec_delay);   // Software delay in microseconds
      digitalWrite(pwm, LOW);  // turn off winch
    }
    else                       // if neither buttons are pressed
      digitalWrite(pwm, LOW);  // turn off winch
  }
}
```

Cutting Mechanism:

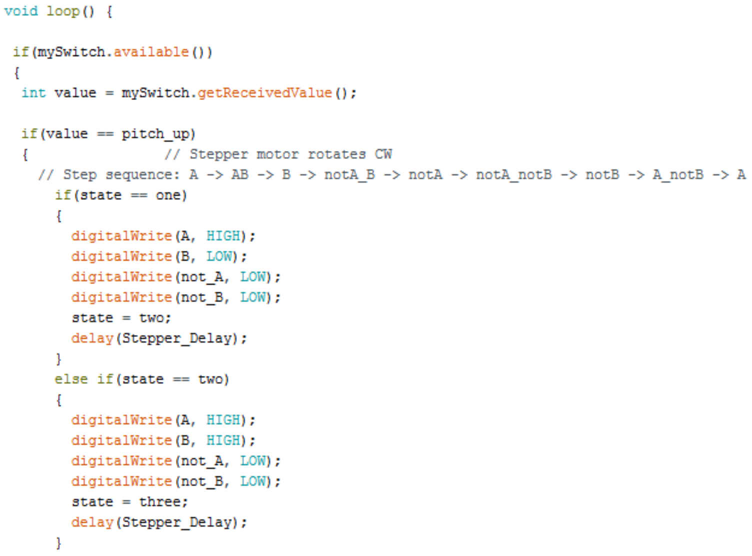


```
/*
 * Author:      Alberto Machado
 * Project:     Palm Harvester
 * Year:        Fall 2015 - Spring 2016
 * Description: This is the code for the cutting mechanism arduino. The ports used for each motor
 * can be seen in the comments below. The user inputs used to move all these motors can also be found in
 * the comments and also in the final report. This code controls 3 DC motors and a Stepper Motor.
 */
#include <RCSwitch.h>

RCSwitch mySwitch = RCSwitch();
// used for stepper phases
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;
// ports for stepper motor
const int A = 11;     //in1 -- Blue cable
const int B = 5;      //in3 -- Black cable
const int not_A = 10; //in2 -- Red cable
const int not_B = 4;  //in4 -- Green cable
const int enableA_Stepper = 13;
const int enableB_Stepper = 12;
```

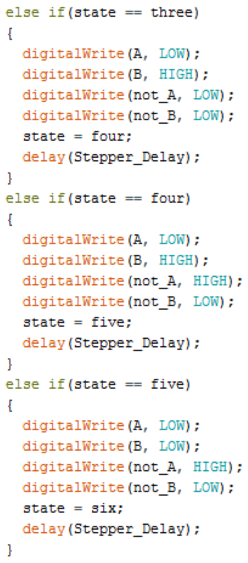


```
const int Stepper_Delay = 100;  // Delay between each Stepper motor step
const int pitch_up = 6;         // value received from transmitter to signal stepper motor to pitch up
const int pitch_down = 7;       // value received from transmitter to signal stepper motor to pitch down
int state = one;                // variable to know which state the stepper is in
int counter = one;              //counts the number of step cycles the stepper has done
const int counter_limit = five; //the amount of cycles the stepper should go through in one press of the button
// ports for in_out motor
const int in_out_pwm = 9;
const int in_out_dir = 8;
// parameters for in_out motor
const int in_out_pwm_cycle = 100;
const int in_out_delay = 1000;
const int in = 5;  // value received from transmitter to signal motor to go in
const int out = 3; // value received from transmitter to signal motor to go out
// ports for left_right motor
const int left_right_pwm = 6;
const int left_right_dir = 7;
// parameters for left_right motor
const int left_right_pwm_cycle = 150;
const int left_right_delay = 1000;
const int left = 2;  // value received from transmitter to signal motor to go left
const int right = 4; // value received from transmiter to signal motor to go right
// ports for saw motor
const int saw_pwm = 3;
const int saw_dir = 1;
const int saw_on = 10; // value received from transmitter to signal saw to turn on
const int saw_off =11; // value received from transmitter to signal saw to turn off
```

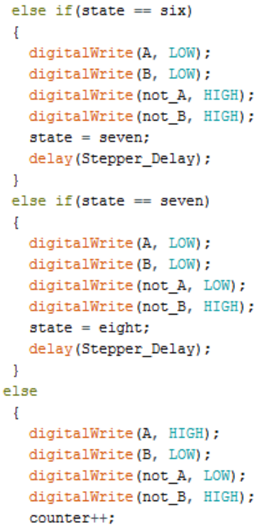
```
void setup() {
  Serial.begin(15000);
  mySwitch.enableReceive(0); // Receiver pin 2
  // Set all ports used to OUTPUT
  pinMode(A, OUTPUT); //blue cable
  pinMode(B, OUTPUT); // black cable
  pinMode(not_A, OUTPUT); //red cable
  pinMode(not_B, OUTPUT); // green cable
  pinMode(in_out_pwm, OUTPUT);
  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(enableB_Stepper, OUTPUT);
  digitalWrite(enableA_Stepper, HIGH);
  digitalWrite(enableB_Stepper, HIGH);
  // Set saw_dir to LOW since the direction doesn't matter
  digitalWrite(saw_dir, LOW);
  analogWrite(saw_pwm, 0); // Assures saw is off
  analogWrite(left_right_pwm, 0); // Assures left_right motor is off
  analogWrite(in_out_pwm, 0);     // Assures in_out motor is off
  // set Stepper to this certain state to avoid back drive
  digitalWrite(A, HIGH);
  digitalWrite(B, LOW);
  digitalWrite(not_A, LOW);
  digitalWrite(not_B, LOW);
```



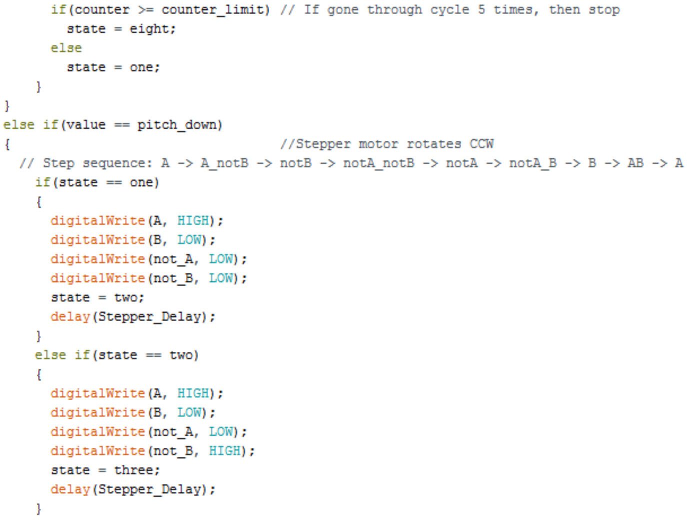
```
void loop() {

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

  if(value == pitch_up)
  {                // Stepper motor rotates CW
   // Step sequence: A -> AB -> B -> notA_B -> notA -> notA_notB -> notB -> A_notB -> A
    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);
    }
```



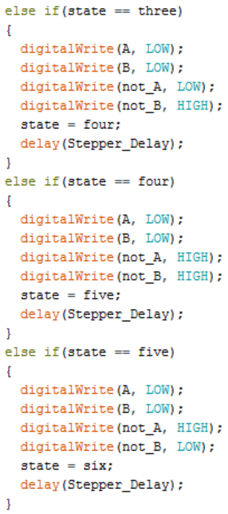
```
else if(state == three)
{
  digitalWrite(A, LOW);
  digitalWrite(B, HIGH);
  digitalWrite(not_A, LOW);
  digitalWrite(not_B, LOW);
  state = four;
  delay(Stepper_Delay);
}
else if(state == four)
{
  digitalWrite(A, LOW);
  digitalWrite(B, HIGH);
  digitalWrite(not_A, HIGH);
  digitalWrite(not_B,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



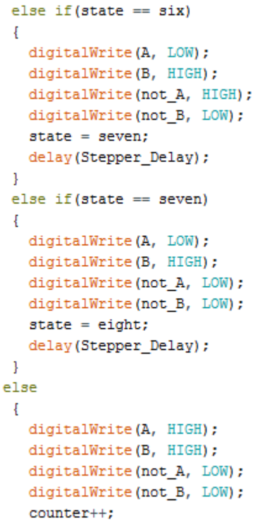
```
  else if(state == six)
  {
    digitalWrite(A, LOW);
    digitalWrite(B, LOW);
    digitalWrite(not_A, HIGH);
    digitalWrite(not_B, HIGH);
    state = seven;
    delay(Stepper_Delay);
  }
  else if(state == seven)
  {
    digitalWrite(A, LOW);
    digitalWrite(B, LOW);
    digitalWrite(not_A,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



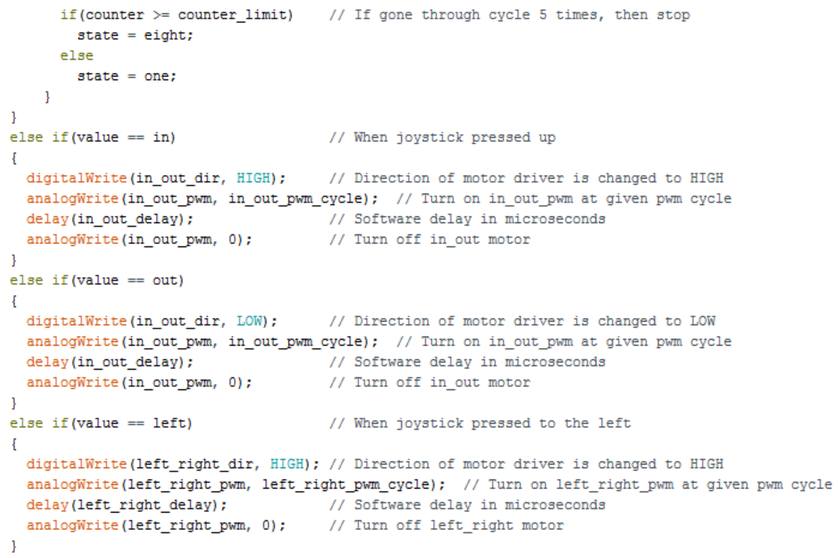
```
      if(counter >= counter_limit) // If gone through cycle 5 times, then stop
        state = eight;
      else
        state = one;
    }
}
else if(value == pitch_down)
{                                  //Stepper motor rotates CCW
  // Step sequence: A -> A_notB -> notB -> notA_notB -> notA -> notA_B -> B -> AB -> A
    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);
    }
```



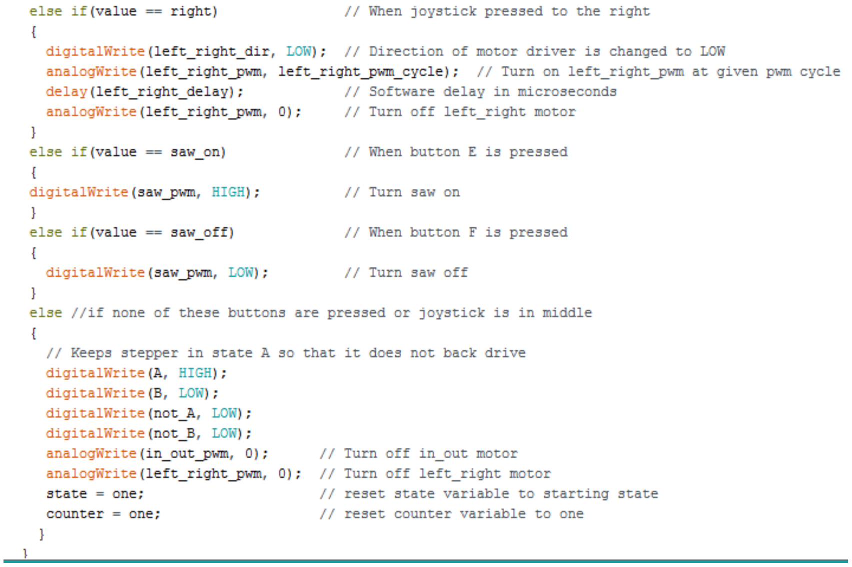
```
else if(state == three)
{
  digitalWrite(A, LOW);
  digitalWrite(B, LOW);
  digitalWrite(not_A, LOW);
  digitalWrite(not_B, HIGH);
  state = four;
  delay(Stepper_Delay);
}
else if(state == four)
{
  digitalWrite(A, LOW);
  digitalWrite(B, LOW);
  digitalWrite(not_A, HIGH);
  digitalWrite(not_B,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



```
      if(counter >= counter_limit)    // If gone through cycle 5 times, then stop
        state = eight;
      else
        state = one;
    }
}
else if(value == in)                  // When joystick pressed up
{
  digitalWrite(in_out_dir, HIGH);     // Direction of motor driver is changed to HIGH
  analogWrite(in_out_pwm, in_out_pwm_cycle);  // Turn on in_out_pwm at given pwm cycle
  delay(in_out_delay);                // Software delay in microseconds
  analogWrite(in_out_pwm, 0);         // Turn off in_out motor
}
else if(value == out)
{
  digitalWrite(in_out_dir, LOW);      // Direction of motor driver is changed to LOW
  analogWrite(in_out_pwm, in_out_pwm_cycle);  // Turn on in_out_pwm at given pwm cycle
  delay(in_out_delay);                // Software delay in microseconds
  analogWrite(in_out_pwm, 0);         // Turn off in_out motor
}
else if(value == left)                // When joystick pressed to the left
{
  digitalWrite(left_right_dir, HIGH); // Direction of motor driver is changed to HIGH
  analogWrite(left_right_pwm, left_right_pwm_cycle);  // Turn on left_right_pwm at given pwm cycle
  delay(left_right_delay);            // Software delay in microseconds
  analogWrite(left_right_pwm, 0);     // Turn off left_right motor
}
```



```
else if(value == right)               // When joystick pressed to the right
{
  digitalWrite(left_right_dir, LOW);  // Direction of motor driver is changed to LOW
  analogWrite(left_right_pwm, left_right_pwm_cycle);  // Turn on left_right_pwm at given pwm cycle
  delay(left_right_delay);            // Software delay in microseconds
  analogWrite(left_right_pwm, 0);     // Turn off left_right motor
}
else if(value == saw_on)              // When button E is pressed
{
digitalWrite(saw_pwm, HIGH);          // Turn saw on
}
else if(value == saw_off)             // When button F is pressed
{
  digitalWrite(saw_pwm, LOW);         // Turn saw off
}
else //if none of these buttons are pressed or joystick is in middle
{
  // Keeps stepper in state A so that it does not back drive
  digitalWrite(A, HIGH);
  digitalWrite(B, LOW);
  digitalWrite(not_A, LOW);
  digitalWrite(not_B, LOW);
  analogWrite(in_out_pwm, 0);       // Turn off in_out motor
  analogWrite(left_right_pwm, 0);   // Turn off left_right motor
  state = one;                      // reset state variable to starting state
  counter = one;                    // reset counter variable to one
 }
}
```