Final Report

Team 11

Autonomous Weeding Robot

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ABSTRACT

Jeff Phipps is a local land owner and entrepreneur who is in need of extra help in maintaining the weeds on his eight-acre farm. As of now, organic farming is costly due to the amount of man power needed to make up for the fact that herbicides and pesticides cannot be used. In an attempt to reduce the cost of organic farming, an autonomous weeding robot was built to monitor the fields 24/7 and take out the cost of labor. This is important because it could mean an increase in the quality of food we produce. No more will we have to sacrifice quality for quantity. Through the process of designing the weeding robot we discovered that we need a system robust enough to adapt to different farm conditions. The variation in farms will not allow for a non-adaptive system. Also there are strict constraints that have dictated the direction of the robot design. These include minimally compacting the dirt, navigating successfully through the plot, removing 60-70% of weeds overall. To complete this task our team went with a robot design that uses computer vision coupled with ultrasonic sensors to control the autonomous navigation of the robot. A basket mechanism coupled with powerful motor carries out the task of removing weeds in our design and adheres to the necessary design constraints of minimally impacting the soil and biodiversity. Upon completion of this project the feasibility of the design was clearly demonstrated. Through further optimization by other teams this weeding robot can have an impact on reducing the costs of organic farming by reducing the amount of manual labor.

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Dr. Chiang Shih: Project Mentor/Mechanical Engineering Chair

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Finally, thanks to Dr. Clark, our advisor, and Mr. Jeff Phipps, our sponsor, because this project would not have been possible without them.

1. Introduction

The idea for this Senior Design project is to design and build a method for getting rid of weeds between the rows of crops on organic farms. Research tells us the idea of integrating robotic systems onto farms to reduce the labor and human dependency is not a new one. A lot of the existing technology will help guide us in the right directions for the purpose of our design.

Organic farms do not use traditional farming techniques such as herbicides and pesticides, so this robot will eliminate the need for a human to pull weeds from the farm plots. The robot will have to navigate between the rows of crops, remove weeds, keep itself charged and running 24/7, as well as follow other design constraints as outlined in this paper. Some of the challenges associated with these desired operations is the method of which the robot will be programmed to navigate through the plot. The team is composed of four mechanical engineers and two electrical engineers, and is sponsored by the mechanical engineering department. The project is sponsored by Jeff Phipps, of the Orchard Pond Organics farm, and is advised by Dr. Clark and Dr. Li.

1.1 Need Statement

The Robotic Weed Harvester Team is sponsored by tinkerer and inventor Jeff Phipps. He owns a plot of land spanning 10,000 acres of which 8 acres is set aside for an organic farm. At present Jeff is struggling to make the organic farm viable for the remaining property. The main issue is that organic farming on such a large scale requires a large amount of manpower, that of which Jeff does not have. With the use of modern machines, herbicides, and pesticides a more traditional farm, of a much larger size could be run by a single person. The capability for Jeff to do the same with organic farming does not exist. Without the use of herbicides and tilling to control weeds they become a major issue. Jeff wants to change this by commissioning the DeepDivers (Team 11) to build him a 24/7 autonomous weeding robot to alleviate the workload synonymous with organic farming.

As the world's population increases, farmers have had to produce larger crops yields. This continual need to ramp up yield has led to a farming industry where bigger is king. With large scale farming comes more aggressive farming practices. Farmers employ tilling to control weeds, shape the soil, and create furrows to aid in irrigation. This method is extremely invasive to the soil.

Tilling destroys the biodiversity in the soil, microbes in the top layers of soils are killed along with beneficial insects such a worms. Having a large microbe biodiversity in the soil makes food such as nitrogen, carbon, oxygen, hydrogen, potassium and other trace minerals available to the plants. As microbes eat they produce waste which is in the form of plant food. The worms that are destroyed loosen the soil in a way that allows a plants roots to more easily take hold and grow toward the area where large concentrations of food lies. It also causes material in the soil to aerate and decompose faster than normal which releases carbon into the atmosphere. This an environmental issue which is at the forefront of public thought. If a no till method was adopted then farms would act more as a "carbon sink" then an annual carbon release.

The main issue with a no-till organic farm is that it require a large amount of manpower to maintain. This makes them costly to run in the market saturated by high yield farms using traditional techniques. With no till organic farms the main consumer of manpower is the weeding of fields. A solution to this is to build a low impact 24/7 weeding robot that can perform the task of weeding without human input. This would be a tool no till organic farmers can use to achieve all the benefits of this type of farming while driving prices down an enabling competition with more traditional farms.

"Organic Farms require too much manpower to run because the weeds cannot be controlled without continuous care by the farmer in the absence of tilling and herbicide."

1.2 Goal & Objectives

Goal Statement: "Design a robot capable of weeding a farm."

- Navigate an appropriate set farm plot
- Be able to properly avoid the crops on each row
- Remove weeds within the rows of crops

2. Background and Literature Review

The idea of integrating robotic systems onto farms to reduce the labor and human dependency is not a new one. This application has been researched extensively, especially in European countries like Denmark, the Netherlands and Italy. Many of these ideas are already prototyped and are being used on farmland on a day to day basis.

The majority of these prototypes require a single person to navigate through the crops and "typically use cameras or infrared sensors to spot the weeds, which they can differentiate from vegetables by using pattern recognition.[1]" The Steketee Machine Factory has developed an automatic hoeing machine that affects ten rows of crops at a time. While this does not remove the weeds, it does agitate the surface of the soil in preparation for planting and allows a consistent and uniform approach to farming. The Steketee IC Automatic Hoeing Machine is pictured below on the left.

One example of a working prototype that hits very close to home comes from a Danish engineering company, F. Poulsen Engineering. They focus directly on creating robots for use on organic and conventional farming that "provides efficient and economical weed control without the use of herbicides"[2]. This machine primarily focuses on cultivating and can affect at most, thirty six rows of crops at one time. It is capable of operating 24/7 and also uses infrared sensors to maintain position between the crops. Currently, the robot is not autonomous but work is continually being done to enable the machine to run on autopilot.

Figure 1. The Steketee IC Automatic Hoeing Machine[1]

Figure 2. ROBOVATOR from F. Poulsen Engineering[2]

There are a few noticeable differences between the prototypes previously mentioned and the focus of our project. These examples do not include complete autonomous motion, one of the main objectives we hope to accomplish. The ROBOVATOR from F. Paulsen Engineering is close to success in autonomous motion but in the majority of the testing, the machine does not always maintain linear motion down the rows of crops. This is a huge issue, especially with such large, damaging equipment. This is something we hope to stay away from in our own design. An additional discrepancy seen between the existing technology and what we hope to accomplish is a robot that has very minimal ground pressure. In the previous examples the machines are able to affect a larger amount of rows at once but largely affects the ground pressure and the soil at the far end of the machine where there is contact with the wheels.

Figure 3. Hortibot in action

According to an article in the Ludington Daily News, Michigan, "Danish agricultural engineers have built a robot to help farmers with weeds. The Hortibot is about 3-foot-by-3-foot, is self-propelled, and uses global positioning system (GPS). It can recognize 25 different kinds of weeds and eliminate them by using its weed-removing attachments. It's also very environmentally friendly because it can reduce herbicide usage by 75 percent. But so far, it's only a prototype and the Danish engineers need to find a manufacturer for distribution.[3]" Hortibot is an excellent example of what we wish to accomplish in our design and is pictured to the left.

There are many similar commercial style "farm robots" similar to our autonomous weeding robot already out on the market. One such robot was developed by inventor Christophe Millot and is capable of pruning and de-suckering grapes in vineyards while also removing unproductive young shoots and collecting data on the heath of the soil and vine stocks. The robot is called Wall-Ye and 'draws on tracking technology, artificial intelligence and mapping to move from vine to vine, recognize plant features, capture and record data, memorize each vine, synchronize six cameras and guide its arms to wield tools'[4]. The similarities between this vineyard robot and our weeding robot is that they both use a vision system for navigation. However, the vineyard robot uses a more advanced collaboration with a GPS to navigate through the vineyard. Also, both robots use a mechanical mechanism to remove an element from a plot of land. Again, the vineyard robot is more advanced in its determination of removal as it uses artificial intelligence to assess the plants of which it interacts with. The estimated cost of Wall-Ye will be about $32,000.

There is also a robot called the Lettuce Bot, a semi-autonomous weeding robot designed by Blue River Technology that is capable of 'using one set of algorithms to determine whether or not it is seeing a plant, another set of algorithms to determine if the plant is a weed or not (to about 98 or 99 percent accuracy) and a third set of algorithms to determine when the correct moment is to inject the deadly dose of fertilizer on the weed'[5] The difference with this robot is that it is not designed for organic farms where there is no use of chemicals and it requires the help of a farmer to control part of the navigation throughout the farm. The cost of Lettuce Bot has not yet been revealed, however it is likely it will be competitive with the cost of manual labor. On a 7-acre farm like Orchard Pond Organics, assuming a wage of $15.00/hour, the price of Lettuce Bot could be anywhere between $25,000 - $28,000 assuming there is work to be done on the farm 5 days out of the week.

There is a significant amount of literature published on the potential applications and development of cooperative robots for sustainable broad-acre agriculture. Most of this literature aims to redefine the methods of agriculture and guide people in thinking of broader and more efficient ways to maintain sustainable agriculture. There has also been numerous proceedings on the topic of field robots. In 2007, the Wageningen University Farm Technology Group from the Netherlands hosted a prototype competition on field robots. The competition involved the prototyped robots competing with each other in Olympic-style competition in rough terrain. With a total of 8 competing robots, each one was capable of robust and advanced navigation, weed control, load-sensitive engine regulation, and spray control and suspension stabilizers, to name a few[6]. Another proceeding worth mention took place in Pisa, Italy in 2012. The Robotics and Associated High-

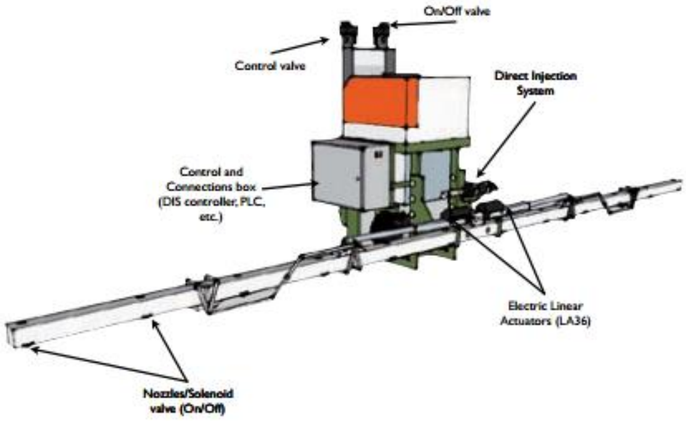


Figure 4. Prototype weed control system from RHEA Proceeding

Technologies and Equipment for Agriculture (RHEA) hosted this event to focus on ‘Applications of automated systems and robotics for crop protection in sustainable precision agriculture’[7]. The proceedings main goal was to join experienced researchers to develop ways in which the use of ‘agricultural and forestry chemical inputs are diminished’. They aim to ‘improve crop quality, health and safety for humans, and reduce production costs by means of sustainable crop management using a fleet of heterogeneous robots-ground and aerial-equipped with advanced perception systems, enhanced end-effectors and improved decision control algorithms’.[8] One of the prototypes presented at this proceeding is pictured below. These are only a few examples of the literature that already exists for this exciting new advancement in agriculture.

It can be noted that some of the existing technology, excluding Hortibot, does not completely focus on weed removal but instead on the cultivation and soil preparation aspects of farming. One of the gaps in this technology we would like to fill and improve upon would be the actual weed removal. Instead of merely sifting the top layer of soil we want to focus on affecting and removing the actual root of the weed.

A tool that was developed to make manual labor easier is the Ergonica Weed Twister. “The Ergonica Weed Twister was designed to more efficiently penetrate the soil with a minimum of soil disturbance and extract both new seedlings and deep roots of various shapes and sizes more precisely and efficiently than other hand tools and weeders[9]." The device is pictured to the right and shows the way in which the root of the weed is directly affected. This is something we would like to integrate in to our design that would be an improvement in comparison to existing designs in which the actual weed removal aspect was not completely satisfied.

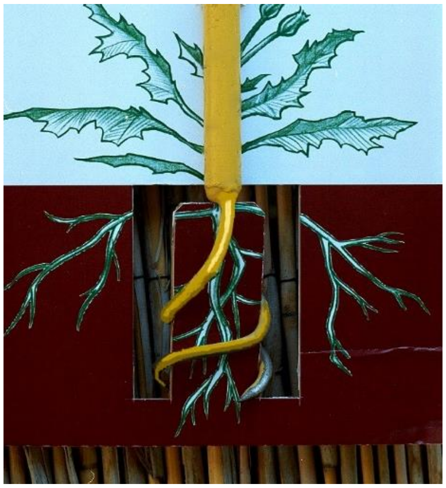


Figure 5. Ergonica Weed Twister

It is imperative that a new technology be developed to assist in this large-scale production of food to balance the ever-increasing population. As with any push in new advancements or technology, not everyone is going to support it or believe it will actually improve mankind. We experienced some of this opposition directly when speaking with the master farmhand at Orchard Pond Organics. The master farmer expressed his concern that with the integration of robots on the farm, people would feel less and less inclined to educate themselves on how to correctly harvest and maintain a farm. He believes it will put many people like himself out of work and result in an ignorant and uneducated group of people relying on technology to feed themselves.

3. Concept Generation

3.1 Mechanical Design Concepts

3.1.1 Teeth

The teeth concept works by having a layered set of teeth, as seen in Figure 6, that will vibrate back in forth which will lead to the cutting the weed or pulling the weed from the ground. One concept with the teeth is to have the material made out of a metal such as aluminum and for the ends of the teeth to be somewhat sharp. This idea is basically the same concept of how a hedge trimmer works. Another idea is to have teeth that are dull and made of rubber that translate slowly in one direction. This in theory would allow for the teeth to trap the weed and pull it out of the ground.

The material that would be used for the teeth would be some sort of an aluminum alloy because the material needs to be strong enough to cut the root system and be able to perform under to top layer of soil. Aluminum is a common material and will be easy to cut and shape. The edges of the teeth will need to be sharpened to a high enough degree that would allow for the aluminum to cut through the weed by just having the two layers translating back and forth.

Some manufacturing considerations are the teeth will not be allowed to go under more than one inch of soil so this will need to be taken into consideration when designing this concept. The size of the teeth will depend on the size of the robot because the teeth will span the entire width of the robot. Another aspect that needs to be taken into account is that another motor will be needed to drive the teeth back and forth.

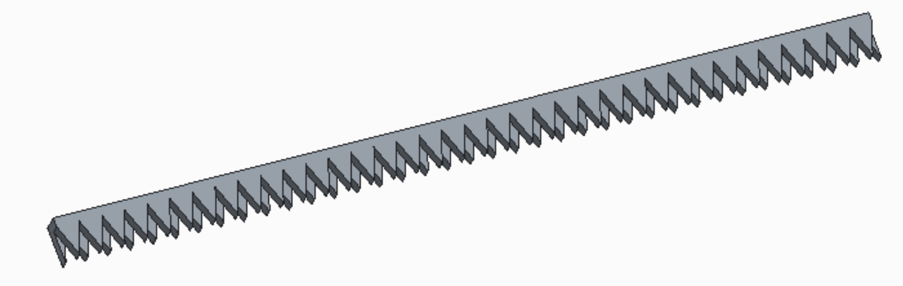


Figure 6. Weed Removing Teeth Design Concept

Some advantages of using this idea is that the design would be cost efficient and easy to design. Aluminum is not a very expensive material and the concept of the design is an easy one to grasp if you consider how a hedge trimmer works. Also the process of cutting the weeds would be fast considering the robot only has to drive in a straight line and the teeth will affect everything in its path and is not dependent of the speed of the robot. The teeth will be fairly reliable if they are strictly going through soil and weeds. However if the teeth encounter something hard such as a rock the aluminum will probably be affected by the contact with the rock. One major disadvantage with this design is that it might destroy the root system. Due to the fact that the robot can only disturb the top inch of soil the teeth might just cut the weed instead of pulling the root system out of the ground and destroying the weed completely.

3.1.2Revolving Doors

The revolving door concept is shown in Figure 7 The idea is to have the blades work essentially like a revolving door that is constantly spinning. The front blades will push the weed toward to wall where the weed will get trapped between the wall and the blade. Once the weed is trapped the blades keep spinning which will cause the root to be pulled out of the ground and will released out of the backside. For this design concept multiple “doors” will be needed so it can cover the full width of the robot. This is due to the fact that the blades will need to be close enough together to capture the larger and smaller weeds.

The frame and shaft will be made out of some aluminum alloy so that they are strong enough to support the spinning blades but also light enough so that it won't weigh down the entire robot. The weight of the robot is of importance because our sponsor does not want the soil to be compacted more than 3/8th of an inch. The blades would also be mad of an aluminum alloy but the ends of the blades will have rubber flaps. These rubber flaps will come into contact with the inner part of the frame which will trap the weed and lead to pulling it out completely.

Manufacturing components that need to be taken into consideration is the fact that you will need multiple revolving doors. The idea behind this is that the blades need to be small enough and close enough together that they can trap the smaller weeds as well as the larger ones. If the blades are too far apart the weed will not go all the way to the wall and will not be pulled. Also a motor will be needed to drive the individual shafts which will in turn spin the blades and run the weeding mechanism.

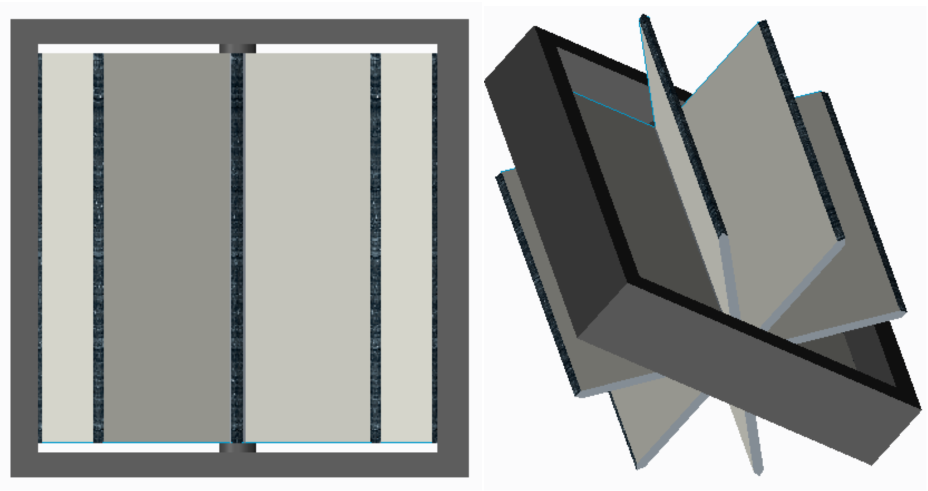


Figure 7. Weed Removing Revolving Door Design Concept

3.1.3Helix

The helix concept is an idea that comes from a turning an auger that is normal vertical, to a horizontal orientation. In this way the helix can shift the dirt that in comes in contact with by a specific amount thereby displacing the weeds. This could move the entire root system away from its nutrients and potentially force the roots to the surface where they will do no good. This apparatus will be placed on the back of the robot so that the displaced dirt and weeds do not affect the path of the robot.

The helix concept will have to be made from a metal with high yield strength such as steel. This is because it will have to go through countless cycles of rotation and be able to withstand large torsional forces brought about by its rotation and the resistance from the dirt and weed that it is trying to displace. The helix itself will have a shaft and bearing on both ends to attach to the robot. This shaft will either be driven by its own motor or it will be driven by the same motor that drives the robot but will be geared to a different speed depending on the needed displacement of the dirt.

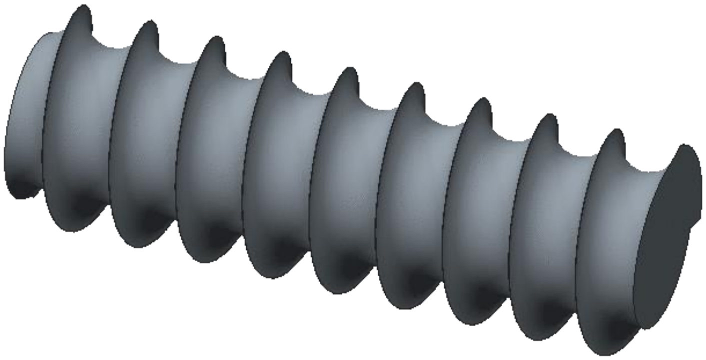


Figure 8. Weed Removing Helix Design Concept

The length of the helix will roughly be the same width of the robot minus what is necessary on both ends to drive the helix shaft. The diameter from the center of the helix to the edge of the blade will be smaller half of the height of the robot from the ground up. This is just to keep the bulk of the helix down. The shaft will have to be driven at a different speed than the robot or there will be no displacement of dirt. The precise speed will be determined when we determine the speed that the robot will go and further prototyping.

If helix blades where to be bought on line it could cost from one to three hundred dollars. Machining them might cost less because our sponsor says that he knows someone who could do it for us. But the price for that is still unknown. If since there are companies that make helix blades it could be possible to reproduce the idea on a larger scale with only minor changes to already existing auger designs such as how they are mounted and driven. The helix itself will remain almost the same.

3.1.4Basket

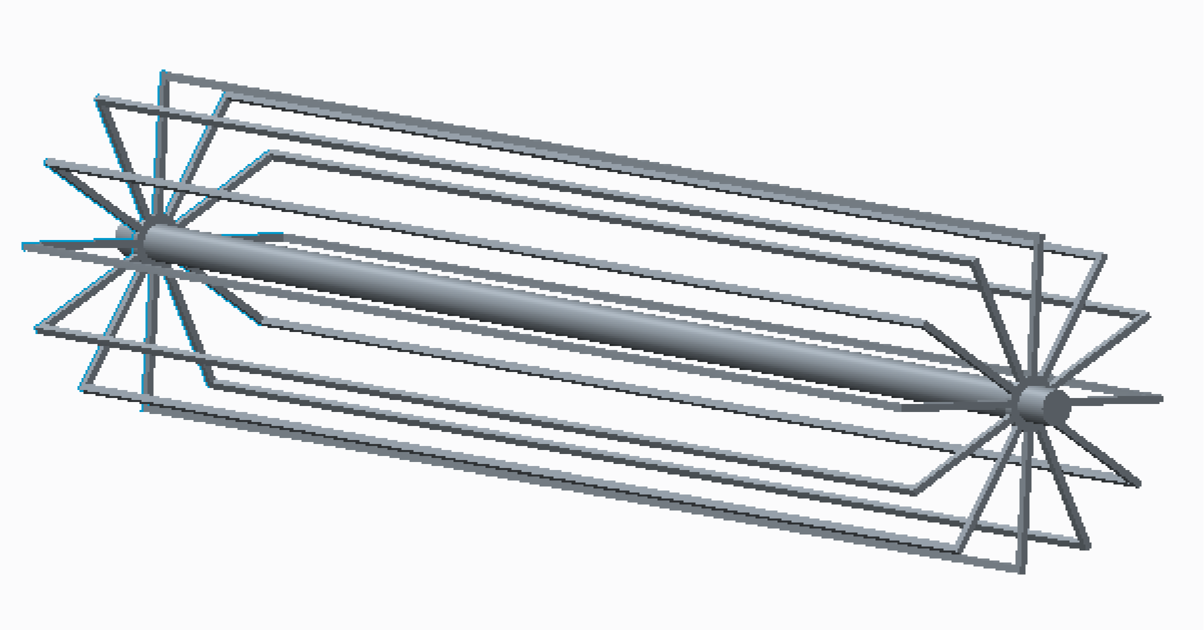


Figure 9. Weed Removing Basket Design Concept

The basket weeding design looks like a cylindrical cage that rotates on the horizontal axis. This basket sits with the edges of the basket digging almost an inch into the ground. The basket will either be driven by a motor, geared to run off of the same motor that runs the robot, or there will be a basket that is rotated by the soil and one that is geared from the first basket to move at a different speed. Regardless off the option that is chosen the main weeding basket will be moving at a different speed than the robot. This will allow the basket to sweep roots out from under the plant thereby removing the weed from its nutrients.

The outside frame will be made an aluminum alloy. The reason for this is that the design has to be light, with only a small impact to the soil. There will be a support shaft that extends through the axis with enough room on both ends for bearings and a driving mechanism that will control the speed of the shaft.

The length of the basket will almost be the same width of the robot minus what is necessary on both ends to drive the basket shaft. The diameter from the center of the basket to the edge will be smaller half of the height of the robot from the ground up. This is just to keep the bulk of the basket down. The shaft will have to be driven at a faster speed than the robot so that the bars of the basket have time to sweep under the root system of the weeds.

Although there are similar designs already in existence, it will be difficult to get them in the size and scale that we are looking for. It may be possible to alter a basket idea that is already in existence, but this will take a deeper look into the current basket designs. Because of this they may have to be machined which will usually cost more time and money. The upside is that the basket requires only a small amount of metal to be able to machine it due to the thinness of each of its parts. Because of the small amount of metal and the simplicity of the design this would not be hard to manufacture on large scale.

3.1.5Pinch Point

This design concept was inspired by John Deere’s Corn Threshing Machine. The pinch point weed removing mechanism is composed of two wheels with spokes. The outer part of the wheel has small extruded rubber ridges to further capture and pull weeds. The idea is to rotate each wheel upwards in opposite directions as to pull up anything in the midline of this wheel contact. Depending on the final design, the wheels will either be aligned along the line of motion or spin perpendicular to the line of motion

The wheels will be made from an aluminum alloy. The proper painting or anodizing procedures or will be carried out to ensure there is no corrosion on any surface. The ridges will be made from rubber in order to pull up the weeds. Chemical protection could be applied to natural rubber to alleviate these issues but these are details we will have to consider when deciding on the final material. Additionally, there must be clearance between each wheel as to minimize frictional losses. The length of this clearance will need to be determined based of factors such as dirt effects and average thickness of the weeds that will be pulled.

The compressibility of the wheels due to normal loading must be considered, assuming the robot will operate 24/7 and that the root of the weeds will apply significant force onto the wheels when being pulled up. Generally speaking, it is safe to assume that our working robot will be operating under high temperature conditions, especially because of the geographical location. With this in mind, sustained loading (creep) tests must be carried out to ensure that the normal loading conditions that will act on the robot will not damage the materials. The size of the wheels will be determined as soon as soil testing is completed and the maximum amount of weight is known.

After this, we will be able to specify how big each wheel will be to efficiently pull up weeds. If the wheels are spun too fast, the weeds will slip through the rubber ridges. If the wheels spin too slowly with not enough torque, the wheels will be backdriven and the entire system could be damaged. The optimum speed for which the wheels will spin will need to be determined through extensive prototyping and testing.

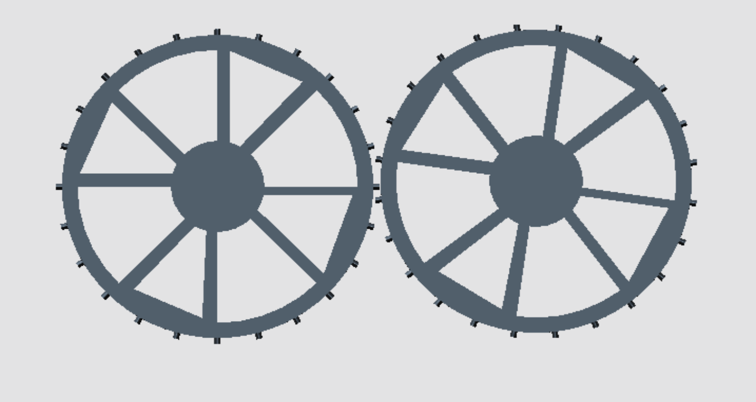


Figure 10. Pinch Point Wheel Design

This design very closely resembles tires with spokes. It is safe to assume there will not be many problems in manufacturing. Additionally, both aluminum and rubber are used on a large scale and are very common materials. Depending on the type of aluminum and rubber used, cost should not be a serious issue.

3.1.6Frame

Because the designs for locomotion, navigation and weeding methods have not been definitively chosen as of yet, it is difficult to formulate an exact design for the frame of the robot. However, keeping in mind the ideas for these designs, as well as some of the constraints on the project, some general ideas about the frame can most certainly be discussed.

One of the main components of the project is to have a low ground pressure on the plot. The weeding apparatus will likely be the heaviest component of the design, but the sensors, microcontroller, wheels and motors will also add a significant amount of weight. In order to maintain the constraint of 1 PSI of ground pressure, the components of the robot will have to be evenly spaced, as to not put too much weight on any one portion of the robot.

Additionally, in order to keep the ground pressure as low as possible, the weight of the frame will have to be light. Aluminum would be the ideal material for this. Aluminum is a light weight material that is readily available. It could be purchased in bars or plates, and is an easily workable material. Additionally, it will be durable enough to withstand the weight of the components. Also, aluminum is still reasonably strong, and it has a reasonable amount of corrosion resistance, which is important since the robot will be operating outside.

Another crucial aspect of the frame is the size with respect to the rows in the farm plot. As referenced previously, it will be important to evenly space out the components to achieve even ground pressure. In order to accomplish this, the robot should be as wide and long as it can be, without being too large. This way, the team can build along the plane of the robot, instead of upwards away from the ground. By stacking components on a smaller frame, the ground pressure will become more concentrated.

The size is also extremely important because it will determine how many the passes the robot needs to do in order to cover each row in the plot. If the robot is about ½ the width of a row (full width of row is 36 inches), it will have to make two passes in each row in order to cover the whole row. Even though this would take more time, this limitation is likely very acceptable; the sponsor has indicated the robot should sacrifice time for efficiency. However, if the robot is the length of the row, it will be able to cover the whole row in one pass. If the width were about the length of the row, the robot would be larger and would weight more.

3.2 Evaluation of Designs

3.2.1Teeth

Categories of importance to our group which will help us make our decision to what design we will use are simplicity, weeding effectiveness, speed, cost, construction, and durability. The design would be fairly simple to design however we would have to take into to consideration a motor that will drive the motion of the teeth which may complicate the design. The teeth would be effective at cutting the weeds but may not be able to destroy the root system of the weed so the weeding effectiveness is moderate. The robot could operate at higher speeds if this design were used because no matter how fast the robot is moving the teeth are still going to affect the same amount of area. This design would also be fairly cost efficient because aluminum is not an expensive material but a motor to drive the teeth would also have to be purchased. Construction of the teeth would also be fairly easy because the aluminum just needs to be cut in a patterned fashion with sharp teeth edges. Since the teeth have to operate underground they could run into something hard in the soil such as a rock causing the teeth to be susceptible to damage.

3.2.2Revolving Doors

Simplicity, weeding effectiveness, speed, cost, construction, and durability are the main categories of concern to rate our design. This is one of the harder concepts to design because all of the dimensions would have to be perfect in order to have the blade trap the weed on the wall and pull it out of the ground. In theory if the product were to work it would be effective in picking weeds because it would pull all of the weed out including the root. This design require the robot to move slowly because the door would need to go through the whole process of trapping the weed and pulling it out. This design might also be a little more expensive because there are multiple components to the design and there will be multiple doors. Also a motor will have to be bought that will drive each shaft. Construction might also be a little tricky due to the fact that there are multiple parts and the dimensions will have to be cut perfectly to size so that the apparatus will trap the weeds effectively. This system will however be very durable because it does not have to go underground so will not be affected by any hard objects in the soil. Also the apparatus will be water resistant and will not be affected by the rain.

3.2.3Helix

The important criteria that we are judging are simplicity, weeding effectiveness, speed, cost, construction, and durability. On the subject of simplicity the helix design gets high marks. The only thing this design needs to came it work is proper gearing. The down side though is that the design does not directly affect the weeds. Since the design only shifts the dirt it is possible that the weeds will remain planted in the soil. The design itself does not hinder the speed of the robot directly but the design is more driven by the speed that the robot travels. The cost on the other had could be a restricting factor. The helix design might require a higher grade metal due to the excess force placed on it by the earth. The assembly of this design after being machined should be simple because of its small number of parts. This and its sturdy materials will cause this design to have a fairly high durability even though it will have a large amount of wear.

3.2.4Basket

For this design, simplicity, weeding effectiveness, speed, cost, construction, and durability are the major criteria that are being judged. On the matter of simplicity, the basket design it probably the best. This design is self-driven and does not contain complicated motion. In addition to this the design is highly effective. Because the bars do sweep under the plant by a small margin, it is likely to pull or cut the weed from the ground. Similar to the helix design, the basket design's speed will be directly related to the speed of the robot, and will not cause much hindrance on its velocity. Because we may be able to modify something already in existence and the materials that will be used will be a cheaper metal the cost for this design should remain lower than some of the other ideas. Its construction will also be easier since we may be able to repurpose something that is already in existence. The one down side to this design is that the bars on the basket are susceptible to being bent by large force. This could compromise the effectiveness of the design but should not completely hinder its weeding capability.

3.2.5Pinch Point

Rotating wheels are not a new concept. Therefore, this concept is very simplistic in its design. Using upward motion and a capturing contact point, this design would be easy to execute. As for the weeding effectiveness, this could depend on how wide each wheel is, and if the clearance between each is sufficient enough to capture weeds but also avoid frictional losses by touching. With the speed of this mechanism, there is a lot of freedom in how fast the wheels should rotate. This now becomes dependent on the method of navigation that is chosen. The materials to make this design are easily obtainable, simple, and would be cost efficient. The construction of the wheels would also be simple, but one thing that may be difficult is ensuring the rubber ridges are securely fastened on to the outside of the wheel and will not become damaged or fall off due to the strength of the root of a weed. Additionally, all materials are waterproof, but the durability is highly dependent on the method with which the system is connected to the frame. This design is desirable because of its simplicity. Instead of using some type of advanced technology to grab the weed and pull it out of the ground, a naturally occurring material would be used that seemingly does the same thing.

3.2.6 Frame

Due to time constraints, the team had to make a decision about the frame. While it would be beneficial to build a frame from scratch, it would also take a lot of time. Building a frame from scratch would allow us to customize the design, pick motors that are fit to the situation, and ensure that the frame is robust enough to withstand the weight of all of the components. However, since the weeding mechanism is the primary interest in the project, it seemed much more desirable to devote time to the weeding mechanism, rather than the frame. Since time was an important factor in the project, the team decided that it was more beneficial to buy a frame to fit with a custom weeding mechanism.

3.3 Decision Matrix

The following evaluation was done with all concepts developed and tested throughout the semester. The evaluation is based on 3 being the best option and 1 being the worst.

Table 1a. Design Matrix for Design Concepts

Criteria	Teeth	Revolving Door	Helix	Basket	Pinch Point
Simplicity	2	2	3	3	1
Effectiveness	2	2	1	3	2
Speed	3	1	2	2	2
Cost	2	2	1	3	3
Construction	2	2	2	2	2
Durability	2	3	2	2	2
Total	13	12	11	15	12

Table 2b. Design Matrix for Design Concepts

Criteria	Purchase Frame	Build Frame
Difficulty	3	1
Customizability	2	3
Cost	2	2
Time	3	2
Total	10	8

3.4 Electrical Design Concepts

3.4.2General Area Method

During and up to the midterm presentation, the group a primary decision that would affect the rest of the development of the weeding robot: general area or find and pick weeding methods. The find and pick method involved identifying each weed in the rows and picking each one individually before moving onto the next weed. The general area method is more like a lawn mower; when it passes over an area in the row, it will ideally remove all of the weeds by agitating the dirt or physically pulling the weeds in a line at once.

For some time, this decision prevented forward progress by the group, as it was necessary to choose a method before moving on. This decision would affect all three components of the project: navigation, locomotion and weeding method. By preventing forward progress, developments in the design of the project was hindered, so it was decided that the group needed to make a decision as soon as possible.

Figure 11. Example of appropriate vision system

After some deliberation, it was decided that the general area method would be used. While the find and pick method could have potentially be successful with pulling the weeds from the plot, it was determined that it would be outside the scope of the project. This is because with the find and pick method, much effort of the group would have been spent on the identification and finding of the weeds. This necessarily would have involved computer vision and filtering. While this is possible, it could have turned out to be unreliable or inaccurate. Such computer vision has been accomplished by the CornStar project (2009 proceedings, pg 40), but this was a complicated project, and the algorithm was only able to detect bright yellow balls among carefully controlled rows. However, computer vision could be a viable method for navigation, as opposed to weed identification.

4. Final Design

The final design is shown below. For complete renderings along with exploded views, please refer to Appendix C.

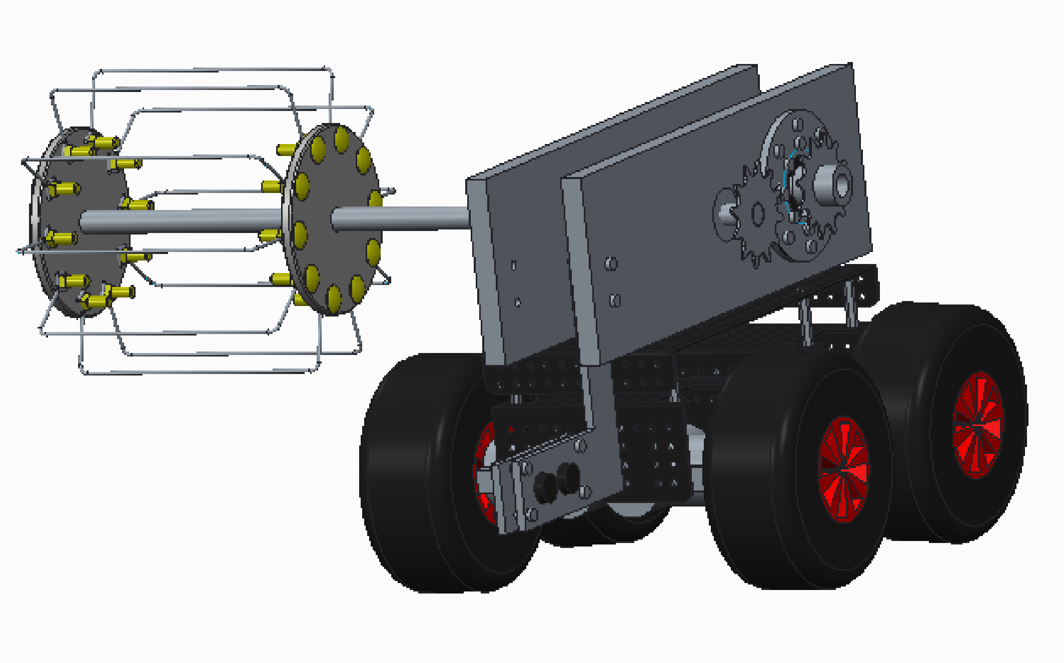


Figure 12. 3D Rendering of Final Design

4.1 Design Components

The weeding robot team assembled two prototypes before creating the final product. The first prototype was rough and made from wood. This took longer than expected, because it was not machined precisely and some of the dimensions did not match up. The second prototype also took longer than expected. Again, this was because some of the tolerances did not allow certain parts to fit and adjustments had to be made. This was also because the team had to cut the materials, rather than the machine shop.

Number of Components

- 10 x Spokes
- 20 x Carriage Bolts
- 20 x Nuts
- 1 x Shaft
- 1 x Small Sprocket
- 1 x Sprocket Motor Fitting
- 1 x Chain
- 1 x Large Motor
- 1 x Motor Plate (Coupling)
- 4 x Small Motor
- 4 x Wheels
- 12 x Phillips Head Screws
- (Electrical Components)
- 2 x Aluminum Plates
- 2 x Bearings

The design has around 80 components. About half of the components come from the carriage bolts and nuts. Ten bolts/nuts are needed for each side of the basket. It is possible that all of the nuts/bolts could have been done away with by welding the spokes straight on to the hub. However, this is undesirable because the spokes are removable with the current design. If a spoke breaks in some fashion, it is easily replaceable. If the spokes were welded, they would be much less easy to replace.

The exploded views of the robot can be seen in Appendix A. Fig. 1 is an exploded view of the basket showing how the assembly goes together. Fig. 2 shows how the ultrasonic sensor will be connected. Fig. 3 shows how the robot appears from a top down perspective. Fig. 4 shows how the motor should be assembled. Fig. 5 shows how the entire top of the robot is assembled.

4.2 FMEA Analysis

The FMEA analysis is seen in Appendix B Table 1. From the FMEA analysis, the most glaring issue that may arise would be debris getting caught in the chain/basket. This could lead to issues such as inoperability of main components. The least prevalent issue would be dirt covering the camera lens. If this occurs, then the robot will stop, and won’t cause damage to the plant beds.

4.3 Programming Flowcharts

Weeding Robot Functional Structure (Micro)

4.4 Dimensions & Tolerances

The robot itself including the frame and chassis is approximately 280 mm long, 300mm wide and stands 180 mm tall. The overall design dimensions can be seen in figure 19. One of the most important parts that connects to the robot is the aluminum plates that sit on top of the robot frame. The dimensioning of this piece allows for the basket to be set at the appropriate height to remove weeds from the bed. The aluminum piece can be seen in the appendix, figure 18.

Each aluminum plate is 10.5 in x 3.5 in (approximately 266.7mm x 88.9mm) and is ½ in thick. The back hole of the plate has a diameter of 52mm to provide clearance for the Maxon motor to be inserted. The middle hole diameter is 28.575mm which is the outside diameter of the bearing so the bearing can be press fit into the hole. This hole is made halfway up the aluminum plate so that the basket will be at the appropriate height to remove weeds from the elevated bed. The basket can be adjusted to the necessary distance away from the plate. The plate is slightly longer than the top frame of which allows for enough clearance for the ultrasonic sensor. The two holes at the front of the plate are each 5mm in diameter which allows for the L shaped ultrasonic sensor can be screwed into place. The bottom holes of the plate are all 4mm threaded holes that are screwed into the top frame of the robot.

4.5 Design Calculations

To calculate the torque required by the motor to till soil, the direct relationship between torque and current had to be incorporated. Attaching a motor to the mechanism that was used for weeding and slowly increasing the voltage to the motor until it was strong enough to till the soil. Capturing the current at that time would allow us to find the amount of torque required by the motor. Running this experiment showed us that a current of 1.16 (A) would be required. After looking up specifications from the motor and using equations 1 and 2 derived from those specifications, a torque of 2.38 Nm is required to till soil

$$Torque(with\ gear\ head) = 38.5(reqired\ current) - 12.086 \qquad \text{eq. (1)}$$

$$Torque(without\ gear\ head) = 43 * Torque(with\ gearhead) \qquad \text{eq. (2)}$$

One of our specification required by this project was to not depress the soil by 3/8th of an inch on top of the bed of plants. To determine the weight of the robot, we set the edge of a circular 10 (lb) weight onto the soil. The depth and area of the depression was used to find the Pressure at that depth. Using a ratio of the depression of the weight and the limit of the depression given by the sponsor, we found that 4psi would depress the soil 3/8th of an inch. Given that the area of the 4 wheels on the ground is about 15 in^2 the total weight of the robot could be 60 lbs. This is assuming that the robot would be on top of one of the beds which later designs proved to be not necessary.

4.6 Manufacturability, Reliability and Economics

4.6.1 Complete Mechanical Project Assembly

Tools needed

- Hex Key
- Phillips head screw driver
- Bearing press
- Wrench
- Welding tools

Assembling the frame

The Dagu Wild Thumper robot frame is the first aspect of the weeding robot that must be assembled. The frame of the robot is mostly assembled out of the box, and all that needs to be assembled is coupling the wheels to the motor. This step only requires the hex key.

Next, the aluminum plates need to be attached to the top of the robot. These will support the weeding mechanism and the motor. Since the top plate comes attached to the robot, it will need to be removed. From the bottom of this plate, align the two aluminum plates with the appropriate holes on the top plate. Insert 2 Phillips head screws into the appropriate holes on one aluminum plate, and then on the other. This top plate can be reattached to the robot.

Using a bearing press, the bearings need to be placed in the appropriate holes. There are two bearings necessary, one on each aluminum plate.

Inserting electronics/Hooking up motors

The motor that will power the basket goes through the larger of the holes on the aluminum plates. An additional circular plate is used. Using Phillips head screws, fix the circular plate to the face of the motor. Following this, again using Phillips head screws, attach the circular plate to the aluminum plate. The fitting for the motor shaft (which includes the sprocket) can be slipped over the shaft. This can be fixed at the end of the motor shaft by placing a washer at the end and fixing it with a screw into the motor shaft.

Assembling the basket

To assemble the basket part of the weeding mechanism, the metal hubs, metal spokes and carriage bolts are needed. Align the square holes on the spoke with the square holes in the hub and couple with the carriage bolt/nut. Tighten with a wrench. Do the same with the other hub.

Using welding tools, the basket should be coupled onto the end of the shaft. The shaft should then be press fit into the bearings. Following this, the sprocket should be welded (?) inches from the opposite end of the shaft. The chain can now be fit over the two sprockets, and the motor should now be able to spin the basket.

4.6.2 Complete Electrical Project Assembly

1. Purchased all needed components
    a. BeagleBone Black
    b. Logitech C310 USB 2.0 HD Webcam
    c. Dual Motor Controller Cape Mk.6
    d. PICAXE-08M2 Microcontroller
    e. SainSmart HC Range Detector
    f. Converter Adapter
    g. HDMI to Micro HDMI cord
    h. Samsung Class 6 SDHC
    i. USB Hub
    j. Polycarbonate Waterproof Case
    k. Ultrasonic Module Distance Sensor
    l. 4A Motor Shield for Arduino

   m. 5000 mAH LiPo Battery Pack
   n. LiPo Balance Charger with AC Adapter
   o. Marker Supplies
2. Attach Beaglebone Black to the two Motor Control Capes
   a. Upload all updates needed for Debian operating system
3. Connect 7.4 V regulated High output battery to BeagleBone Black 5 volt input.
4. Connect the unregulated 7.4 Volt battery to the BeagleBone Motor Control Capes.
5. Next connect the four motor control wires to the motor control capes.
6. Connect the Webcam to the BeagleBone Black via USB
7. See wiring diagram attached for connection of Ultrasonic Ranging Module to the Beaglebone Black.
8. The Arduino will run off the same regulated high output battery that the Beaglebone Black runs off. Connect this into the 5 volt input on the Arduino Uno
9. Wire the Arduino and BeagleBone Black to the same common ground, and connect pin 4 to pin 8 on the Beaglebone black.
10. Begin coding BeagleBone Black and Arduino; See Appendix A for code

This design did not take long to assemble, due to the fact that it is an electronic system. The most time consuming aspect of this design is the programming of the navigation system. The navigation system consists of the vison system which works in unison with the ultrasonic ranging module to accurately weed the field.

This design could have been simplified by utilizing the system on a chip to handle all the motors on the platform instead of using a separate Arduino UNO. The reason for this complication is the limited time till completion of the project. The motor for the weeding mechanism was added near the end when the main code had already been developed.

1. 5 Volt supply from the main rail to the BeagleBone Black. This provides power to system on a chip and all peripherals attached (Camera, Ultrasonic Ranging Module)
2. Unregulated power to the two BeagleBone Black Motor control capes.
3. Connection of the Ultrasonic ranging module to the BeagleBone Black, See Fig. 7 for detail connections.
4. Connection of Webcam to BeagleBone Black via USB
5. 5 Volt Regulator to reduce the voltage of the 7.4 volt batteries for use with the Arduino UNO and BeagleBone Black

6. Motor control connections for the four motors on the robot chassis
7. Control connections to the motor driving the weeding mechanism from the Arduino motor control shield.
8. Connection for communication between the BeagleBone Black and the Arduino Uno
9. Unregulated power to the two BeagleBone Black Motor control capes.
10. 5 Volt supply from the main rail to the Arduino UNO used to power the Arduino UNO and all GPIO pins.

See Appendix C for a pictured summary of this.

4.6.3Mechanical Design for Reliability

When used once, the weeding robot performs as expected, with only minor deviations from expected operations. In terms of durability of the parts, after one use, there are no loose parts and there is no visible wear on the robot. When used 100 times, it is possible that some of the spokes could bend or even break, and that some of the bolts/nuts could have come loose. After this many uses, it is still unlikely that the shaft would bend or the welds would come undone. When used 1000 times, is it possible that some dirt could have gotten into the motors or bearings, and it may affect the performance of the product. After this time, it is still unlikely that the shaft would bend. After 10,000 uses, the motors could likely fail after so many repeated uses and the shaft might possibly be bent. However, with regular maintenance and careful observation of the robot, it is likely that the robot could last for 10,000 uses. The reasoning for this evaluation is the quality of the components used. The shaft is quite heavy and would require much force to bend. The spokes on the basket are thinner sheet metal and are more prone to bending. The motors are high quality and shouldn’t be receptive to letting dirt into the motor. The bearings are double sealed and should also prevent dirt from entering.

The main reliability concerns for the weeding robot are the spokes on the basket. These are made of the thinnest material. It is important that these spokes are made with a light and thin material so they are more easily able to cut into the dirt of the plant bed. One answer to these concerns would be to make the parts out of a stronger material that still maintains the desired thickness. However, the method of currently addressing these concerns is to make them easily replaceable, simply by removing the bolt/nut and putting a new spoke on the basket.

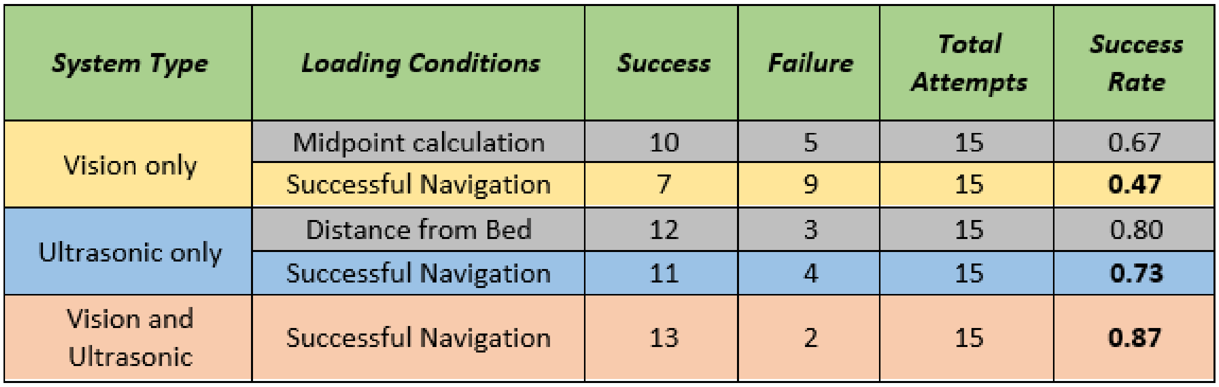
Another reliability concern comes from the environment in which the robot will operate. Since there are many metal parts used in this robot (chain, sprocket, frame, basket mechanism), there is some concern that the parts could rust. The team has attempted to address this concern by choosing materials that are much less prone to rust, namely weather/corrosion resistant aluminum. Further, the group could clear coat some of the parts to prevent water from getting to them.

4.6.4ECE Design for Reliability

The navigation system of the weeding robot is the major part of the electrical reliability for the robot. The navigation system has two main parts, vision and ultrasonic system and then the motor control for driving the robot. The main reliability concern for this project is how well the robot is able to identify its position in the row in order to drive down the furrow successfully.

The vision and ultrasonic sensors are made to work in unison in order to improve the reliability of robot navigation. The vision system on its own did not provide accurate enough data to safely drive the robot down the row. This data can be used to position the robot and identify that the robot is still driving down the row, but identifying the center of the markers was not accurate enough to drive off of individually. The visions system alone had approximately a 47% rate of success in driving the robot down the row. In order to improve the reliability of this system, an ultrasonic sensor was added to the front of the robot in order to determine its position from the side of the bed. By itself this system was able to drive the robot down the row about 73% of the time. When these two systems are combined the robot is able to drive down the row successfully at least 90% of the time. With the updated controller the robot is able to drive itself down the row over 90% of the time which is accurate enough to navigate the field. If the robot loses the balls in the row to make sure it doesn’t hit the plants it simple stops the robot. This data was gathered from a set number or trials as shown in the Table 2.

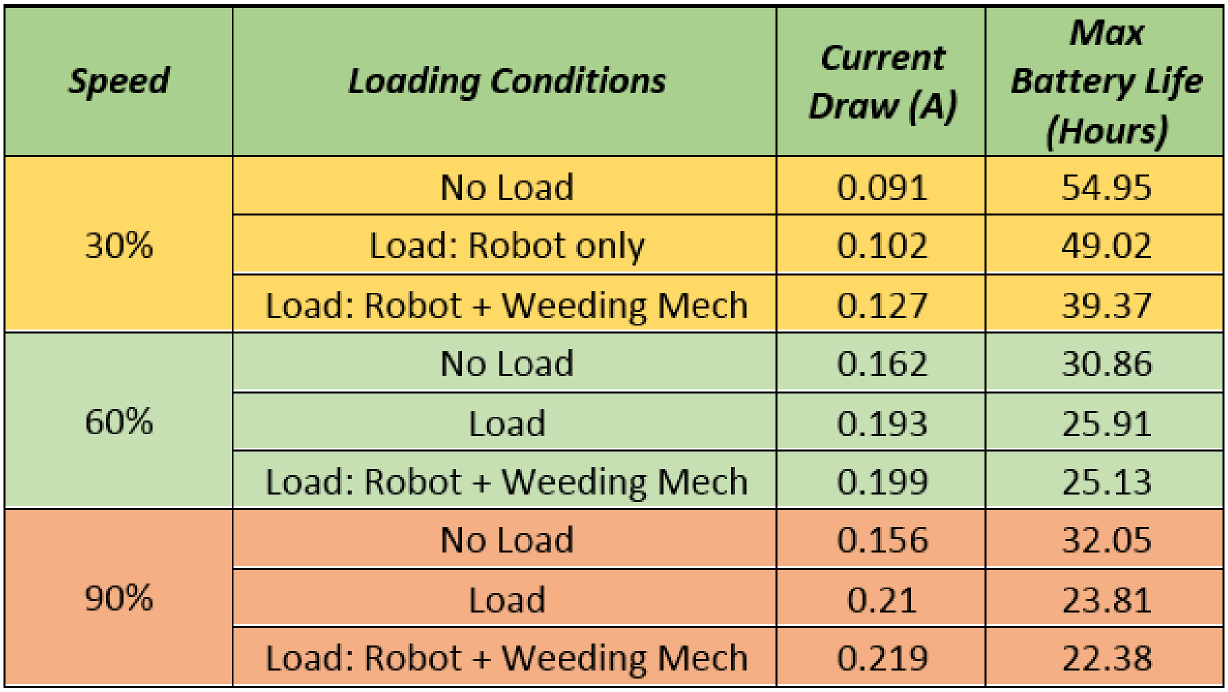
Table 3. Performance Data



System Type	Loading Conditions	Success	Failure	Total Attempts	Success Rate
Vision only	Midpoint calculation	10	5	15	0.67
	Successful Navigation	7	9	15	**0.47**
Ultrasonic only	Distance from Bed	12	3	15	0.80
	Successful Navigation	11	4	15	**0.73**
Vision and Ultrasonic	Successful Navigation	13	2	15	**0.87**

The next reliability concern is the motor control system, which is all run through the Beaglebone black. The actual control of the motor power and speed is run through a software controller, so this is not a reliability concern as long as the data it receives from the sensors is accurate. However, the scope of the project requires an operability time of the robot which exceeds a certain number of hours per day so it is able to affect as much of the plot as possible. The concern affiliated with this and the battery would supply enough power to run the robot all day. Some tests were run and it was insured that this was not a reliability concern. This can be seen in Table 3.

Table 4. Motor Power Analysis



Speed	Loading Conditions	Current Draw (A)	Max Battery Life (Hours)
30%	No Load	0.091	54.95
	Load: Robot only	0.102	49.02
	Load: Robot + Weeding Mech	0.127	39.37
60%	No Load	0.162	30.86
	Load	0.193	25.91
	Load: Robot + Weeding Mech	0.199	25.13
90%	No Load	0.156	32.05
	Load	0.21	23.81
	Load: Robot + Weeding Mech	0.219	22.38

4.7 Operations Manual

4.7.1 Operation Instructions

- Field set up

The farmer should first take the orange markers provided and place them in the middle of each bed spaced every 10 feet along the row

- Robot Orientation

Before the robot is turned on it has to be lined up in the first row. To do this the robot should be tuned so that its webcam is facing the down the row. Next the robot should be centered in the furrow. Finally the robot is placed so that the weeding mechanism is touching the first bed on its right.

- Powering on

Press the red button and watch for the led to signal that the robot is on.

- Monitoring

There should be someone watching the robot to ensure that it doesn't go off track and that it makes it to the end of the row.

- End of row

Once it is at the end of the row the robot should turn and go down the next row if it does not the user must pick it up and repeat the operation instructions starting at Robot Orientation.

- End of plot

Now that the robot has finished weeding the entire plot the user should power off the robot and charge the batteries for later use.

4.7.2 Troubleshooting

Mechanical Component Problems

Potential problems that could arise in the mechanical components during operation:

- Wheels
    - Come loose
- Chassis
    - Screw could come loose
- Basket
    - Spokes could deform
    - Could accumulate debris
    - Not rotating properly
- Chain
    - Things can get stuck
    - Can slip off gears

    - Can rust or break

Solutions if problems occur:

- Wheels
    - Make sure wheel is securely fastened to the axle
- Chassis
    - Replace with extra screws
- Basket
    - Replace spokes
    - Turn off power to motor, use a brush to clean debris from spokes
    - Check to see if
        - Power is on
        - Robot is moving
            - If not, charge batteries
            - If moving, check to see if chain is still attached, shaft is still aligned, and chain is free of debris
- Chain
    - Turn power off to motor, check chain. Remove any debris
    - Rotate sprocket with hand and align gear as it rotates
    - Buy a new chain at local hardware store with design specification

Electrical Component Problems

Potential problems that could arise in electrical components during operation:

- Navigation
    - Robot traverses over beds
    - Robot does not move
- BeagleBone
    - No lights coming from computer
- Motors
    - Two motors do not spin, signifying the battery is low or dead

Solutions if problems occur:

- Navigation
    - Check that robot is powered on. Make sure ultrasonic sensor is clear of debris. If necessary, clean with dry cloth.
    - Check that camera is clear from obstruction and ensure the orange balls are not covered. Also make sure the webcam is plugged into the USB port.
- BeagleBone
    - Charge batteries

- Motors
    - Charge batteries

4.7.3Regular Maintenance

For optimal operation, it would be best to complete a number of actions approximately once per week. An overview of the key components that should be evaluated before operation of the autonomous weeding robot are broken down into three categories.

Maintenance of Categories

A. Chassis

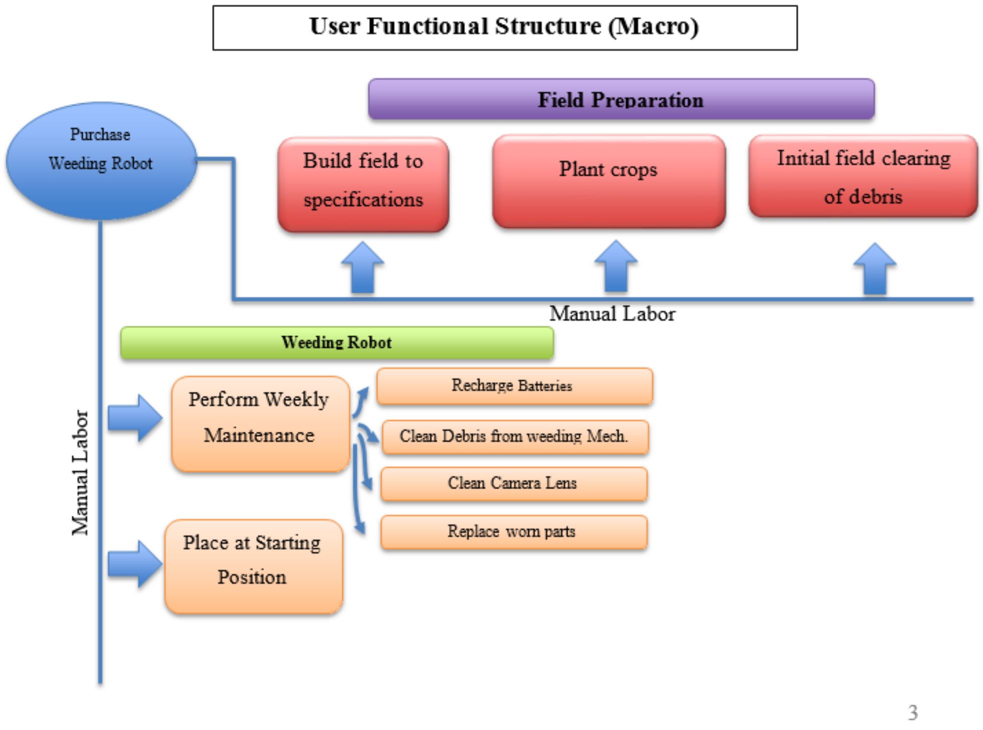
- Suspension check – Frame suspension should always be locked, make sure there is no horizontal or vertical movement.
- Aluminum support – Make sure support is still securely attached to the frame.

B. Basket Weeding Mechanism

- Spokes – Check for any bending or shearing that may have occurred during previous operation.
- Coupling – Check to make sure the bolts are all tightened to ensure the spokes are fastened completely.

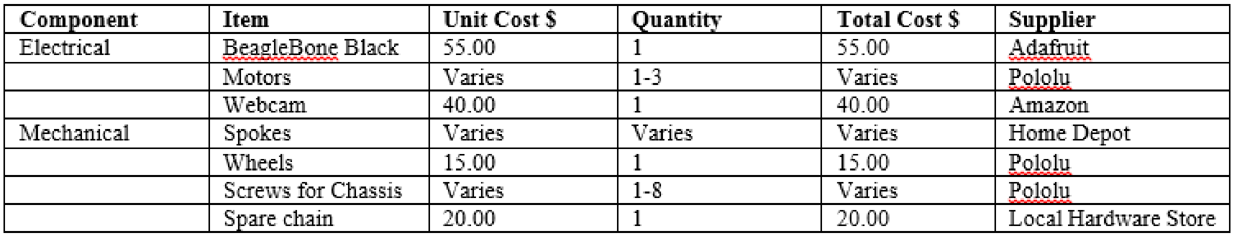
C. Electrical Components

- Battery – Routine battery charging weekly.
- Webcam – Check to make sure there is no damage to the face and ensure there is no debris.
- Motors – Make sure they are still rotating with the correct speed and efficiency.



4.7.4Key Component Replacement

The rugged terrain and environment of which the robot will be operating in makes it evident that parts will often need replacement as it is likely the parts will become worm from the weather and other outside conditions. The key components that might need replacement over others would be the basket weeding mechanism. This part will experience the most wear and the most degradation from the soil. We have made this part very modular by making the connections simple and the material easily attainable. The consumer can have the option of making the spokes larger smaller, depending on their desired application.



Component	Item	Unit Cost $	Quantity	Total Cost $	Supplier
Electrical	BeagleBone Black	55.00	1	55.00	Adafruit
	Motors	Varies	1-3	Varies	Pololu
	Webcam	40.00	1	40.00	Amazon
Mechanical	Spokes	Varies	Varies	Varies	Home Depot
	Wheels	15.00	1	15.00	Pololu
	Screws for Chassis	Varies	1-8	Varies	Pololu
	Spare chain	20.00	1	20.00	Local Hardware Store

Figure 13. Spare Parts Inventory

5. Design of Experiment

Experiments were primarily conducted in order to test the weeding apparatus. With the first prototype, the team tested the action of the weeding baskets in sand, in order to give a proof of concept. This was done in order to see that the mechanism worked, but it was done in sand because the materials it was constructed from were not final. The results showed that the weeding baskets turned as expected. Next, the team tested the second prototype, which was a two basket system. This was tested on a plant bed, much like the ones at the organic farm. The robot was driven along the side of the plant bed, so that the first basket would turn the second basket faster, weeding the bed. It was originally expected that this method would work correctly, allowing the baskets to spin smoothly. However, the actual outcome of this did not match with the expected results. The basket was not able to spin smoothly, and instead, it dragged through the dirt, not producing the expected turning motion.

For the electrical systems experiments were created to optimize the navigation system. For the computer vision a proper threshold must be used to clearly filter out the orange markers used in the field. It was necessary to experiment in many different lighting conditions in order to ensure that the vision system is usable in all lighting scenarios encountered outside. This was done by designing a small scale farm row outside, and then running the robot through at different times of the day. By doing this we were able to accurately measure the vision systems reaction to the different lighting and then rework our thresh holding to account for these conditions. Next more testing in the small scale plot was done to optimize the ultrasonic ranging module in unison with the vision system to provide smooth navigation through the field. The results of the testing showed that the vision system was not enough for smooth navigation. Although the vision system could maintain the correct bearing of the robot, it had no ability to maintain a close offset to the beds for effective weeding. To solve this the ranging module was added to provide needed data about the wheel distance from the beds. Upon completion of testing it was decided that both system must work together to effectively weed and safely avoid damaging the farmer’s crops.

6. Consideration for Environment, Safety, and Ethics

A large portion of the design of our robot revolves around adhering to the fact that it is an organic farm where the agriculture is not chemically treated. With this in mind, the design of an autonomous weeding robot was more difficult. One of the main considerations Mr. Phipps asked us to keep in mind was the impact of which our design would affect the soil of the crops. Organic farming aims to keep the rich biodiversity of the soil and with this it is crucial that the soil is minimally compressed. This leads to a richer, fuller crop as the soil has room to breathe.

Our design addresses this concern and uses a method in which the majority of the weight of the design is kept in between the beds where the soil compression is not an issue. The basket rotates along the top half inch of the soil to remove the weeds and keep the soil aerated and loose.

The navigation method for our design uses minimally evasive markers that only require a small portion of the soil to place firmly in the dirt. The navigation system is designed so there only needs to be a marker every 3-4 feet which is designed to minimally affect the health of the crops that are growing along the centerline of the bed where the markers are placed.

7. Project Management

7.1 Schedule

Throughout both fall and spring semester, the design and implementations of our project fell under three phases; Navigation, Weeding Mechanism and Locomotion. A Gantt Chart was used to organize these phases of the design. The team took a very conservative estimate for how long it would take things to get machines and shipped. The Gantt Chart was valuable in keeping our focus on the bigger picture of the project and giving us an idea of exactly how much time remained in getting certain tasks completed. Throughout the semester we had unforeseen circumstances and we did our best to follow the scheduling of our Gantt Chart. Therefore it was subsequently updated throughout the semester to maintain its accuracy. The Gantt Chart can be found in Appendix D.

7.2 Resources

The FAMU-FSU College of Engineering had many resources for the team to use. One resource that was particularly helpful was the FAMU-FSU College of Engineering Machine Shop for manufacturing purposes. The machine shop has a lathe, drill press, laser cutter and other very useful tools for the assembly of our design. Additionally, if there was ever an issue in getting our parts machined here, the Stride Lab at the Aeropropulsion, Mechatronics and Energy building was another great resource the team used for parts. The team also used a few computer programs for various aspects of the project. The entire design was modeled using the program Creo Parametric and the sprockets were designed using a program called OMAX.

7.3 Procurement

Mr. Phipps provided a total budget of $3000 for the completion of the autonomous weeding robot. The entire product as is it currently developed costs a total of $2,005.00. The electrical components cost a total of $636.00 while the mechanical components cost a total of $1,346.00. Overall, there is 33% of the budget remaining. It is our hope that in the future, additional components will be designed to add onto the robot to complete additional tasks on the farm. It is likely with all of the added features we would have liked to incorporate into the design, our finished product might cost anywhere from $4,000 - $6,000.

With the time constraints of senior design the budget provided to us was enough. This is even with a few crucial backup parts. It is likely that with more time and resources, the total budget would have been used up to account for the additional features like designing the basket mechanism to allow for an adjustable height on the frame as well as designing a custom built frame.

The budget was handled professionally with the majority of the purchase order requests going directly through the Mechanical Engineering Purchasing Department. Other purchases made through team members personally were necessity-based only, in that the parts were purchased because they were needed for testing that day. Additionally, any large purchases made were first discussed with the entire team and one of the advisors, if it seemed necessary.

Table 5. Complete Bill of Materials

Component	Item	Unit Cost	Quantity	Total Cost	Supplier
Electrical	BeagleBone Black	55.00	3	165.00	Adafruit
	Logitech C310 USB 2.0 HD Webcam	40.46	1	40.46	Amazon
	Dual Motor Controller Cape Mk.6	68.00	2	136.00	Exadlers Technologies
	PICAXE-08M2 Microcontroller	15.67	1	15.67	PICAXE
	SainSmart HC Range Detector	8.42	1	8.42	Amazon
	Converter Adapter	6.08	1	6.08	Amazon
	HDMI to Mictro HDMI cord	3.99	1	3.99	Amazon
	Samsung Class 6 SDHC	6.99	1	6.99	Amazon
	USB Hub	6.99	1	6.99	Amazon
	Polycarbonate Waterproof Case	24.47	1	24.47	Plano Storage Solutions
	Ultrasonic Module Distance Sensor	8.99	1	8.99	Amazon
	4A Motor Shield for Arduino	38.50	1	38.50	NKC Electronics
	5000 mAH LiPo Battery Pack	43.00	2	86.00	Hobby Partz
	LiPo Balance Charger with AC Adapter	48.50	1	48.50	Hobby Partz
	Marker Supplies	40.00	1	40.00	Michaels
Component	Item	Unit Cost	Quantity	Total Cost	Supplier
Mechanical	Corrosion-Resistance 5052 Aluminum	48.77	1	48.77	McMaster Carr
	Steel Ball Bearing	10.25	4	41.00	McMaster Carr
	Wood (Basket)	15.00	1	15.00	Home Depot
	Wood	50.00	1	50.00	Home Depot
	4 WD All-Terrain Chassis	174.95	1	174.95	Pololu
	Shaft	15.00	1	15.00	Tractor Supply
	Nuts	0.35	20	7	Home Depot
	Bolts	0.75	16	12	Home Depot
	Sheet Metal	5.00	1	5.00	Home Depot
	Motor	1,000.00	1	1,000.00	Maxon
				TOTAL	**2,005.00**

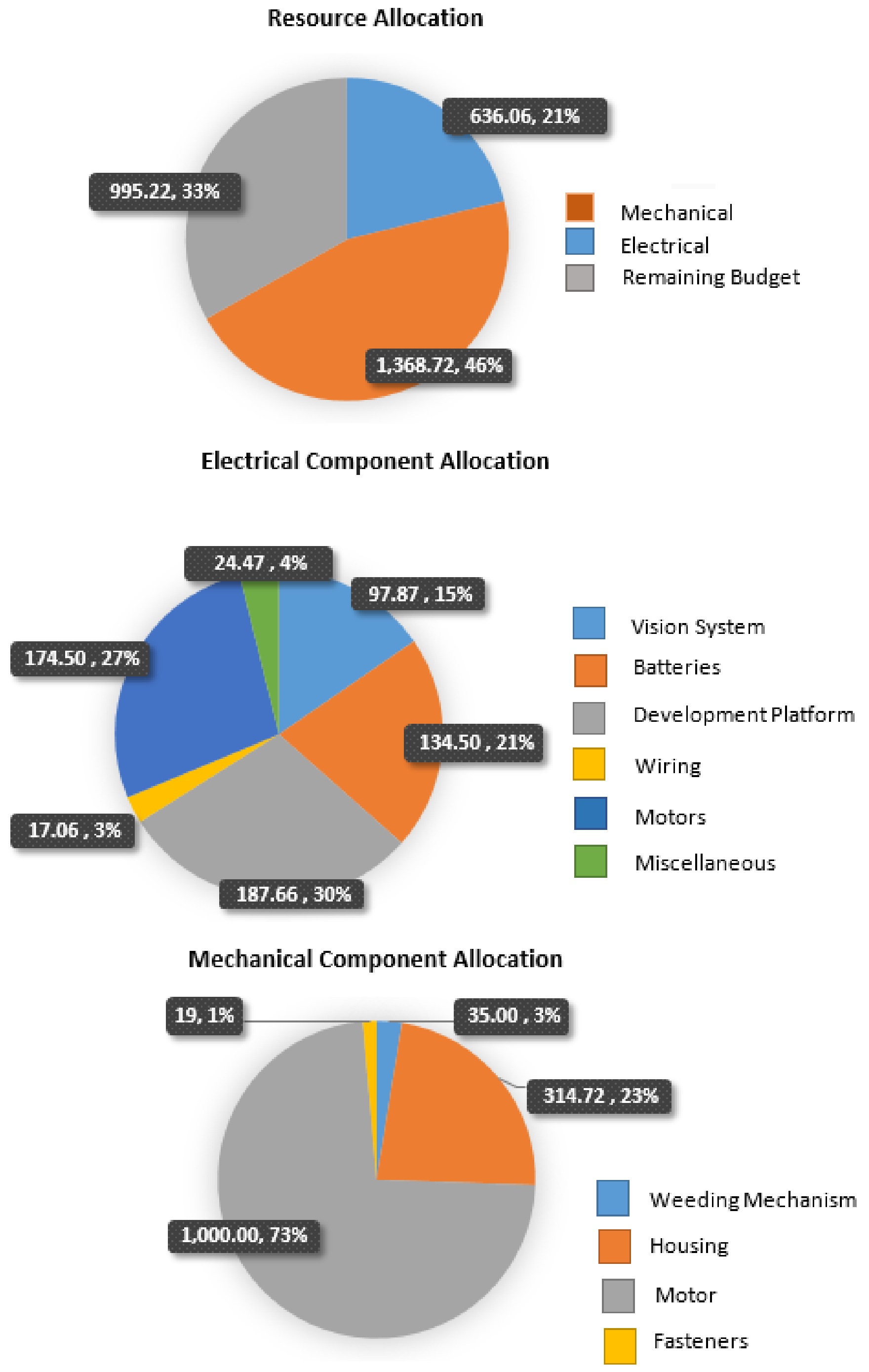


Figure 14. Overall Budget Allocation

The charts in Figure 3 above show the overall budget allocation for each discipline of the project as well as allocations for certain subcategories of materials.

7.4 Communication

Throughout this senior design project, it was pivotal that the team, advisor and sponsor stay in contact. In order to stay in contact with the team, a group text message chat was created, in which all group members participated. Through this medium, meetings were announced and team members were able to communicate while apart. In order to keep in communication with our advisor, the team set up individual meetings with Dr. Clark when they were needed. This mostly included going to Dr. Clark’s office and asking for his advice on specific issues. He was also invited to all presentations in order to keep him up to date on the progress on the project. With our sponsor, Jeff Phipps, email, telephone and face-to-face meetings were employed. The most helpful method of communication with the sponsor was face-to-face meetings when the team visited the farm. Jeff was also invited to all presentations. As for the TAs and instructors, they were available by email, class time and bi-weekly staff meetings.

8. Conclusion

Ultimately, for this senior design project the goal of the weeding robot team was to create an autonomous robot that could effectively remove weeds from a plot. The method chosen to remove weeds from the plot was the basket weeding method. The basket weeding method uses spokes that dig into the ground and sweep the weeds out from their root system. This basket is driven by a motor that is powerful enough to overcome the torque needed to drive the mechanism into the dirt. A Beaglebone Black is used to control the robot as well as the motor driving the weeding mechanism. The robot navigates through the plot by using a vision system in parallel with an ultrasonic sensor. The vision system uses a webcam to identify markers on the sides of the row, and then compares it with the data from the ultrasonic sensor in order to autonomously drive the robot straight through the furrow. By using these two systems together they are able to correct any errors or bad data from one of the sensors alone. The mechanical and electrical designs work together to affect 100% of the weeds that the robot encounters.

If this project is to be continued next year, it is recommended that a few design parameters be changed. For the weeding mechanism design, it is recommended that the basket be spring loaded to allow for the height to be adjustable depending on the height of the bed to be weeded. This would make the autonomous weeding robot more marketable as it could be placed on any farm and perform under specific conditions. Additionally, because the batteries currently need a person to charge them weekly, it is recommended the next team develop a charging station for the robot to return to, making it completely self-reliable.

Advice for the next team to ensure for the best possible comes from the experiences our team had during the course of fall and spring semesters. A crucial point of advice would be to construct and test a preliminary prototype before spring semester starts. With every prototype there are lessons learned and this will be invaluable. Also, it is recommended to pay attention to tolerances when machining parts as well as annotate everything. As far as communication, make sure to have the professor review any presentation slides before the actual presentation, as well as make sure all designs are thoroughly communicated with the sponsor before constructing.

Looking back over the year, the team could have started building and testing earlier in the semester. Ideally creating a prototype before the spring semester started. Also, we should have been proactive about getting our parts into the machine shop as early as possible to avoid delays.

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Appendix A

The following is the complete code used for the design of our robot.

```
#include <iostream>
#include <opencv2/opencv.hpp>
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <cmath>
#include "DMCC.h"
#include <prussdrv.h>
#include <pruss_intc_mapping.h>
#include "GPIO/GPIOManager.h"
#include "GPIO/GPIOConst.h"

//standard and openCV namespaces
using namespace std;
using namespace cv;
void Mdrive(int,int,int);
int ultradrive(float);
float ultradistance();
//declare some global variables which will be used
double width = 1280;    //camera sizes
double height = 720;
int thresh = 100;       //threshold values for colors
int max_thresh = 255;
int speed = 4400;       //default robot speed
int noinput = 0;        //checks for bad data
int badsonic = 0;
int turnratio = 0.65;   //defulat turn speed
int ultraset = 0;       //check if ultrasonic sensor is set

int main(){
      //set camera and size
      VideoCapture capture(0);
      capture.set(CV_CAP_PROP_FRAME_WIDTH, width);
      capture.set(CV_CAP_PROP_FRAME_HEIGHT, height);
      double width = capture.get(CV_CAP_PROP_FRAME_WIDTH);
      double height = capture.get(CV_CAP_PROP_FRAME_WIDTH);

      Mat imgInput, imgResize, imgHSV,  imgNew;
      Mat canny_output, threshold_output;
      vector<vector<Point> > contours;
      vector<Vec4i> hierarchy;
      sleep(5);
      while(1){
            //check if camera is detected
            if(!capture.isOpened()){
                  cout << "No Camera" << endl;
            }

            //capture image here
            capture >> imgInput;
```

```
        //resize image
        Size size(640, 360);
        resize(imgInput,imgResize,size);

        //convert to HSV color space
        cvtColor(imgResize, imgHSV, CV_BGR2HSV);
        inRange(imgHSV, Scalar(5, 130, 90), Scalar(17, 255, 255), imgNew);

        // Detect edges using canny
        Canny(imgNew, canny_output, thresh, thresh*2, 3 );
        // Find contours
        findContours( canny_output, contours, hierarchy, CV_RETR_TREE,
CV_CHAIN_APPROX_SIMPLE, Point(0, 0) );

        //Creaste contours for polygons + get bounding rects and circles
        vector<vector<Point> > contours_poly(contours.size());
        vector<Rect> boundRect(contours.size());
        vector<Moments> mu(contours.size());
        vector<Moments> mu2(contours.size());
        vector<Point2f>mc(contours.size());
        vector<Point2f>mc2(contours.size());
        vector<Point2f>center(contours.size());
        vector<float>radius(contours.size());

        //generate circle around center of object
        for(int i = 0; i < contours.size(); i++){
            minEnclosingCircle( (Mat)contours[i], center[i], radius[i]
);
        }

        int temp = 0;
        //j is the largest object, k is the second largest
        int j = 0;
        int k = 0;
        //find the largest object
        for(int x = 0; x < contours.size(); x++){
            if(contourArea(contours[x]) > temp){
                temp = contourArea(contours[x]);
                j = x ; //set the new largest object
                mu[j] = moments( contours[j], false );
                mc[j]   =   Point2f(   mu[j].m10/mu[j].m00   ,
mu[j].m01/mu[j].m00 );
            }
        }
        temp = 0;
        //find the second largest object
        for(int y = 0; y < contours.size(); y++){
            if(contourArea(contours[y]) > temp){
                if(y != j){  //ignore the largest contour
                    mu2[y] = moments( contours[y], false );
                    mc2[y]  =  Point2f(  mu2[y].m10/mu2[y].m00  ,
mu2[y].m01/mu2[y].m00 );
                    //check to see that countours aren't the same
                    if(abs(mc[j].x - mc2[y].x) > 60){
                        temp = contourArea(contours[y]);
```

```
                                    k = y ; //set the new largest object
                              }
                        }
                  }
            }
            //check if we found two objects
            if((j != 0) && (k != 0)){
                  cout << "found objects" << endl;
                  //make sure objects found aren't just random blobs
                  if((contourArea(contours[j]) > 1) &&
(contourArea(contours[k]) > 1)){

                        //check if the balls are on the side of view
                        if(((mc[j].x > 427) && (mc2[k].x < 213)) || ((mc2[k].x
> 427) && (mc[j].x < 213))){
                              //loop ultrasonic code unless weird data
                              while(true){

                                    //call function to get ultrasonic sensor
                                    float ultradis = ultradistance();

                                    //call motor drive controller, if bad data
exit while loop
                                    if(ultradrive(ultradis) == 1){
                                          break;
                                    }
                              }
                        }
                        //reset bad data counter
                        noinput = 0;
                  }
            }
      }

}

//setup the ultrasonic sensor and call the asm program
//to return the data timing value in order to be converted
//into a distance usable by the robot
float ultradistance(){
      /* Get measurements */
      printf(">> Initializing PRU\n");
      tpruss_intc_initdata pruss_intc_initdata = PRUSS_INTC_INITDATA;
      prussdrv_init();
      /* Open PRU Interrupt */
      if (prussdrv_open (PRU_EVTOUT_0)) {
            // Handle failure
            fprintf(stderr, ">> PRU open failed\n");
            return 1;
      }
      /* Get the interrupt initialized */
      prussdrv_pruintc_init(&pruss_intc_initdata);
      /* Get pointers to PRU local memory */
      void *pruDataMem;
      prussdrv_map_prumem(PRUSS0_PRU0_DATARAM, &pruDataMem);
      unsigned int *pruData = (unsigned int *) pruDataMem;
```

```
      /* Execute code on PRU */
      printf(">> Executing HCSR-04 code\n");
      prussdrv_exec_program(0, "hcsr04.bin");

      // Wait for the PRU interrupt
      prussdrv_pru_wait_event (PRU_EVTOUT_0);
      prussdrv_pru_clear_event(PRU_EVTOUT_0, PRU0_ARM_INTERRUPT);

      // Print the distance received from the sonar
      // At 20 degrees in dry air the speed of sound is 342.2 cm/sec
      // so it takes 29.12 us to make 1 cm, i.e. 58.44 us for a roundtrip of 1
cm
      float ultradis = ((float) pruData[0] / 58.44);
      return ultradis;
}


//controller function to drive the robot based on the
//ultrasonic distance value from the sides of the beds
int ultradrive(float disvalue){
      if(badsonic > 5){
            Mdrive(0, 0, speed);
            return 1;
      }
      else if(disvalue < 25){
            turnratio = (0.65 - (((19-disvalue)/19)*.2));
            Mdrive(1, 1, speed);
            badsonic = 0;
      }
      else if(disvalue > 50){
            badsonic++;
      }
      else if(disvalue > 30){
            turnratio = (0.65 - (((disvalue - 24.5)/24.5)*.2));
            Mdrive(1, 2, speed);
            badsonic = 0;
      }
      else{
            turnratio = 0.65;
            Mdrive(1,0,speed);
            badsonic = 0;
      }
      return 0;
}


//Mdrive is the function used to control the motor capes which
//are placed on top of the beaglebone. It is possible to set
//the motor power, direction, and cape with this function call
void Mdrive(int direction, int turn,  int speed){

      int session = DMCCstart(0x00);

      switch(direction){
            case 0:
                  setMotorPower(session, 1 ,0000);
```

```
            setMotorPower(session, 2 ,0000);
            break;
        case 1:////forward
            setMotorPower(session, 1 ,0000);
            setMotorPower(session, 2 ,0000);
            if(turn == 0){////straight
                setMotorPower(session, 1 ,speed);
                setMotorPower(session, 2 ,(-1)*speed);
            }
            else if(turn == 1){/////right
                    setMotorPower(session, 1 ,speed*0.65);
                    setMotorPower(session, 2 ,(-1)*speed);
                }
            else if(turn == 2){/////left
                    setMotorPower(session, 1 ,speed);
                    setMotorPower(session, 2 ,(-1*0.65)*speed);
                }

            break;
        case 2:////backward
            setMotorPower(session, 1 ,0000);
            setMotorPower(session, 2 ,0000);
            if(turn == 0){////straight
                setMotorPower(session, 1 ,(-1)*speed);
                setMotorPower(session, 2 ,speed);
            }
            else if(turn == 1){/////right
                    setMotorPower(session, 1 ,speed*(-1*0.65));
                    setMotorPower(session, 2 ,speed);
                }
                else if(turn == 2){/////left
                    setMotorPower(session, 1 ,-1*speed);
                    setMotorPower(session, 2 ,(0.65)*speed);
                }
            break;
        case 3: // turn left
            setMotorPower(session, 1 ,0000);
            setMotorPower(session, 2 ,0000);
            if(turn == 0){////straight
                setMotorPower(session, 1 ,speed);
                setMotorPower(session, 2 ,speed);
            }
            break;
        default:
            break;
    }

    DMCCend(session);
}
```

Appendix B

Table B1. Performance Data

Failure Modes Effects Analysis

Team #:	11
Project Title	Weeding Robot

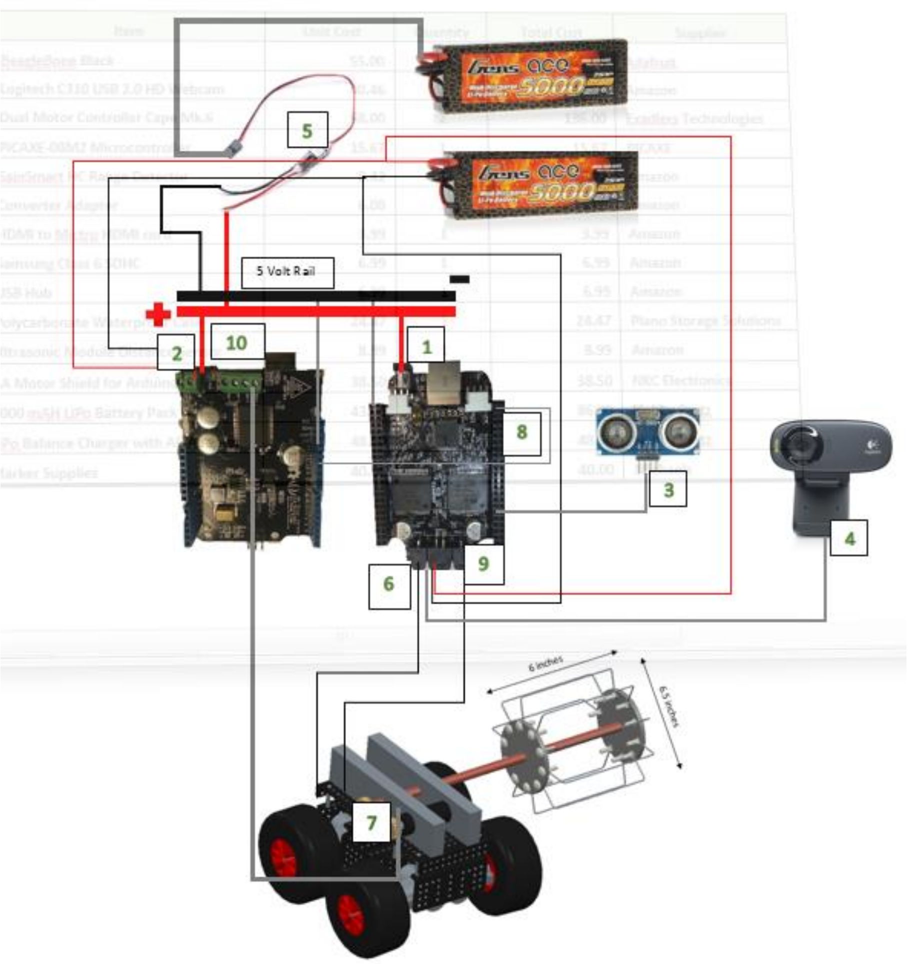
Key Process Step or Input	Potential Failure Mode	Potential Failure Effects	SEV	Potential Causes	OCC	Current Controls	DET	RPN	Actions Recommended	Resp.
What is the Process Step or Input?	In what ways can the Process Step or Input fail?	What is the impact on the Key Output Variables once it fails (customer or internal requirements)?	How **Severe** is the effect to the customer?	What causes the Key Input to go wrong?	How **often** does cause or FM **occur**?	What are the existing **controls** and procedures that prevent either the Cause or the Failure Mode?	How well can you **detect** the Cause or the Failure Mode?		What are the actions for reducing the occurrence of the cause, or improving detection?	Who is Responsible for the recommended action?
Rotating basket	Basket gets stopped by large object	Spokes on the basket break	5	Field is filled with rocks or very large roots	3	The rotation of the basket will free itself from objects	3	45	Remove large objects from the plot before using the robot	The farmer or users of the robot
Rotating basket	Basket gets stopped by large object	Motor burns out	8	Field is filled with rocks or very large roots	3	The rotation of the basket will free itself from objects	3	72	Remove large objects from the plot before using the robot	The farmer or users of the robot
Rotating basket	Basket fills with debris	The basket no longer removes weeds	4	If robot is operating in a wet or overdamp enviornment	5	Spaces inbetween basket spokes allow debree to fall through	5	100	Remove large amounts of debree form the field before use	The farmer or users of the robot
Spinning chain	Chain slips off of the gears	The basket no longer rotates	3	Misalignment occurs	3	Gear alignment and tension cause the chain to stay on the gear	4	36	Check alignment of the gears before operating the robot	The farmer or users of the robot
Spinning chain	Chain slips off of the gears	Chain starts hitting other parts of the robot	6	Misalignment occurs	3	Gear alignment and tension cause the chain to stay on the gear	4	72	Check alignment of the gears before operating the robot	The farmer or users of the robot
Spinning chain	Debris gets caught in chain	The chain slips off the gears	4	If robot is operating in a wet or overdamp enviornment	5	The spinning of the chain allows for debris to remove itself form the chain	6	120	Remove large amoutns of debris form the field before use	The farmer or users of the robot
Spinning chain	Debris gets caught in chain	The chain breaks	5	If robot is operating in a wet or overdamp enviornment	5	The spinning of the chain allows for debris to remove itself form the chain	6	150	Remove large amoutns of debris form the field before use	The farmer or users of the robot
Driving down the row	Camera gets dirty	The robot stops	2	Dirt is thrown onto the camera lense	2	The robot stops	3	12	Clean camera before use	The farmer or users of the robot
Driving down the row	The ultrasonic sensors get obstructed	The robot drives with less accuracy	5	Too much debris in the field	5	Use the camera system	5	125	Clean ulrasonic sensors before use	The farmer or users of the robot

	BeagleBone Black $55
Processor	AM3358BZCZ100, 1GHZ
Video Out	HDMI
DRAM	512MB DDR3L 800MHZ
Flash	4GB eMMC, uSD
Onboard JTAG	Optional
Serial	Header
PWR Exp Header	No
Power	210-460 mA@5V

Specifications:

- Dual DC motor control (5V to 28V)
- Motor speed and Motor direction (reverse / forward) control
- High Current (up to 7A continuous per motor)
- Stackable, up to 4 DMCCs can be stacked
- Dual Quadrature encoder interfaces on each board
- Built in PID control firmware
- Reverse/Forward motor indicator LEDs
- C library available on Github
  - https://github.com/Exadler/DMCC_Library
- Eagle Schematic and Layout
  - https://github.com/Exadler/DualMotorControlCape

Figure 15: BeagleBone Black Specifications



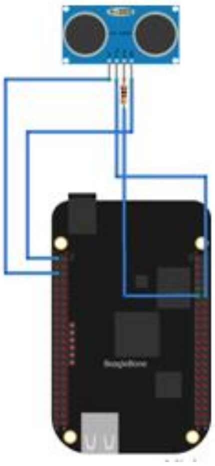
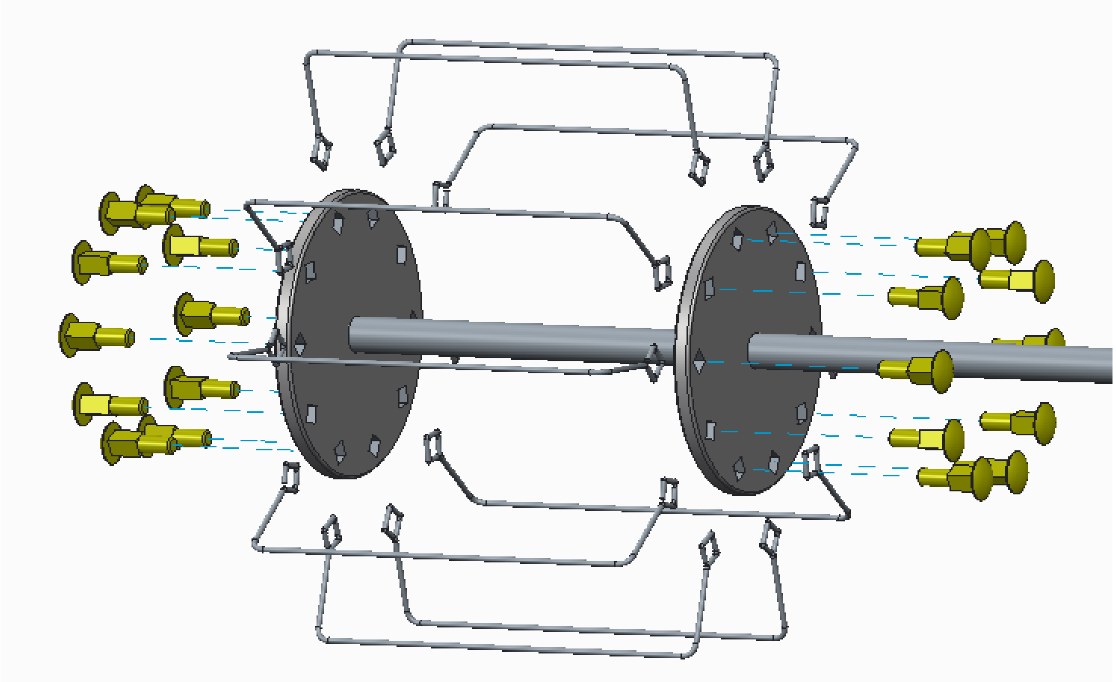
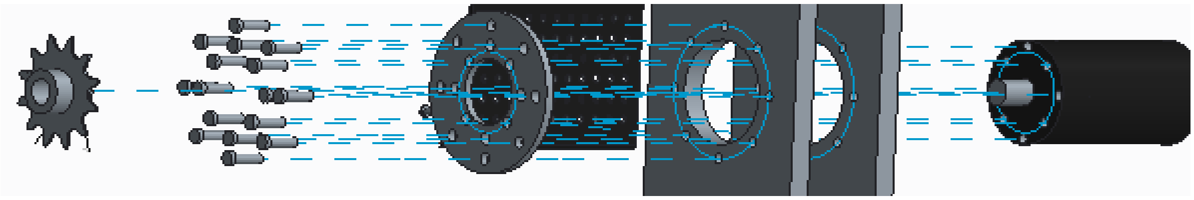


Figure 16: Detailed Ultrasonic Ranging Module Pin layout

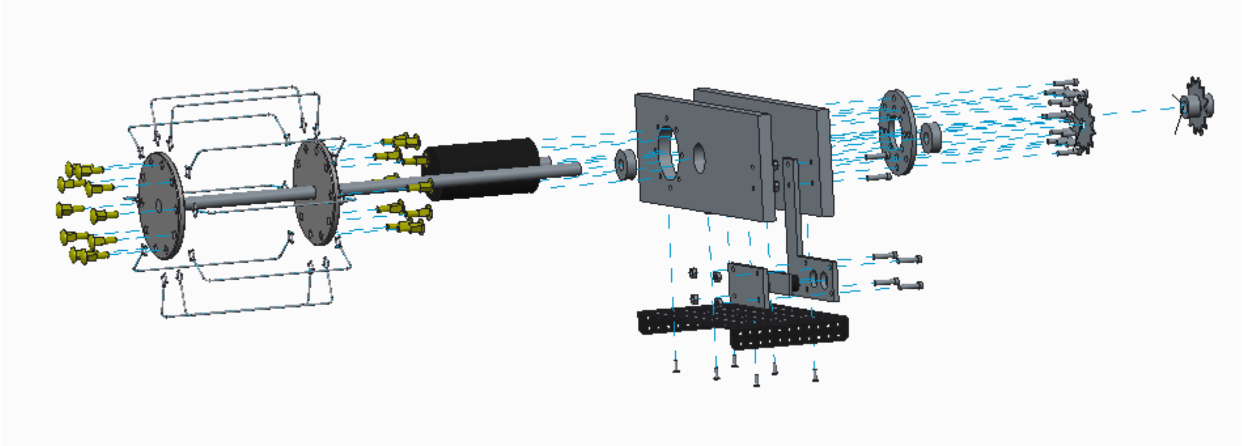
Appendix C



Exploded view of basket



Exploded view of motor



Overall exploded view

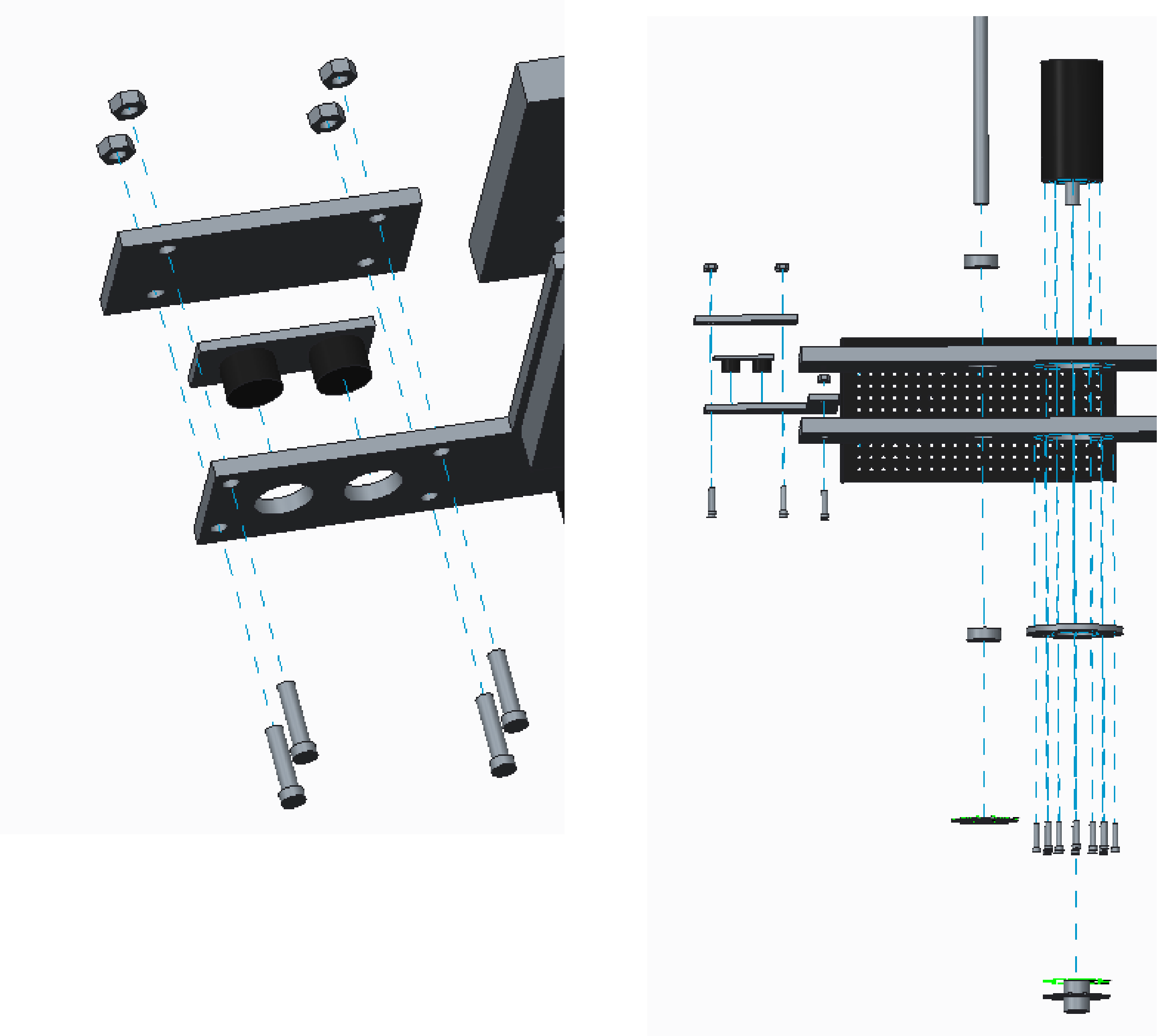
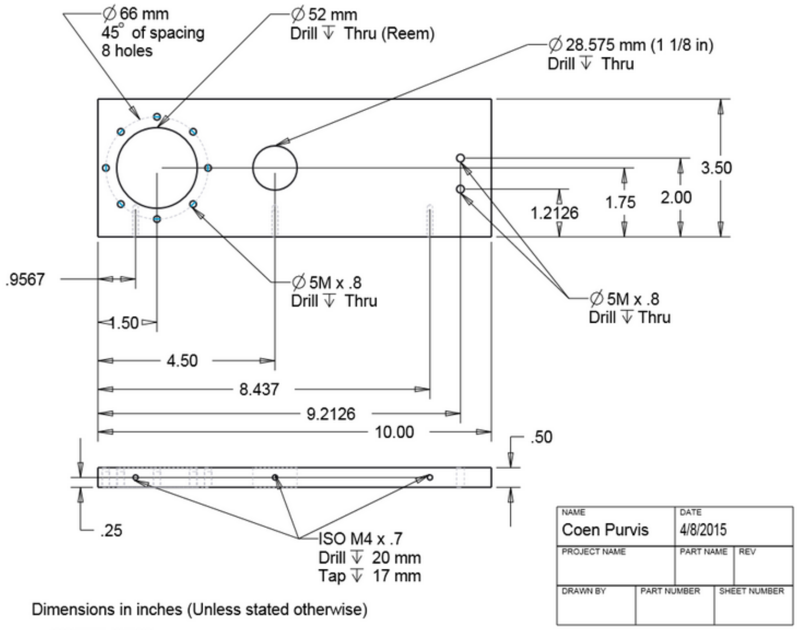


Figure 17: Exploded views of robot

Appendix D



NAME Coen Purvis
DATE 4/8/2015

Dimensions in inches (Unless stated otherwise)

SCALE 0.500

Figure 18: Dimensions of Plate

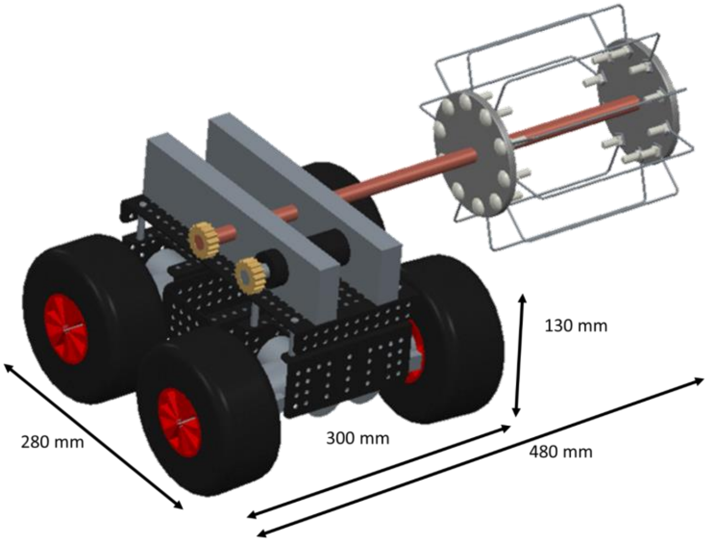
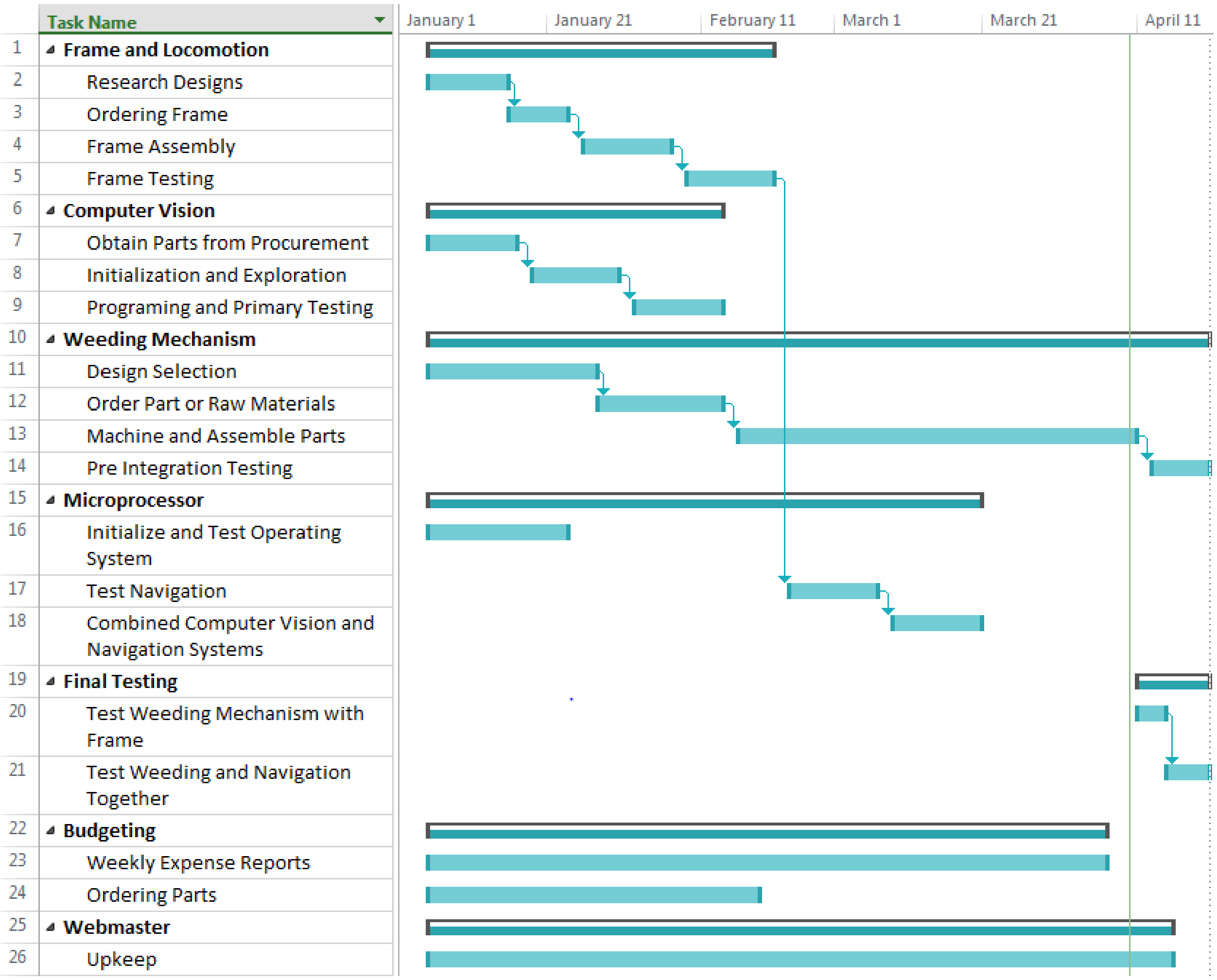


Figure 19: CAD of robot

Appendix E



	Task Name
1	**Frame and Locomotion**
2	Research Designs
3	Ordering Frame
4	Frame Assembly
5	Frame Testing
6	**Computer Vision**
7	Obtain Parts from Procurement
8	Initialization and Exploration
9	Programing and Primary Testing
10	**Weeding Mechanism**
11	Design Selection
12	Order Part or Raw Materials
13	Machine and Assemble Parts
14	Pre Integration Testing
15	**Microprocessor**
16	Initialize and Test Operating System
17	Test Navigation
18	Combined Computer Vision and Navigation Systems
19	**Final Testing**
20	Test Weeding Mechanism with Frame
21	Test Weeding and Navigation Together
22	**Budgeting**
23	Weekly Expense Reports
24	Ordering Parts
25	**Webmaster**
26	Upkeep

Figure 20: Gantt Chart

Biography

Mr. Jeff Phipps: Jeff Phipps is a landowner and entrepreneur in Tallahassee. Among other business ventures, including the Marshmallow Fun Company, he is also creating a toll road through a large amount of land he owns. This toll road is intended to help wildlife and nature in the area. He also had roles in many other corporate ventures.

Ian Nowak: An Electrical Engineering student that attends the FAMU/FSU College of engineering. He works at the Center for Advanced Power systems (CAPS) doing work on a Piezoelectric Disconnect Switch. He also has plans to attend Graduate School for Digital Signal Processing after completing his undergraduate degree.

Coen Purvis: A Mechanical Engineering student who attends the FAMU/FSU College of Engineering. He is on track to finish his undergraduate studies in the spring of 2015. He plans to attend Graduate School to further his education after completing his undergraduate degree.

Amanda Richards: A Mechanical Engineering student who attends the FAMU/FSU College of Engineering. She currently works at Modern Professional Engineering drafting for HVAC systems. She plans to move to Charleston, SC after graduation to work for Cummins Inc. as a Product Validation Engineer for marine engines.

Grant Richter: A Mechanical Engineering student that attends FAMU/FSU College of Engineering. He currently works as a Teaching Assistant at FSU for Mechatronics I. After graduation, he will move to Orlando, FL to work with Lockheed Martin as a Systems Engineer.

Jeremy Rybicki: An Electrical and Computer Engineering student that attends the FAMU/FSU College of engineering. He works part time as an IT consultant for medical ad surgery centers. Has recently accepted a position as Systems Engineering intern at Northrop Grumman for the summer of 2015. After graduation he is interested in working with embedded systems and software engineering.

Nathan Walden: A Mechanical Engineering student who attends the FAMU/FSU College of Engineering. Interests are in the robotics and controls section of engineering. He is the President of Pi Tau Sigma