Final Project Documentation

April 29, 2019

Project B.A.R.I. (Blossom Assisting Robotic Intelligence)

Team 10

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Executive Summary

Most farmers spend about $180.00 per acre per year, depending upon the type of farm, to rent bee hives for pollination services. The state of California, the nation's largest beekeeper and agricultural state, still relies on importing billions of bees per year to meet its pollination needs. This large-scale importation is in spite more than half the country's bee hives located in the state. While colony collapse disorder is a significant contributor to the farmers' demands exceeding the local supply, it is becoming apparent that large and medium scale farming operations would put a strain on local pollination supplies regardless of colony collapse disorder. This paper presents the problem of pollination supply, the inconvenience that some farmers face when climate, market, and competition affect access to pollination, and an engineering solution that will allow farmers to pollinate at will. An M.I.T. study in 2015 found that it was significantly cheaper to preserve the bee population than to pollinate crops though crop dusting or hand-pollination. The figures were calculated for 379,000 acres of apple orchards. For just one year it would cost $38,458,371 to pollinate the orchards through crop dusting or $876,538,125 to pollinate those same orchards by hand. Bees are still the most efficient pollinators, and the cheapest. By designing and building a robot that can mimic the process of hand-pollination, we can mitigate the inconvenience farmers face when their demand for pollinators exceeds the readily available supply. An automated robot can free up the farmer for other matters that require attention and help to offset some of the long-term costs of bee importation and hive rentals. The intention of this project is not to replace the honey bee, but to augment the honey bee's role in our nation's food supply. The two-semester project taught our team the importance of research and the testing process. While the project in its current iteration is not ready for the market, some of the team members are interested in pursuing an improvement on the current design and careful testing over the next few years to create and patent a viable product that can help our nation's farmers save money on operation costs and provide a convenience that could improve crop yield and quality. In its current state, the robot is effective yet crude in its execution. The pursuit of automation in this project led us to the realization that we had to continuously control the environment the robot operates in. This was to limit the number of decisions the robot needed to make in order to reduce the possibility of error. For an effective autonomous robot that could operate independently in a farming environment we need to account for more scenarios, improve the processing speed of our microcontroller, and invest a lot more time in coding to reach an effective level suitable for the commercial market. Our focus is on self-pollinating crops that do not require pollen to be transferred from one flower to another. The pollen from a self-pollinating crop can fertilize its own flower. By focusing on self-pollinating crops, we can alleviate some of the pressure on farmers by creating more availability for farmers who grow self-pollinating crops like almonds, that are 100% dependent on bees for pollination. Early testing on a simulated hand-pollination process yielded promising results that should be taken with caution. The survey of plants was too small to declare definitively that our process would be effective for commercial use. Further testing on a larger scale is warranted after a complete redesign of the prototype in its current state. Our deployable prototype is encouraging, and we hope that the improvements made post-university will lead to a viable product. We present to you, B.A.R.I.: Blossom Assisting Robotic Intelligence.

Abstract – **Over the course of two semesters, Team 10 was assigned a task to research a societal problem and offer an engineering solution to mitigate the problem. With colony collapse disorder present, California farmers have a hard time pollinating all of their crops. Team 10 proposed a solution which consists of a semi-autonomous robotic pollinator which will stimulate self-pollinating plants and assist in the pollination process. This paper covers the design process of an engineering process, going from the planning to the laboratory prototype, then from testing to the deployable prototype. Elements such as the risk assessment, funding, project overview, and work breakdown structure will also be discussed. Supporting all their research and testing are the results and design documents found in the end.**

Index Terms –Bees, Colony Collapse Disorder, Pollinators, Robotics

I. INTRODUCTION

A conversation with a Stockton, California farmer about his recent experiences with trying to arrange pollination services for his cherry and walnut trees was an eye-opening experience. Kevin Solari, owner of F&S Solari spoke of the year 2018 and the perfect storm of everything that could go wrong for the area's cherry farmers. The cherry blooms had already come in further south due to a changing climate that year. As such, those farmers had a successful growing season and were able to get to market first and set the price. Further north, in the Stockton area, a changing climate led to an unusually smaller cherry crop with blooms that had come in later. Add to that the availability of domesticated pollinators. California's almond farmers typically control the honey bee market. Every year they are among the first farmers to import domesticated honey bees from around the United States to meet their needs. Almonds are 100% dependent on bees for pollination. Almond farmers also tend to hold on to the bees longer than many other farmers, so they pay a higher rental fee for the bees. This means that most beekeepers give priority to almond farmers for their higher fees and reduces the need for transportation. It just so happened that in 2018, Solari's cherry blossoms started to come in while the almond farmers were still utilizing their pollination services. Solari had to scramble to find other pollination services and even resorted to buying very expensive bags of pollen. The price for pollen came out to $118.58 per acre with no guarantee that the pollen would even make a difference. Since 2018 was already going to be a down year for the area's cherry farmers, he did not believe he would have an accurate way of determining whether the pollen was effective enough to warrant the expense. But, as Solari said, "The moment my blossom come in, I want to start pollinating because there is no solution for having no crops." The availability of domesticated pollinators like the honey bee is a significant factor in the cost of food production for our nation's farmers.

The United States is the world's second largest food producer, behind China, and the world's largest food exporter. Clean water, fertile soil, and the space to grow crops are key to a world-leading food producer. But what many people take for granted, or do not even consider at all, is that bees are also significant to the yearly efforts of our farmers. The demand for domesticated pollinators such as honey bees is so great in agricultural states that farmers across the country rely on importing bees from out of state. A solution to mitigate the demand for out of state pollinators is to design and build a semi-autonomous robot that mimics the act of hand pollination for self-pollinating crops.

Starting around early February is typically when the almond blooms start in California. Almonds are 100 percent dependent on domesticated bees for pollination. Even with 51 percent of the nation's bee colonies located in California, the state's farmers are still reliant on importing bees from out of state. Almonds are not the only crop reliant on bees for pollination. However, almonds and grapes are the state's biggest food crops and dominate the domesticated bee rental market when their blooms come in. Almonds usually hold on to their rented hives longer than other farmers and, as such, pay a higher rental rate. If their blooms start to come in when other farmers' crops start to come in, the other farmers are left scrambling for a new bee source until those bees become available. The almond bloom is only the beginning of the season for the honey bee. While other California farmers start to pollinate their crops when those almond bees become available, many hives start to head north to Washington and Oregon for their apple and potato crops. As spring and summer approaches, Michigan needs pollinators for their blueberry crop, Wisconsin has cranberry bogs, the Dakotas have sunflowers, clover, and alfalfa, and Texas has squash and melons. The east coast has their own year-round pollination needs up and down the coast and many bees travel thousands of miles a year to meet the needs of these farmers as well.

There are 2 types of pollinating crops: cross-pollinating and self-pollinating. Cross-pollinators rely on the pollen from one of their blooms to be transferred to another bloom for successful fertilization. Almonds are an example of a cross-pollinating crop, which also explains why they are wholly dependent on bees for pollination. Self-pollinators can have pollen from the same bloom fertilize itself or another bloom. Self-pollinators are also reliant on bees for pollination, although not as much as cross-pollinators. Plants require pollination to reproduce, which makes honey bees very effective pollinators. Bees primary purpose is not to pollinate flowers, but instead is to gather the nectar inside the flower as well as pollen. The bees use this nectar to make honey, which is their food. To reach this nectar, the bees brush against the male and female reproductive organs of the flower, known as the stamen and the pistil respectively. The honey bee has these tiny sticky hairs on their legs called spindle hair. While the honey bee tries to reach this nectar located at the bottom of the flower bulb, its legs brush against the stamen of the flower and some of the pollen sticks to their legs via their spindle hair. When it flies over to the next flower to grab more nectar, this pollen rubs off their leg hairs and gets deposited on the pistil of the flower while also gathering new pollen from this flower. This is the basic process of cross-pollination. In self-pollinating plants, the bee simply knocks the pollen from the stamen loose and into the pistil when trying to collect nectar.

Bees are not the only pollinators, but they are the most common and significant pollinator. Most insects can act as pollinators, but bees are the most common because they intentionally seek out the blooms for their nectar and pollen. Most other insects act as pollinators unintentionally. Birds and bats also act as pollinators in much the same way that insects other than bees act as pollinators. There are also different types of pollination, other than insect and animal pollination. Wind pollination is the process of pollen carried by the wind to other blooms. Crop dusting can also be used to pollinate crops. Both wind pollination and crop dusting are not very precise. Water pollination is the process by which pollen is carried by water currents to other aquatic plants and is not the focus of our project. Hand pollination is the process by which plants are pollinated by hand. This is a very tedious and time-consuming process. A person will transfer the pollen from one bloom to another or create a disturbance in a self-pollinating plant to loosen the pollen into the pistil. A simple brush can be used or even a small vibrating machine that creates a harmonic vibration.

We plan to focus on self-pollinators. Our proposal is to design and build a robot that can simulate the process of hand-pollination for self-pollinating plants. By building a project that focuses on self-pollinators we can provide farmers with the ability to pollinate ate will, should the availability of domesticated honey bees become scarce. We chose to focus on strawberry plants because they grow low to the ground, they are a tough plant, easy to grow, and self-pollinating. The strawberry plant's blossoms are well protected and would also be very likely to withstand the potentially disruptive actions of our pollinator design. This will, hopefully, account for any deficiencies we have as farmers. They are also a significant cash crop in the state of California, where we will be testing our prototype.

Before deciding on a robot that would simulate hand-pollination and a plant to test our project on, several design ideas were discussed. Since we were discussing the problem of the availability of domesticated honey bees, we naturally started with the idea that we could develop a drone that could simulate the actions of a bee. There were several complications discussed about this idea. We would need to work with an existing drone that is small enough so as not to be too intrusive with the plants. Yet at the same time the drone would have to be large enough to hold a power source that would allow for extended flight and precision flying. Most commercially available drones allow for flying times of 5 to 10 minutes and up to 30 minutes before they need to be recharged. In addition to extended flight, there would need to be enough power for a microcontroller to run complex computations, which would cut into the flight time. A drone would not be a viable option. A wheeled robot would be much more effective for stability and serve as a solid platform for a series of complex systems. Funding is also an issue and we would need to be careful in our design. We ended up designing and building a four-wheeled robot from scratch.

The robot is called B.A.R.I. An acronym for Blossom Assisting Robotic Intelligence. Our design for B.A.R.I. is based on 6 specific features; maneuverability, a movable arm for pollination, path planning, rechargeable power supply, voice recognition, and status indicators to inform the user. B.A.R.I. needs to function outdoors and in the tight spaces of a farm's crop rows. Maneuverability of B.A.R.I. will entail size and how it moves in tight spaces. The movable arm needs to orient to either side of the robot, extend upwards, and have the ability to move back and forth over the plants as the robot navigates the crop rows. Path planning is the most integral feature of B.A.R.I. Path planning consists of mapping the surroundings, plotting a path that avoids damage to the crops, and object avoidance. An efficient rechargeable power supply allows for a quick recharge of the robot's batteries so as to keep the robot out in the field as long as possible. Voice recognition enables the user to interact with B.A.R.I. by speech for ease of use. Status indicators are a series of LED lights that inform the user of what state B.A.R.I. is currently in.

II. Societal Problem

A. Availability of Domesticated Honey Bees

According to surveys taken by the U.S.D.A., California is by far the nation's largest beekeeper with 51% of the nation's domesticated bee colonies. Even with such a supply of domesticated pollinators located nearby, the nation's largest agricultural state also needs to import billions of bees each year to meet its pollination needs. Every year bees are transported thousands of miles to meet the nation's pollination demands. In California it starts in February with the state's almond farmers before the beekeepers move their livestock on to other crops such as grapes and berries. Others make the trip north to Oregon and Washington for apples and potatoes, and still others start making the trek to the Dakotas for sunflowers and alfalfa. This is all going on while the east coast maintains a year-round circuit of honey bee transportation up and down the coast.

B. Colony Collapse Disorder

Disappearing Disease, Spring Dwindle, May Disease, Autumn Collapse, and Fall Dwindle Disease are all now more commonly known as Colony Collapse Disorder [1]. Colony collapse disorder (CCD) is the phenomenon that occurs when the majority of worker bees in a colony disappear and leave behind a queen, plenty of food, and a few nurse bees to care for the remaining immature bees [2]. While it has happened often enough in the past to warrant several different names, a drastic rise in the number of disappearances of honey bee colonies circa 2006 has been a cause for alarm and an impetus for renewed study. In fact,

"During the winter of 2006-2007, some beekeepers began to report unusually high losses of 30-90 percent of their hives. As many as 50 percent of all affected colonies demonstrated symptoms inconsistent with any known causes of honey bee death: And according to an article from CBS News, 40% of U.S. bee colonies died between 2014 and 2015 [3]. "The availability of diverse and nutritional forage was noted as being particularly important for building colony populations prior to and throughout pollination (especially of almonds) and afterward, because colonies need to recover from stresses associated with transport. Beekeepers remarked that colonies with access to good floral resources were generally healthier than those located where few floral resources exist (i.e. sites dominated by row crops) and fed dietary supplements. Undernourished or malnourished bees appear to be more susceptible to pathogens, parasites, and other stressors including toxins. Thus, nutrition might be a fundamental factor in mitigating negative effects of other stress factors on bee health [4]."

C. Cross-Pollinators vs. Self-Pollinators

The goal of our project is to build a robot that can simulate the process of hand pollination. There are many different methods of pollination that occur in nature; pollination by animals, wind pollination, where the wind carries pollen from flower to flower, and water pollination, where water current carries pollen from plant to plant [5]. In addition to natural methods, there are also artificial methods. Crop dusting is commonly known as a method of pollination, but it is not very effective. In times of great duress, it is also not unheard of for farmers to resort to pollination by hand, which can be very time consuming

D. Pollination

Pollination is the act of transferring pollen grains from the male anther of a flower to the female stigma [6]. Pollinators are the modes of transferring the pollen to the stigma. Many people assume that the honey bee is the only kind of pollinator. While the honey bee is the most efficient and prevalent pollinator, insects other than bees, birds, bats, and other kinds of animals can function as pollinators as well [7]. Every flowering plant has a similar biological construction. The flowers are the plants' means of reproduction. This project is primarily concerned with the stamen and the pistil. The stamen is made up of a filament and an anther, which contains the pollen. The pistil is made up of the ovary, style, and stigma, which receives the pollen [6].

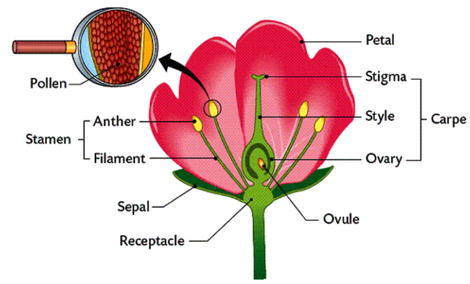


Fig. 1. Diagram showing the reproductive organs in a flower [8].

E. Self-Pollination

Self-Pollination occurs when the pollen from the anther gets deposited on the stigma of the same flower. It will still be called self-pollinating if the anther of one flower gets deposited on the stigma of another flower of the same plant [9]. In the plants which have the stamen and carpel maturing at the same time, there will be a higher chance of self- pollination to occur. Maturing of stamen and carpel at the same time positions them together so that the pollen can land on the stigma of the flower. Self-pollination reproduction doesn't require plants to make nectar and pollen as the food for pollinators [9]. The independence from other organisms makes the self-pollinating plants adaptable and need less energy to produce nectar or attractions for pollinators [10]. Moreover, self-pollinating plants can survive in places of high elevation and the arctic. Pollinators might not be available in these places. The offspring reproduced by the self- pollinating plants are uniform but not identical [10]. Examples of self-pollinating plants are peanuts, orchids, peas, wheat, rice tomatoes, etc. There are plants which have both male and female flowers that can self- pollinate, but the chances are increased with cross-pollination. Examples of self- pollinating plants include oaks, birches, corn and pumpkin [10].

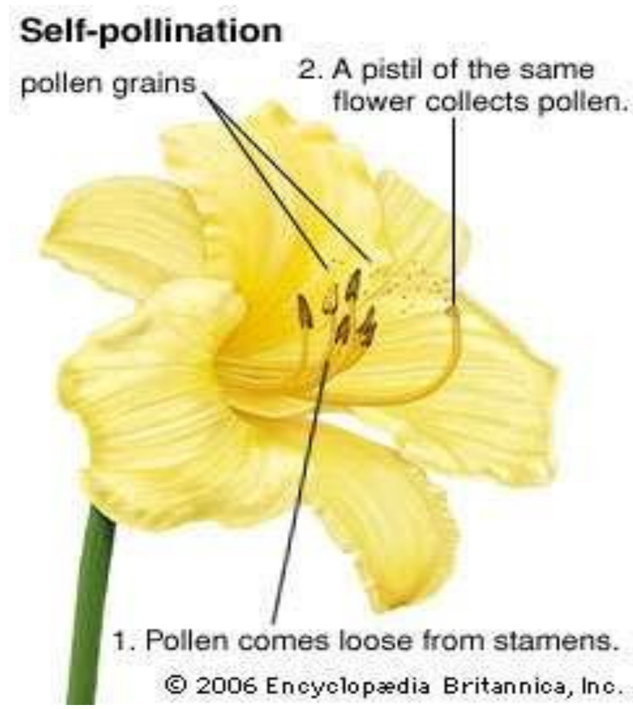


Fig. 2. Self-pollination process in a flower [11].

F. Cross-Pollination

Cross-pollination is the process of reproduction in which the pollen is transferred from the anther of one flower to the stigma of another flower of different plant but same species [9]. Cross-pollination allows for more genetic diversity. In some species, the ovary and pollen mature at the different times, which makes self-pollination impossible. In plants such as cucumbers, male and female flowers are located on different parts of the plants [9]. In cross-pollination, the pollen can be transferred by bees, other insects, wind, water, other animals, and by hand [12]. This pollination process has its advantages since genetic information of different plants is combined, but it relies on the existence of pollinators that travel from plant to plant. This makes it hard for the plants to grow and survive without pollinators. When cross-pollination occurs, the new plants often exhibit characteristics from both parents [13].

Animal pollinators are organisms that travel from flower to flower and transfer pollen to each flower they visit. They are one of the pollinators that help in the process of cross-pollination. “This type of pollination is very important because around 80% of all flowering plants and 75% of staple crop plants require animals to help complete the pollination process” [14]. Examples of cross-pollinating plants are coconut, maize, poppy, and acaena, apple trees.

We see a large decline in the honey bee population, where the average is about a 25% decline and, in some years, it is as large as a 40% decline in population. With this large decline in the honey-bee population, one might ask “what can we do to help this situation?” An interesting fact is that there are over 20,000 different species of bees around the world and about 4,000 of them are native to the United States. While these numbers might seem to be insignificant, there are only about 44 subspecies of bees that are special to us, and those are called the honey bees. These are the ones that spend long, tedious hours collecting nectar for themselves to produce honey while pollinating our crops. To narrow it down even further, there is only one species of bees, the *Apis mellifera,* that has been extensively used for commercial pollination of fruit and vegetable crops.

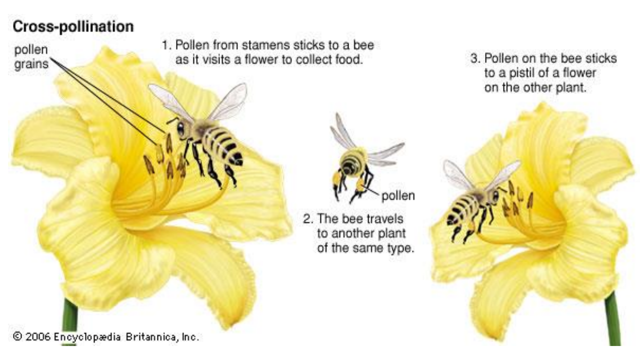


Fig. 3. As seen in the figure above, bees are a primary source of cross pollination. Bees go from one flower to another transferring the pollen attached to them. [15]

G. Bee Shortage

Regardless of what the contributing factors are as to why CCD is occurring the simple fact is that CCD is happening. We wouldn’t have so many ways to describe it if that was not the case. “Between 2008 and 2013, modeled bee abundance declined across 23% of US land area [16].” CCD has become such a cause for alarm that in 2016 the United States Department of Agriculture began surveys on major domestically raised bee colony operations as well as the cost to farmers of primary crops in their respective growing regions to rent bees for pollination. There are over 2.6 million domestic bee colony operations in the United States, with the lion's share of those operations in California, who maintains almost 1.2 million [17]. Of the roughly 2.6 million domestic hives surveyed from January to March in 2016, almost 400,000 suffered from CCD [17]. But CCD is a part of a much bigger problem. Most farming regions in the United States do not have enough domesticated and wild honey bees to meet their pollination needs. The primary problem faced by farmers is the availability of domesticated honey bees, with CCD being a significant factor.

It is easy to take for granted the impact that such a small insect could have on our nation's economy. It has been estimated that honey bees contribute nearly $20 billion to the value of U.S. crop production [18], and in 2009, "bees contributed an estimated 11% of the nation's agricultural gross domestic product [16]. What most of us don't realize is that many of our nation's farmers rely on travelling beekeepers, who rent out their hives across the nation, sometimes commanding as much $190.00 per hive for just a few weeks [19]. The USDA monitors such expenditures from major farming operations across the nation. Of the farms surveyed by the USDA in 2017, over $658 million was spent on renting bee hives for pollination purposes [20]. Due to a shortage of bee colonies in California in 2013, just California almond farmers alone were forced to import 31 billion bees from out of state to pollinate their almond crop [18].

In times of great duress, it is not unheard of for farmers to pollinate by hand. Hand pollination has had some limited success with anywhere from 42.2% to 93.3% successful germination across various cultivated species [21], so it is not outside the realm of possibility that artificial methods could be developed that, down the road, will become cost effective. As it stands right now, an M.I.T. study in 2015 found that it was cheaper to try to preserve and grow the bee population than to crop dust or pollinate by hand. The two primary methods of artificial pollination were crop dusting, also known as pollen dusting, and hand pollination. Crop yield from crop dusting was "73.5 percent less as compared to insect pollination, and fruit weight from pollen dusting is estimated to be 42 percent less when compared to insect pollination [22]." The study also found that, while hand-pollination was just as effective or more effective when it came to both fruit yield and weight, the costs were prohibitive compared to the benefits [22]. The period of time over how long the hives were rented for was not mentioned in the study of cost for pollen dusting, but it was estimated at $250.00 per hectare, not including plane maintenance [22]. The total losses for just the 379,000 acres of apple orchards alone would be $38,458,731 annually for pollen dusting, and hand-pollination would cost $876,538,125 per year as well [22].

When access to honey bees is scarce, farmers may have to resort to more expensive and labor-intensive measures. One such method is hand pollination, which can be very expensive and tedious. In those times when domesticated pollinators like honey bees are difficult to come by, an engineering solution can mitigate the short supply. Hand pollination has had some limited success with anywhere from a 42.2% to a 93.3% successful germination rate across various cultivated species [20]. So it is not outside the realm of possibility that artificial methods could be developed that, down the road, could become cost effective. However, an M.I.T. study in 2015 found that it was cheaper to try to preserve and grow the bee population than to crop dust or pollinate by hand. The two most prevalent methods of artificial pollination were crop dusting, also known as pollen dusting, and hand pollination. Crop yield was "73.5 percent less as compared to insect pollination, and fruit weight from pollen dusting is estimated to be 42 percent less when compared to insect pollination [21]." The study also found that while hand-pollination was just as effective or more effective when it came to both fruit yield and weight, the costs outweigh the benefits [21]. While time was not mentioned in the study of cost for pollen dusting, it was estimated at $250.00 per hectare, not including plane maintenance. The total losses for just the 379,000 acres of apple orchards alone would be $38,458,731 annually for pollen dusting, and hand-pollination would cost $876,538,125 per year as well [11]. Approximately 235 billion to 577 billion USD worth of annual global food production relies on direct contributions by pollinators. Hand pollination is way more "labor intensive" than it seems to be because workers must transfer pollen from male flowers to female flowers with a brush to fertilize them. Although in China, the cost of hiring human pollinators was 12-19 USD per day while the cost of renting a beehive at the time was $46.88 per day [23].

III. Design Idea

The purpose of this project was to provide a solution to a societal problem. With colony collapse disorder as our issue, our team designed and built a robotic pollinator. The project was split into six major features, each with its own measurable metrics. During the first semester, we focused on building a laboratory prototype that would have been ready to be a deployable prototype as well. Figure 4 shows how the project looked like at the end of the first semester. Over the course of the two semesters, the teams understanding of the problem had changed along with their understanding of the project. At the end of the second semester, we realized that the way we defined the features should have been written differently compared to the way they were defined during the first semester.

Fig. 4. The robotic pollinator at the end of the first semester. [24]

A. Maneuverability

The maneuverability feature focused on the robot's design and movement aspect. With a primary focus on a rugged and small design, the robot was developed with the farm environment as the key guider. The robot was designed to drive on dirt without much issue and fit between crop rows once the plants were fully grown. It was later during testing that the team found that the body could have been designed even better since it presented problems during the testing phase.

Alongside the farm factors, pollination speed was something that the team considered. To complete a large patch of land, the pollination speed was set up to 1.5 ft/s which translates to about 1 mph. During testing, this speed seemed too fast for pollination, so the team slowed the robot to about 1.1 ft/s which showed better results. Even though the robot was slowed down, it is two values in the code that needs to be modified to get different speeds. Maybe one day the team could develop a UI for the robot that would allow the user to specify parameters such as plant height and pollination speed.

B. Movable Arm

The whole robot was technically designed for just this one feature. The moveable arm (poor word choice) was a feature that would do the actual function of the robot which was pollination assistance. The robotic arm stimulates the pollen by continuously waving a horizontal arm back and forth as the robot drives forward. The pollen stimulator needed to be a light material so that it wouldn't add too much weight on the arm, which was controlled by three separate servos, each having their own function. The pollinator used the first semester was ostrich feathers, but those proved to be too rough on the plants so during the second semester, the team moved over to horse hair which was gentler on the crops.

The primary servo that sat inside the actual robot dictated the direction the arm would be turned to, whether it was left or right. This servo was the torquiest of them all since it had to rotate the entire weight of the arm. The elbow servo controlled the elevation of the arm. This servo moved in a 120-degree manner allowing to deploy the arm downward or raising it up for taller plants. The third servo, served as the actual pollinator, sweeping continuously to stimulate the plants.

C. Path Planning

The path planning feature was a critical feature in the whole robot and was the hardest to implement. Essentially this feature contained components such as Lidar, motor control, and lots of software programming. The lidar which was placed on top of the robot, generated a 2-D environment surrounding it. Using an algorithm that Kanwar had created, the robot would react to the values it received from the lidar. The lidar we used was capable of seeing things as far as 23 feet away which was much further than we needed.

D. Rechargeable Power Supply

Maximum product usage on a single charge cycle is what a lot of manufactures strive for when creating a product that needs an energy source. Since the sole purpose of this robot is to pollinate and pollination season only exists for a few weeks for crops, this robot was designed to run for quite some time. During initial planning, we thought we would only be able to operate the robot for 1.5 hours but it proved to run longer. More information can be found in the Section IX.

E. Voice Recognition

A lot of devices these days are going to hands free. Our team decided to do the same with this robot to make the whole process seamless. The feature was designed to make it easy for farmers to operate. The user would just need to bring the robot to the crop row, turn on the robot, say the starting command and watch the robot do the rest of the work. This was harder to implement than originally anticipated.

F. Status Indicator

User feedback is always necessary for us humans. Without it, there would be no knowledge of whether the product is working. Since we didn't have any user interface, the team implement LED's into the robot that dictates the various states that the robot could be in. This provides feedback once the user gives the robot an input.

IV. Funding

A. Project Cost

With a project this large, our team spent a few weeks during the first semester looking for sponsors. One sponsor that we were certain that we would be able to get to support us was the California agricultural department. Unfortunately, they were not able to sponsor us since this was an undergraduate level project and they only recognized master's projects. This led to the team having to spend their own money to finance this whole project. Thankfully, everyone was able to split the cost evenly. The budget allocation was appropriate for this project and the team would buy parts as needed. At the end of the semester, we would divide the amount we owed each other. For major purchases the team voted on whether it was needed or if there was an alternative. Sometimes purchases occurred without consulting the team first, which led to money that was needlessly spent. The team has extra materials that were never used and at this point are beyond the return date.

The total cost of this robot pollinator was around $1,346. With this cost split equally, each individual team member spent about $269. The fall spending's was higher compared to the spring spending's because we purchased majority of the necessary material to complete the laboratory and deployable prototype in the fall. During the spring semester we purchased a few parts built our testing facility. As seen in Table I, the total cost of the robot is just under a thousand dollars. The breakdown of the whole project spending can be found in Appendix G.

TABLE I
THE COST OF THE PROJECT

Category	Cost
Electrical/Electronics	$889.15
Mechanical	$106.66
Test Facility	$205.40
Total Build Cost	$995.81
Overall Cost w/Facility	$1,201.21
Total Project Cost w/Extras	$1,346.85

B. *Donations*

Our team fortunately was able to get donations from a few companies which helped us a lot, especially when it came to the physical build. Companies such as Clark Pacific, Home Depot, and Omniduct, were generous enough to donate supplies to aid in the design and build this robot. Clark Pacific donated PVC sheets and cut them to our specifications. Omniduct, donated metal pieces that were used for motor mounts. Finally, Home Depot donated the wood pieces that were used to create a housing for our grow facility. Team 10 is very thankful for all these donations that had helped the team meet their goals.

V. PROJECT MILESTONES

A. *Societal Problem*

The first milestone the team met was to find a societal problem and evaluating if it was feasible and could be completed in two semesters. Since the team had 5 team members, and everyone brought their own ideas for the project, it was hard to decide which project to choose. The team members decided to evaluate every project and consider the skills, time, resources, cost related to those projects. A voting was considered, and the project was most points was chosen. This resulted in choosing this robot as the project for Fall 2018 and Spring 2019.

B. *Design Idea*

After choosing a project, one of the major milestones came ahead. It is the implementation of the project. All that team had was the skills to solve a problem and what the robot is supposed to do. But how the robot should do it what yet to be implemented. This resulted in break down the goal of the project into smaller parts. It included the design of the body and the movale arm. Also, the type of motors to be able to hold the weight of the robot. It also included the hardware components such as microcontroller, types of servos, the type of LIDAR, and the cost of each part. The design of how the software needs to work and be efficient was also considered.

C. *Physical Build*

The major milestone that we met as a team was the physical build of the project. After many hours collaborating with Clark Pacific to get the body material cut out to our specs, we were able to begin piecing the robot around November of 2018. This was where Jose and Pavel worked together measuring, bending, and cutting the aluminum L-beams that would provide a structure the body as well as protect the plastic edges of the body. Soon after the rolling chassis was completed, we were able to place the motors along with the batteries inside. We connected the R/C receiver to the motor controller and were able to see the robot move for the first time. This was the beginning of a long journey of troubleshooting and coding.

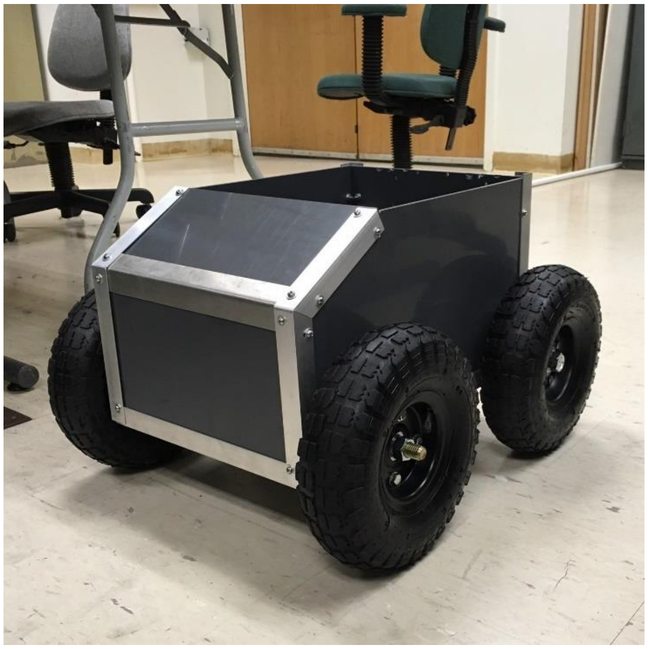


Fig. 5. Rolling Chassis that was completed in November [25]

D. Pollinating Arm Built

The pollinating arm was built soon after the rolling chassis was completed. This arm was built in a small apartment room because campus was closed due to Camp Fire which was an unexpected circumstance that delayed many things in our project. Fortunately, we were able to gather our tools from our lockers in the engineering building. Once the rolling chassis and arm were put together, the team had a project reading for the coding journey that didn't really begin until the following semester.

E. Navigation & Path Planning

This was the last incredible milestone in our project which probably took the most amount of time. An obstacle that we had to overcome was the fact that coding is difficult with hardware that wasn't yet implemented into the system. With a delay in the building of the robot, most of the coding began in the second semester.

1) Lidar Libraries: The lidar libraries were something that wasn't readily available. Kanwar, the main programmer of this system, spent over forty hours setting up the lidar. This was completed during the first semester as the fire was going on. He had worked on it from home and was able to display a 2D image of his room.

2) Encoders: Reading the data from the encoders was a large milestone for this team. It was the beginning stepping stone that gave the team the ability to drive the robot in a straight line. The team had wanted to use an additional component, the Kangaroo X2 by Dimension Engineering, which would take the feedback from the encoders and autotune the motors. This would have allowed us to spend less time figuring out how to make the motors behave the way we needed them too. The encoder data allowed us to gather vehicle velocity which satisfied one of our measurable metrics.

3) Straight Line: Once encoder feedback was set and we were getting correct data, we ran into a small issue. We had some sort of build flaw that was causing the robot to always steer to the left, no matter however matched the two motor speeds were. To correct that, we put shims by the front axles to have the point a little outward which partially corrected the issues. To make it complete, we called the left motor the primary motor and the right motor was the secondary motor. The secondary motor would constantly

4) Making a turn: One of the most recent miles stones was the making a turn. This was a milestone because we used the lidars data to build triangles around itself and based off the distance and angle, it would correct its orientation. The team is planning on using a compass instead to perform the same task.

VI. Work Breakdown Structure

The team spent a considerable amount of time on this project. While we didn't track how much each feature took individually, Table II lists the hours each team member spent on the project. Pavel worked on the motor control, wheel encoders, path planning, wiring, and the status indicators. Jose had worked on the physical build and installing the recharging system. Nick focused on the building of the arm and pollinator. Jason worked on the ultrasonic sensors, maintaining the test facility, and the primary writer of the reports. Kanwar was the lead programmer who worked on the path planning, motor controlling, voice recognition, and status indicators.

TABLE II
TOTAL NUMBERS OF HOURS WORKED PER FEATURE

Feature	Total Hours
Maneuverability	611
Movable Arm	307.5
Path Planning	339.5
Rechargeable Power Supply	140
Voice Recognition	70
Status Indicator	50
Total	**1518**

A. Maneuverability

To achieve the desired maneuverability required for navigating the rough terrain of planting fields in a farming environment, our team had to take into consideration: narrow crop rows, the uncertain terrain of a dirt field, and the unwieldy movement of our robot near a farmer's crops. A compact body, rugged design, durable materials, and a slow-moving speed will address those concerns. The compact body design takes into account a typical width of 48 inches to 52 inches between crop rows. There was some give and take here, as we also needed enough room to place our components. An area of 1 foot by 1.5 feet was worked out based on our desired motor specifications, orientation of the motors, sensors, and arm. The base of the chassis and component housing was provided by Clark Pacific and there was no need for a time commitment with regard to cutting or shaping the material. The durable material used for the chassis and housing is made of Polyvinyl Chloride (PVC); a material easy enough for us to drill into, but tough enough that it can handle the weight of the components it will be supporting

1) Interior component mapping: Design and building of the robot was split into interior and exterior regions. The exterior region encompasses all parts, components, and work done outside of the protective housing, and the interior regions encompass the same for all areas that will fall inside the protective housing. Before we ordered the parts, we would need, we had to determine various specifications for our components, but they also had to meet our compact size requirement. Interior component mapping would entail balancing performance characteristics with their respective physical size.

The first thing we needed was to determine what kind of motors we need to power the wheels. We had to find a balance between the amount of current they draw, their physical size, and many other characteristics. While we were determining the various characteristics and requirements for the motors, we also mapped out how they would look on the chassis' base to determine a proper area that would suit our needs for a compact body. We knew we would be limited by our compact size requirement due to the amount of space between crop rows. The best choice for our project would be two brushed DC motors oriented at a right angle with respect to the wheels.

2) Motor Mounting: While it may seem simple at first, mounting motors to a body is a challenge of itself. There are a variety of ways to mount motors and since we are building our own body design, we needed to make our own mounts. The motors will lay flat on the surface of the chassis base on the interior. They will be attached to a metal mount that will have been attached to the base. This will allow the motors to stand firm in their position without moving anywhere.

3) Creating Axles: Axles were made to transfer the torque from the electric motors to the tires. The axle shaft needs to be able to fit into the axle hole of the tire. Since we are avoiding the design process and creation of a hub assembly, the axle will be a unique design that works around that problem. It will be a solid rod that will need to be lathed, drilled, and tapped in order to fit the tire onto it and the motor output shaft into it.

4) Mounting Bearings and Axle: Once the motors and orientation were determined, problems like securement and power transfer is what had to be figured out. Since motor output shafts cannot bear too much load, a bearing and axle system needs to be fabricated. The bearing will be attached to the outer shell of the robot which will allow it to be secured and provide support to the axle. This will allow to take the load off of the motor shaft and place all the load on the frame. The axle that was created will slide through these bearings and will let it rest on them.

5) Power distribution from batteries: The battery supply will consist of two AGM (Absorbed Glass Mat) 12-volt batteries that will be ordered October 13, 2018. They will be mounted inside the body frame measuring 7.1 x 3 x 6.6 inches. They will be mounted and connected in series outputting a total of 24 Volts and 22Ah (amp hours) which will allow us to use the robot for about 2 hours. The batteries will be recharged using an AC recharging controller. The user will plug in a charging cable into the outlet and will be able to recharge for an estimated time of about 8 hours, allowing us to reuse the batteries.

Making the motors drive: The motors will be driven by a Sabertooth 2x32 motor controller. The purpose of a motor control board is to deliver the high currents that motors required without burning the board. This board is able to deliver 32A per motor which is far more than what we need for our application. This ensures that we won’t overload the controller and the board will be protected. Attached to this motor controller will be motion controller which will be the “middleman” for communication the motion direction and speed.

6) Reading data from encoders: The encoders in the motors allows us to have feedback from the motor. For this project, each drive motor will have a two channel Hall-effect encoder attached that will send its data to a dual LS7366R quadrature encoder. With this feedback we are able to get data such as speed and direction. The encoders will be connected to a buffer board which will keep track of using the differential of the two encoders we will be able to tell which direction it has turned based on the output of the two encoders. With the possible help of the LIDAR system we will be able to tell which direction the robot is facing based on its original position.

7) Design Housing: Designing the housing has its own challenges associated with it. To begin, there had to be a few parameters to be considered. Things such as farm row widths, type of tires used, types of motors used, and the materials we can acquire to produce a chassis. The design should be aesthetically pleasing, small, but at the same time large enough to fit everything well. After the design has been finished, the individual pieces are ready to be manufactured. We outsourced our design to Clark Pacific to get the body pieces cut out by CNC. The angle brackets that will provide a skeleton for the frame need to be cut out and drilled. They will be secured together and they body pieces that were cut will be attached to these assembly. Assembly of the protective housing consists of four sides and a hatch for the top for ease of access. It will be built according to the basic schematic from the design process.

8) Ultrasonic sensors will be mounted on top of the chassis for object avoidance. We cannot place them low because of the way ultrasonic sensors work. Placing them on the bottom could result in false readings. This will be necessary to meet the requirement for handling. The rough terrain and maintaining proper distance from the plants in farming environment

9) Wheels: Four 10-inch diameter wheels will be mounted onto the axles after the axles have been mounted to the body of the chassis. They will be secured to the axles by washer and nuts.

10) Charger port: The batteries will be recharged using an AC recharging controller. The user will plug into the outlet and will be able to recharge for an estimated time of about 8-10 hours, allowing us to reuse the batteries.

B. Moveable Arm

The robotic arm will be facilitating the pollination process. It needs to have the ability to move in the three-dimensions: the XY, XZ, and YZ planes. The vertical shaft, that we have defined as the torso shaft, will be mounted to the center of the chassis' base. It will rotate horizontally on the XZ plane with a range of motion of 180 degrees, oriented to reach either side of the robot, rotating towards the fore of the robot's body. Attached to the end of the torso shaft is the secondary arm shaft, oriented parallel to the ground. The secondary arm shaft will be manipulating the pollinator over its intended targets. Servo motors at the base of the torso shaft and shoulder between the torso shaft and secondary shaft control movement of the arm.

1) Main Servo: Attach the main servo to the chassis' base. The primary (shoulder) servo is programmed and controlled through a raspberry pi using C or Python code. When the robot is operated, the servo will turn all the way to the side that has strawberry flowers and perpendicular to the robot. Let's call this reference point is at zero degrees. When the robot reaches the end of the row and turning into the next row, the servo will turn 180 degrees to the opposite side and the process repeated in a loop program.

2) Torso Shaft: Attach the torso shaft to the chassis' base and servo motor. The primary shaft of the robotic arm is a ½ in diameter and 5 feet long non-toxic PVC cylindrical and hollow rod that is attached to the center near the rear end of the robot. The rod will sit at the base and going through the top if the body chassis. Two smooth ball bearings of ½ in inner diameter with mounting brackets are used in order to both secure this shaft in place and let it rotate smoothly 180 degrees from left to right. One ball bearing with mounting bracket will be installed at the bottom inside the chassis while the other will be installed at the roof inside the body. A set of load reduction gears are connected to the primary shaft and the servo using a serpentine belt to transfer maximum torque effectively to the shaft.

3) Second Servo Motor: Attach the main servo to the chassis' base. The primary (shoulder) servo is programmed and controlled through a raspberry pi using C or Python code. When the robot is operated, the servo will turn all the way to the side that has strawberry flowers and perpendicular to the robot. Let's call this reference point is at zero degrees. When the robot reaches the end of the row and turning into the next row, the servo will turn 180 degrees to the opposite side and the process repeated in a loop program

4) Secondary Arm Shaft: The secondary arm shaft in designed to lift vertically up and down using a high torque servo between 20-25kgf.cm or 45-57lbs.cm. This second high torque servo base is securely placed on top of the primary shaft with screws and washers. The servo gear in then connected to the secondary shaft which is made of PVC material or 3D printing ABS material in order to reduce the total load weight on the servo. The overall length of this secondary shaft should be between 12 to 18 inches long in order to extend over the robot body and to the strawberry flowers. At the other end of this secondary shaft, the hair sweeping/ brushing system is attached to it using nuts and bolts.

5) Third Servo: Attach third servo to the secondary arm shaft. The third servo is programmed and controlled through a raspberry pi using C or Python code. The hair sweeping system is operated when the robot drives in parallel to the plants row following a given path. The sweeping rod will be sweeping from -60 degrees to +60 degrees on a XY plane that is parallel to the ground. This rod will stop sweeping when the robot gets to the end of the row where there are no more strawberry plants. The sweeping motion is a loop program and it will let the arm starts sweeping again at the beginning of the new row.

C. Rechargeable Power Supply

In this age of robotics, running cordless is the best way to create a great product. Our design incorporates rechargeable batteries that will allow our robot to run for a few hours. How do we determine its total run time? This number can be approximated from simple power calculations and we can estimate a total run time.

1) Power Calculations: We took the approximate maximum power that the components will consume and compared it to the total power the batteries can supply. The robot will be able to run for approximately 5.6 hours.

2) Research and Procure Batteries: When choosing the batteries to purchase, there were different options that we had to consider. First and foremost was the total amount of power our system would expend. Looking at Table 1. We see that we will use approximately 200 watts of power. Since we need to balance the capacity, the size (volume) of batteries, and the weight, finding the battery will be the challenge. The goal is to find batteries that will give us the most operating time while being conservative with the weight

VII. Risk Assessment

The fall semester of 2018, and the first semester of our two-semester long project, saw an unexpected event that delayed progress. The Camp Fire, starting on November 8, 2018 and not contained until November 25, 2018, affected the air quality on campus to such a degree that it was closed on a day-to-day basis for a week until ultimately shutting down for an additional week right before school broke for Thanksgiving weekend [26]. This presented a unique problem rarely experienced by design teams. Our team, comprised of five individuals, had members living as far as thirty-five miles away from campus. With only one member living near campus and the rest of us living off campus in four different directions, our central meeting place was campus itself. When we were finally allowed onto campus to remove all materials needed to complete our laboratory prototype, we set up a space just off campus where we could prepare for our laboratory prototype demonstration on December 7, 2018. The Camp Fire was the biggest impediment to reaching the deadlines our team needed to hit specific milestones in our project. Ironically the sixth most devastating wildfire in United States history was not considered when assessing risk factors and risk mitigation for our project earlier in the semester [27].

There were also a few other unforeseen and preventable mistakes or risks throughout the project that set our team back a bit. The first issue came about when shopping around for an acceptable Lidar sensor for path planning. Cost was a major factor and most of the Lidar sensors we found were prohibitively expensive. We were finally able to locate a very affordable foreign-made model but, with affordability comes some sacrifice in effectiveness. For this model, we discovered that there was no existing documentation on how to implement any of the files or how the sensor worked with the coding. We had to parse through what files existed and figure out which were applicable to our project and edit our own libraries to make the Lidar sensor work. This was very time consuming and would have been preventable if we had either spent more money on an established Lidar model or chosen a different route for path planning. The second significant risk factor that we encountered could have been solved with some very basic troubleshooting. What we thought was some current leaking into our pollinating arm's base servo motor would not have been a problem if we had just asked some very basic questions from the very start. If we had just checked the power source and grounding from the very beginning, we would have saved a lot of time and trouble looking into how to stop unwanted current flow with either a transistor or a diode. The third unnecessary risk would have been prevented with basic communication between teammates. A team member was troubleshooting a problem by changing the voltage output of one of our buck converters. Without changing the voltage output back to its intended level and not communicating what was done, our team came very close to frying most of the systems in our project. All three of these issues have helped our team reinforce some basic troubleshooting steps and the experiences have helped with some valuable lessons. First, do not try to make your desired hardware fit the solution. Perform thorough research so that you can make an informed decision. Second is that the easiest and cheapest solutions should be tried early. Such as never assume that the power source and grounding are correct. Always check those first before spending time on more labor-intensive solutions. Third is to keep clear lines of communication with your teammates and keep everyone abreast of what you are doing so that you can prevent potential damage to your project.

There are three categories of risk factors that apply to our project; mechanical, electrical, software risks. Our team brainstormed an incredibly large amount of risk factors, trying to cover every contingency both internal and external to our design and build. For example, a weather event that delays delivery of a component would be an external risk factor to our build, whereas a piece breaking, or overheating, would be an internal risk factor to our project. For the sake of expediency, we decided that our imaginations were getting the better of us and we limited our risk factors to the most common or likely risks for each level of risk and category. For example, a battery coming loose during operation has a low likelihood of occurring but is more likely than the body of the robot cracking. We wouldn't specifically mention cracking of the body, as that would fall into a category of hundreds of other failures that would lead us down a rabbit hole of endlessly listing other unlikely failures. We are more likely to list the battery coming loose, as that is a more likely scenario considering the nature of our project. Our risk factor rating is a cross-section of the following: A score of one through five with one being little or no impact and five indicating that a risk factor will jeopardize the project. A score of 0.1 to 0.9 indicates a likelihood of an event occurring with 0.1, meaning not likely, and 0.9, meaning a near certainty.

A. *Mechanical Risk Factors:*

The process of assembling B.A.R.I. and the use of B.A.R.I. during testing and proof of concept creates opportunity for mechanical failure. Any error in assembly included as a mechanical risk factor. Products that have any sort of mechanical moving parts are bound to have some risks and failures. All parts have life expectancies which means component maintenance and visual inspections should be done regularly for them to perform well.

TABLE III
MECHANICAL RISK FACTORS

		Impact				
Likelihood		Minimum Or No Impact (1)	Tolerable Impact (2)	Limited Impact (3)	May Jeopardize Project (4)	Will Jeopardize Project (5)
	Will Happen (0.9)					
	Very Likely (0.7)					
	Likely (0.5)					
	Low Likelihood (0.3)					LIDAR Mount Breaks (10)
	Not Likely (0.1)	Stripped Threads (3)	Motor Mounts Break (1) Axle Breaks (2) Disconnected Pins (8) Loose Housing (11)	Bearings Crack the Housing (4) Axles Have Difficulty Spinning (5) Chassis Breaks (9)	Motors Stop Working (7)	

1) Motor Mounts Break: The motor mounts are custom made from sheet metal. Proper measurement of the space occupied by the motors and the motor's dimensions reduce the already low probability of the motor mounts breaking. If the motor mounts are not fastened properly, they will become damaged or break after prolonged use over a period of many years, which is well beyond the necessities of this project. (*Not Likely – 0.1, Impact can be tolerated – 2)*

2) Axle Breaks: Maneuverability plays a large role in our project. We chose our axles to be made from aluminum because it is a cheap material and durable enough for our needs. Although it may be light, a risk we are to account for is the fact that it is malleable when under great strain. However, this will have a limited impact to our project and will likely only happen if dropped from an excessive height or if great weight is applied to the axles. The material is very affordable and easy to find, so a broken axle will have a tolerable impact. *(Not Likely-0.1, Impact can be tolerated-2)*

3) Stripped Thread: One common problem with threaded fasteners is that they can become stripped if improperly used. Since we used a soft material such as aluminum, it is more prone to happening. The great thing about aluminum is that it is affordable, easy to work with, and durable enough for the job. If properly looked after, aluminum is sufficient for the task at hand. This means that when tightening the nut onto the axle, the person should check that they have placed it on the threads properly and not crooked. This will prolong the longevity of the axles and allow for them to be used for a long time. If we take just a little care, stripped threads will be unlikely and have no impact on the project. *(Not Likely-0.1, Minimum or no impact-1)*

4) Bearings Crack the Housing: We used flanged sleeve bearings since they were easy to install, affordable, and the correct hardware for the job. One issue that could arise with such bearing is not in the fault of the bearing itself, but the material used for the housing. Since we are using PVC to construct the housing, it will not hold up as well if the bearings were made of steel, like most farm equipment. Plastic was used because it is lightweight and durable enough for the job. Since the PVC shell is a quarter inch thick, this allows for some support for the bearings and more material can be added around the bearing attached to the base to reduce the chance of this occurring. While the likelihood of such an event is low, if it were to occur, it would have a noticeable impact. We would have to reorder one of the pieces, which are special ordered, and replace the broken component. This could set us back a week or more from testing. *(Not Likely-0.1, Limited Impact-3)*

5) Axles have Difficulty Spinning: Axles are the components that connect a tire to the output of a motor or transmission. In our project, axles will connect the drive wheels to the output shaft of the transmission. This axle will rotate inside a metal sleeved flanged bearing. Since we have metal on metal contact, this could add extra friction and unwanted stress onto the axles, bearings, housing, and motors. An event like this is not likely to occur and won't have much an impact if diagnosed quickly. It is easily reduced or eliminated by occasionally oiling the bearing/axle contact. This will reduce the wear and tear on the components and increase their lifespan. *(Low Likelihood-0.3, Minimum or No Impact-1)*

6) Battery Mounts Become Loose: Sealed lead acid batteries are the only source of power for our components, which is why it is important for the batteries to be secured and held down properly. The batteries will be secured by brackets that are fastened to the base of the chassis. Since the robot will moving over rough terrain, it is important to constantly inspect the security of the batteries. If they did become loose, the batteries, as heavy as they are, could jostle around and damage parts inside the shell. Since we have our microcontrollers, a servo, and other delicate components inside the housing, this could have a tremendous impact on the project. *(Not Likely-0.1, May Jeopardize the Project-4)*

7) Motors Stop Working: Motors are very durable components but if they break down, the project will suffer serious consequences. Only one manufacturer sells these motors. The chances of the motors failing are low. It will be difficult to burn out the motors since they are being controlled by a motor control board, but they can burn out from too much stress. What we did before buying these motors, was to acquire ones that were able to deliver more power than the job had asked for. This gave us "insurance" in the sense that we can be comfortable when working the motors. *(Not Likely-0.1, May Jeopardize Project-4)*

8) Disconnected Pins: The threat for damaging other components is negligible. If the microcontroller becomes loose, the biggest issue would be figuring out which pins were disconnected. Performing regular inspection of the microcontroller, careful mapping and color coding the wires, and secure wire fasteners will mitigate this issue. *(Not Likely-0.1, Impact Can be Tolerated-2)*

9) Chassis Breaks: The chassis and housing are made from PVC and extra stress could potentially crack them. Since the whole chassis is built from PVC, it can be considered a fragile and vulnerable design. The likelihood of such of an event is very low since we added aluminum angle beams to give it a robust frame. If it were to crack, it would have a great impact that could set us behind a week or two, depending on the manufacturer. *(Not Likely-0.1, Limited Impact-3)*

10) LIDAR Mount Breaks: The LIDAR sensor is a very critical component to our project. It needs to be mounted on the top of the chassis for a clear line of sight for optimum mapping and path planning. If the mount does break, there is a distinct possibility that the sensor will be damaged. This will set the team back in both time and money. Routine inspection and careful handling of the sensor will mitigate possible damage to the LIDAR. *(Low Likelihood-0.3, Will Jeopardize Project-5)*

11) Loose Housing: The housing is secured by nuts and bolts. Vibration and constant movement could possibly loosen the nuts and bolts in the housing, which could compromise the integrity of the body structure. Most of the fasteners are in easy to reach areas should the need arise to tighten any of them. This risk has a very low impact on the project. *(Not Likely-0.1, Impact Can Be Tolerated-2)*

B. Electrical Risk Factors

All systems on the robot require electrical power. The biggest issues would be drawing too much current from our power supply or frying the circuits or sensors from supplying too much voltage. Any instance of this happening could be potentially time consuming should we have to troubleshoot the location of the malfunction or find a suitable replacement for a sensor or other electrical component.

TABLE IV
ELECTRICAL RISK FACTORS

Likelihood	Impact: Minimum/No Impact (1)	Tolerable Impact (2)	Limited Impact (3)	May Jeopardize Project (4)	Will Jeopardize Project (5)
Will Happen (0.9)					
Very Likely (0.7)					
Likely (0.5)	Hardware Doesn't Respond (5)				
Low Likelihood (0.3)		Raspberry Pi Burns Out (1)	Power Supply Overloaded (2) Sudden Spike in Current (3)		
Not Likely (0.1)	LED Status Failure (4)				

1) Raspberry Pi Burns Out: The Raspberry Pi operates on 5 volts, GPIO pins operate on 3.3 volts, and it draws 2.5 amps of current. If the Raspberry Pi burns out, there could be a myriad of issues as to why. Damp conditions, more than 5 volts powering the Raspberry Pi, or more than 3.3 volts delivered to one of the GPIO pins. If any of these were to happen, the Raspberry Pi could burn out. Sudden power surges or a static discharge is also possible. The most likely possibility is that we overload the Raspberry Pi with more than 5 volts or one of the GPIO pins with more than 3.3 volts. We are using 24 volts to power the robot, so it is possible that we fry the Raspberry Pi. The possibility of this happening is moderate to low if we carefully follow our design specifications. The impact is low as well since the Raspberry Pi is easily replaceable in a very short amount of time.

To mitigate this possibility, a buck converter or voltage divider could be used to decrease the amount of voltage supplied to the Raspberry Pi. *(Low Likelihood-0.3, Impact can be tolerated -2)*

2) Power Supply Overloaded: Overloading the power supply is a low possibility. The power supply is significantly high relative to the power needs of the robot. This was intentional to increase the amount of time the robot can operate on one charge. To prevent an overloaded power supply from occurring we can make ensure that everything is properly grounded. *(Low Likelihood-0.2, Limited Impact-3)*

3) Sudden spike in current load: There may be times where there is a sudden spike in the current load which could fry the components. Fuses are placed to burn out instead and prevent from any more current flowing through that rail. If everything is wired correctly, fuses will be placed in all the wires running power to all electronics to prevent accidental damage. *(Not Likely-0.1, Limited Impact-3)*

4) LED Status Indicators: There are a series of LEDs that indicate to the user what status the robot is in. There are two possibilities for failure the status notification system. One is that the robot is in a status, but not notifying the user of this status. The other possibility is the converse of this; the LEDs are notifying the user of a status that it is not currently in. The impact is moderately significant, but the probability of either of these two scenarios is low. The most likely solutions are to change out the LEDs if they are not lighting up, or to check the coding if they are lighting up incorrectly. *(Not Likely-0.1, Minimum or No Impact-1)*

5) Hardware devices don't respond: There is a reason why the most common things to check first when trouble shooting, are to check the power source and then check the ground. They are typically the most common errors to occur. Check if the devices are powered and connected properly. *(Likely-0.5, Minimum or No Impact-1)*

C. Software Risk Factors

Programming is the most critical section of this project. It involves testing, debugging, and error checking. Most of the errors will not be visible until we enter the field-testing phase. The processing, interaction of devices, logic errors will receive more focus during the second semester of the project when we start integrating the systems together. The probability of systems not working is not that high throughout the project but increases during the integration phase.

TABLE V
ELECTRICAL RISK FACTORS

		Impact				
Likelihood		Minimum /No Impact (1)	Tolerable Impact (2)	Limited Impact (3)	May Jeopardize Project (4)	Will Jeopardize Project (5)
	Will Happen (0.9)					
	Very Likely (0.7)					
	Likely (0.5)				Data From LIDAR Not Detected (2)	
	Low Likelihood (0.3)		Libraries Not Available (1)		Support For O.S. Expires (3) Robot Makes Incorrect Decisions (4) Controller Continues Functioning (5)	
	Not Likely (0.1)					

1) Libraries Not Available: The chances of this happening are a little high. However, the impact can be decreased. Backing up all libraries constantly in case they become unavailable is one of the solutions.*(Low Likelihood-0.3, Impact Can Be Tolerated-2)*

2) Data from LIDAR not Detected: Data from

LIDAR can't be detected because LIDAR is not working, the software controlling the motors can't be run because the motor control board is not responding, one of the cores of the Raspberry Pi fails and can't run a program in parallel. Check if the LIDAR is powered on and detected by the raspberry Pi. Use the command *lsusb* to detect the connected devices. Check if motor control board is connected to power and properly connected to the raspberry pi. The likelihood of all these scenarios occurring at once is extremely unlikely. The probability that just one of these events occurs is more likely and could jeopardize the project depending on how far into the project it happens. *(Likely-0.5, May Jeopardize the Project-4)*

3) Support for operating system expires: The libraries can't be installed because there is no support for the Raspberry Pi operating system. Writing manual codes for libraries and drivers and having backup for Lidar can be helpful. *(Low Likelihood-0.3, May Jeopardize Project-4)*

4) Robot Does Not Make Correct Decisions: Robot does not follow optimum path. Changes to the path such as terrain, weather, objects in its path can affect its decision making. The most likely factors affecting the optimum path are water, since mud collecting on the tires will alter its correct speed readings, and sudden appearances of objects crossing the sensors' range of detection which affects the processing speed of the controller. Steps for mitigation include code debugging sensor data filtering to keep the controller from slowing down due to processing unnecessary data. *(Low Likelihood-0.3, May Jeopardize Project-4)*

5) Controller Continues Functions When Not Necessary: The debugging, testing, and integration process may reveal compatibility issues between the different written programs that may keep certain in an endless loop. The best option for mitigation will be continuous testing and debugging that includes hardcoded conditions in the main code that ends unnecessary functions. *(Low Likelihood-0.3, May Jeopardize Project-4)*

VIII. Design Philosophy

Everything has a starting point. The beginning of this project began in a small backyard in the city of Elk Grove just outside of Sacramento. Jason picked up gardening over the summer of 2018 as a hobby and soon discovered how important pollination was to farming. This sparked the idea of a robotic pollinator that would help farmers with their pollination demands. Jason has a few friends in farming and they told him certain farmers are struggling because of the lack of pollinators to go around to all the farms. Jason brought this idea to his team and they made it a reality. Over the course of two semesters in senior design, the team built a robot from an idea to an operable machine.

After countless hours of researching pollinators, farms, flower anatomy and other various things, the team settled on working with self-pollinating flowers. The team also wanted a low growing, sturdy plant that had a flowering season between February through April. Strawberries were the perfect candidates that fit all the listed criteria. This choice of crop influenced a lot of the design that the team took to produce a working prototype over the course of the two semesters.

A. Body Design

The body design began with knowing the plant that we were designing this robot for. While the team wanted to do all self-pollinating plants, they were not able to achieve something like that. Some self-pollinating plants such as tomatoes vary greatly in height. The team would have needed more time to address a problem like that, so they stuck with strawberry plants. These plants are grown 40" to 44" apart which at first can be very deceiving. The plant size then needs to be taken into account which left little room for a robot width. The team originally wanted a body that was roughly 28" wide which would have provided stability, but it would not have fit between the rows. The body design was a simple rectangular design. The technical drawings can be found in Appendix D-1.

1) Plastic/Metal: When it came to the choice of material, the team wanted something that was light, durable, and didn't submit to the elements. Plastic, specifically PVC was chosen which we were able to acquire by a donation from Clark Pacific. They also cut the material to the specifications given to them. To speed up the build of the robot and not to put in a lot of focus into the physical design and manufacturing, the team decided that robot panels would be joined together using aluminum L-brackets. This too was a material that was light, durable, and didn't submit to the elements. It also provided with a tough edge for the plastic pieces which ensure that no chipping at the edges would occur.

2) Tires: The tires used were simple wheel burrow tires from a local hardware store. Since the robot needed some heavy-duty outdoor grade tires, this seemed as a good idea. It was later discovered during testing where the real problem with the tires were. The tire diameter between all the tires varied which cause a problem and would propagate the error in the autonomy. Also, the bearings used in the tires were not very good which caused the tire to follow and elliptical pattern instead of the typical circular path. Custom axles had to be designed and created to connect the output shaft of the motor to the tire. Since this tire and rim combination didn't have the ability to connect to a hub, we had to directly tighten it to the rod.

3) RWD: During the design phase of the robot, the team had the choice between an AWD or RWD robot. RWD was chosen based on a few factors. First, we were limited in the size of the robot that were able to design. This meant that the internal space available was a key factor to the type and amount of motors we could use. Secondly, since we were trying to build a pollination assisting robot, we needed it to work long hours to meet pollination demands. Since an AWD robot would take more energy, we designed it with RWD since RWD are capable of oversteer, something FWD are not capable of. Later during testing in the second semester, this design choice presented problems errors that had to be accounted for.

B. Power

Efficiency of the system was a partial concern when designing this robot. We wanted it to operate as long as possible to maximize the amount of land the pollinator could cover. This caused us to design the system using only certain sensors while also carefully checking the number of components being used. Powering the whole system are two 12V SLA batteries connected in series to give the system 24V. This was used to reduce the amount of current the motors would draw which increases the operating time of the robot. Since the batteries hold a certain amount of energy, we always had to do simple power calculations to estimate whether the component would affect the target operating time of 1.5 hours. This target time was far below what we wanted but since we didn't have much experience with a project like this, we set achievable metrics. It turned out after testing, our system was able to operate for roughly ten hours, far above the value we initially proposed. The system is charged using an electric scooter smart battery charger which use PWM charging to slowly charge the SLA batteries as the manufacturer recommends while delivering the 5 A-hr. This allowed our batteries to be charged in under 6 hours which was something we said we would be able to do.

TABLE VI
POWER CALCULATIONS

Components	Voltage (Volts)	Current (Amps)	Power (Watts)
Motor 1	24	1.5	36
Motor 2	24	1.5	36
Raspberry Pi	5	2.5	12.5
LIDAR	5	0.45	2.25
Servo 1	5	0.6	3
Servo 2	5	0.6	3
Servo 3	5	0.18	1.2
Total Power			93.95
Battery 1	12	22	264
Battery 2	12	22	264
Total Power			528

C. Motors

When choosing the motors, factors such as torque, RPM, and power required had to be considered. From those factors, we were able to start limiting the selection of motors to choose from The motors that were chosen were high in torque, fairly efficient, and were 90-degree angled which allowed to fit into the narrow body that we had originally planned for. These motors had the option of 12V or 24V in which the 24V option was chosen. This option was considered because at 24V it would lower the input current necessary to turn the motors. This is a simple P=IV problem where if the motors draw a certain amount of power, increasing the V will decrease the I. With the increased voltage, this allows us to use a higher gauge wire since the current will be smaller. This is a V = IR problem. With a decrease in current, we can use a higher resistance wire such as the higher gauge. In some applications where wire weight needs to be considered, using a higher voltage source helps by decreasing the size of the wire we need.

The motors that were chosen were a 4-in-1 package deal. The complete set came with a motor, a gearbox, a torque-converter, and shaft encoders. This was a perfect fit for the application we had. The motor is attached to gearbox that reduces the RPM but increases the output torque. The max rpm of the motor running at 24V is 7000 rpm with no load. Its rated speed is 5900 rpm with the torque at 570 g-cm. With the gearbox that has a 1:49 reduction ratio, the rpm is brought down to a max of 122 rpm producing torque at 15 kg-cm. That brings up the amount of torque we have at the output shaft by 26 times which will allow for the robot to have more power to move itself around. Attached to that gearbox is a 90-degree torque converter with a 1:1 ratio that keeps all the power and torque constant, even though the direction had changed. One drawback with the torque converter is that it has a little bit of play between the two gears that causes a very small delay between movement of the motor vs the movement of the output shaft. This delay is negligible.

The goal is to run the robot for as long as possible so efficiency is something that must be considered. According to the spec sheet of the motors, with the reduction ratio of 1:49, the motors can operate at 60% efficiency at around 4000 rpm according to *Figure 1* and the spec sheet. This means at the output shaft the peak efficiency is at 83.6 rpm. While that would be the optimal speed, to run the motors at, we are looking at operating at about 34 rpm. Efficiency and actual rpm is still yet to be tested.

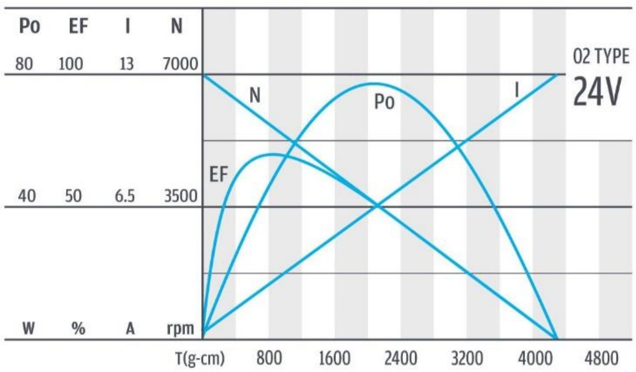


Fig 6. The power, efficiency, current, and rpm over the torque diagram. This is the motor alone without the gear box that we have installed. [28]

D. Motor Controller

The motors are connected to a motor controller. The purpose of a motor controller is to provide power to the motors since a microcontroller such as the Raspberry Pi cannot handle the current that a motor draws. The motor controller that was chosen had specifications that were above anything the robot needed. This was justified because a motor controller that was around the current limits that the motors would draw were similar in price as one that was beyond the specs that the robot needed.

The motor controller that is inside the robot is a Sabertooth 2x32. It has a max voltage rating of 33.6V which is far beyond the 24V the motors will be using. It is able to supply 32A of current to each motor which is far beyond the 13A the motors could potentially draw at peak load. It has different settings on it that allow for different input modes such as analog, R/C, or serial inputs which will be discussed later. This motor controller allows for regenerative power to pass through it. It sends this power back to the batteries without the need to add in a resistor to dissipate this extra energy. Since this recharges the batteries, this allows the system to be more efficient which allows it to run for longer.

An addition to the motor controller, Dimension Engineering, the company that builds the motor controller builds an additional component that simplifies the control process. This device known as a Kangaroo x2 is a motion controller that plugs directly into the motor controller. The Kangaroo accepts feedback from things like encoders and limit switches to decide how to drive the motors. It has PID feedback programmed into it, so it takes the data from the feedback inputs and provides an output.

E. Encoders

Wheel encoders have a big part in electronic control systems. The encoders provide a feedback loop, letting the microcontroller receive information about the rotation of the tires. The encoders are directly linked to the motor shaft, so it receives data about the shaft and nothing else. This means to know the rotation of the tires, some simple math has to be calculated.

The encoders that were provided are considered quadrature, magnetic encoders. A magnetic disk attached to the motor shaft rotates while hall-effect sensors pick up the magnetic fields of the disk. This means that there are two input channels reading the data on the encoder. The sensors are spaced apart, meaning that the encoder ticks occur at different points in time allowing the system to know which direction the shaft is moving. The testing will be discussed in the white-box testing section.

We used a buffer board known as the LS7366R that read the encoder count. This is placed so that the microcontroller doesn't need to constantly read the pulses of the encoders but just has to call out to the buffer board to receive a count on the data. The LS7366R is then called using two pins to select which encoder needs to be read. Its clock is in sync with the CPU clock so that it sends and receives the data at the speed the main microcontroller can handle.

After reading the data from the encoders, we could then determine things like speed and linear distance by some simple mathematics. When we know the RPM of the motor, we then can multiply it by the reduction ratio of the gear box and get the rpm of the tire. Using the dimensions of the tire and rpm they are rotating at we can tell solve for linear distance and speed of the tire.

CPR: Counts per Revolution = 20
CPI: Counts per inch = 29.9
CPF: Counts per foot = 358.8
dt: time sleep given by program

$$rev_{motor} = CPR_{quadrature} \quad (1)$$

$$rev_{output} = 49 rev_{motor} \quad (2)$$

$$CPI = \frac{rev_{output}}{circumference} \quad (3)$$

$$CPF = 12 * CPI \quad (4)$$

$$dx = \frac{x_{[k]} - x_{[k-1]}}{CPF} \quad (5)$$

$$v_{left} = \frac{dx_{left}}{dt} \quad (6)$$

$$v_{right} = \frac{dx_{right}}{dt} \quad (7)$$

F. Controlling

The Saber Tooth has different modes on it that allows the user to choose the way they want to control the motors. Some of those options include radio-controlled, serial, analog, or a combination of them. The ultimate goal is to control it by sending serial packets with the ability to have R/C override. A benefit to this motor controller is that it has a pre-programmed library on it which allows the users to control the motors much simpler. The user has the ability to send commands such as ‘M1:200’ to rotate motor at 20% of the peak operating speed.

During the first semester, Team 10 made the robot move using R/C. It does this by sending pulse widths from the receiver and the pulse width would dictate the direction and speed of the motors. The beneficial part of using a radio-controller is that it allows to bypass all the coding necessary to move the robot. This allowed for rapid prototyping, something we had to do for the first semester.

The Sabertooth has two modes to drive the motors, mixed or independent. With independent setting, the motor speeds are individually controlled. This means that if the robot needed to turn, the user would have to vary the speed of the motors to achieve what they need. The mixed setting controls throttle and direction. This runs both motors together where one channel controls the throttle, forward and reverse, and the other channel controls the direction, left and right. The team went along with independent control as it allowed us to control the motors individually. Once testing had pursued, the team found out that the physical build had a small error. The exact cause was never found but to correct this error, the team set one motor as a master motor and the second as a slave. The slave motor would vary its velocity to match the velocity of the primary motor.

G. Pollinating Arm

The main axis consists of a stable primary shaft that is aligned in the center of the robot for balance and maximum reachability range in both directions left and right. The primary shaft consists of two layers: an inside 2 feet long 0.5 inches diameter hollow aluminum rod followed by 2 feet long .67 inch diameter durable hollow PVC rod on the outside. The aluminum rod in placed inside the PVC rod while they are both securely connected to each other using #10 screws. These rods are then connected to the main high torque servo that is securely placed inside the body for shielding purposes. The primary servo allows the robotic arm to fully rotate from left to the right side of the robot in 180 degrees range of motion. This servo is powered with 4.6~6 V by the rechargeable supply through a specific buck converter to eliminate the overdrive of current. Through the servo python condition statement code, this servo is controlled by output PWM signal from the Raspberry Pi. The main axis has been successfully tested and measured in late 2018 and ready to for pollination.

The secondary axis is responsible for vertical movements of the robotic arm with 120 degrees range of motion. The secondary axis consists of two 2-feet thin L-shape aluminum columns that are connected to each other using 2-inch #8 screws. These two columns are selected to minimize the total amount of weight that the robotic arm has to carry. Both end of these column on one side are connected to the secondary servo. The secondary servo is a high torque digital servo that allows the arm to raise up and down depending on the height of the plants. The secondary servo is powered between 4.6~6V from the rechargeable source. Similarly, to the primary servo, the PWM signal is sent to the servo from the Raspberry pi to control the movement. The secondary servo is safely attached to the top of the primary shaft. The secondary axis has been successfully tested and measured in late 2018 and ready to for pollination

The pollinating axis is responsible for pollinating process of the robotic arm with 60~90-degree horizontal sweeping range of motion. The goal for the pollinating arm is to knock the pollen off from one flower to another to assist fruit growth and reproduction. The pollinating material has to be lightweight and nonstick in order to prevent pollen getting stuck to the pollinating arm. Therefore, Team 10 decided to use horse hair for pollination purpose. The hair strands are over a foot long and are able to reach the flowers of the plants. The horse hair is attached to the pollinating rod which is attached to the pollinating servo to allow stability and durance of the arm. The pollinating rod is lightweight and durable and is attached to the pollinating servo at one end. The pollinating servo is a medium-low torque servo that allow the pollinating arm to rotate horizontally. The pollinating servo is also controlled by the PWM input signal coming from the Raspberry Pi and powered with 4.6-6V from the supply.

H. LED

Our pollination robot has the capability to show the user the current status of robot. It is needed because user should be able to see somehow what the current state of the robot is. For example, did it start, did the pollination process start, did the robot pollination stop, or if there is any error such as getting stuck in the ground. Position where it was stopped and resume the process.

The status indicator has been able to communicate with the other program files such as motors, LIDAR, voice recognition commands and main program used to run the robot. This has been implemented in a way that if the robot is started, it should display the yellow LED light. If the LED is green, the robot is in moving state. If the robot is doing pollination like moving the arm, it should have blue red on. If the robot is in idle state, the robot should have a bold RED LED light on where in case of emergency, it should be blinking the LED light very fast. It means to turn the robot off the robot and turn it on to start the process and let it move again.

To not burn out the LED's the forward voltage was measure on all of the LEDs and an appropriate resistor value was found to run 15mA of current through them to get the brightest light without burning the LED out.

TABLE VII.
LED CURRENT LIMITING RESISTOR CALCULATION

LED Color	Tested Fwd Volts	Max Current (mA)	Input Voltage (3.3V)	Resistor Value
Blue	*2.72V*	*1.50E-02*	*3.3 V*	*38.7Ω*
Green	*2.52 V*	*1.50E-02*	*3.3 V*	*52.0 Ω*
Red	*1.96 V*	*1.50E-02*	*3.3 V*	*89.3 Ω*
Yellow	*1.96 V*	*1.50E-02*	*3.3 V*	*89.3 Ω*

I. Voice

The Voice Recognition is another feature of the robot that helps in taking the voice commands from the user and then able to perform tasks such as starting the system, starting the pollination process and stopping the pollination process to make the system idle.

Furthermore, this feature has been implemented by writing the python code that communicates with the Google's API to convert the speech commands into text and get them back to the program to process the commands. These text commands are further used to process the commands for starting the robot, starting the pollination process and stopping the robot. This feature has been implemented to run at all the times when the robot power is turned on. It has required created shell programs to run at all times and then, help in communicating with different parts such as LIDAR, which takes the commands from the voice and help in moving the robot to the destination.

The robot is always running a shell program in parallel to listen for any commands such as stopping the robot in case of emergency. This is further implemented in way that an interrupt can be caused to stop all the processes and listen to what the user is saying. After that, it should have the capability to start the state or position where it was stopped and resume the process. The robot has been designed in a way that if there is no connection to Google's API, we will be able to communicate with the robot using other software libraries for offline connection.

The voice commands are designed in way that they can communicate with other programming files such as motors, arm and then perform the task. One of the other important tasks is to connect it to the status indicators to let the user know that it is listening mode. This will be a debugging process to help the user in better understanding of using the product and avoid frustration in case something is not working.

J. Ultrasonics

The HC-SR04 ultrasonic sensor has a working voltage of DC 5 Volts and working current of 1.5 mA [1]. With 4 sensors mounted onto B.A.R.I., the sensors will be wired in parallel and have a total working voltage of DC 5 Volts and working current of 60 mA. This is well within the working current of the Raspberry Pi, which is 5 A [2]. The GPIO pins of the Raspberry Pi can tolerate DC 3.3 Volts, so a stepdown converter will be required between the ultrasonic sensors and the GPIO pins.

K. LIDAR

Introducing a product like this is not an easy task. It includes so many factors to design the robot in a way that it can go to the destination on its own. But to get it to the destination, it has known its surroundings. Detecting the surrounding means giving the eyes to the robot. However, the eyes of our robot is the LIDAR. This is the system which works by using laser and creating the 3D model of the surrounding. The special algorithms were developed to read the data received from the LIDAR on the 3D maps and the coordinates received. These algorithms give it a good chance of how far and what does the detected object look like.

Getting started with the LIDAR is to buy the right product under the right budget then being able to find a way to connect it to the microcontroller for the robot, which is Raspberry PI. This process requires knowledge of drivers, TX and RX connections to the microcontroller and getting familiar with the ' YDLIDAR F4 Pro 360° Laser Scanner' Product.

The decision was made to buy this LIDAR System because of the financial constraints of the team and good reviews of the product. The device had 12 meters of range. However, while testing, the data accuracy was the the best at 5 meters because at this point the data was at the best accuracy. The system has the scanning rate of 6000 times/second and keeps rotating 360 degrees to get the data from all points around it. Scanning frequency can be chosen from 5 HZ to 12 HZ, however, the more frequency was losing data, so 8 HZ was the chosen point for frequency and when the results were optimistic.

The unique algorithms are designed in a way that they are able to look at the raw number data received to map the 3D model and then able to detect what kind of object is around it. During research it was found that the strawberry plants, our focus plants in agriculture, are cropped in the fields in a way that the rectangular in shape. This information was used to design the algorithms that can detect the object and the strawberry plants.

Using the system integration, the LIDAR is able to store the data, the program is able to make a decision and able to communicate with motors and other parts to perform the actions such as driving, stopping, going to destination and use the arm to start the pollination process.

Fig 7. This is a Lidar that is used in the Robot Pollinator. Its circular design lets it rotate 360 degrees to get better data. [29].

IX. Prototype Status

B.A.R.I. met its measurable metrics by the end of the second semester. However, in its current form, it requires a lot more work if it is to be deployable on an actual large-scale farming operation. The final prototype did not meet the form we had in our heads when we were still working on the design back in October. We had to limit its autonomy by placing more restrictions on its environment to reduce opportunity for error. Most notably, B.A.R.I. cannot actually operate between crop rows as a typical person would interpret a crop row to look like. We manipulated the environment by placing strawberry plants in plastic bins that are fifteen inches high. This was so we could ensure B.A.R.I.'s sensors would detect the desired path we wanted it to take. B.A.R.I. was also not weather-proofed, so it is only effective in clear weather and in dry conditions. The pollinating arm was effective, as is demonstrated by the hand-pollination results found in our field testing, but the method is somewhat crude and there is potential for some light damage to the plants when deployed over the crop rows. Although no damage was found after B.A.R.I. was deployed for field tests. B.A.R.I.'s movement hit our metric of 1.5 ft/s. The problem with 1.5 ft/s, which is about walking speed, is that it may be too fast for our purposes. However, we had trouble with getting B.A.R.I to move any slower. The motors needed to provide enough power to overcome the initial friction of the uneven and rough terrain it needs to operate on.

Fig. 8. This shows the robot near its final stages in the second semester. [30]

There are some bright spots. B.A.R.I. was able to move in a straight line on uneven terrain, straying only three inches after twenty-eight feet. Voice operation was successful and worked in the field tests. The only drawback might be ambient noise interfering with the robot's microphone. The body is durable and worked well under constant operation. An improvement on the body's design would be to make it larger and extend the arm out to both sides to reach more intended targets in a shorter amount of time.

Some of the team members have discussed improving the design after graduation. We see a lot of potential in this project and have several design, hardware, and software improvements that we are not prepared to publicly disclose at this time. The research and design process of this project taught us a lot about how to test and retest our prototype and we expect that over the next three years we will have the ability and experience to create a prototype worthy of a patent.

X. Market Review

A. Opportunities in the Market

Introducing a product like this would be a strong arm to some businesses, such as commercial beekeepers. Since they rely on farmers to rent bees from their business, a robot that does the job of what their bees do, would prompt a threat to them. Our focus was not on the wealth of the beekeepers, but to protect the future of humans. We built a robot that provided a solution to help society live even if the bees were to completely go extinct. Our product is not to completely harm the beekeeper's business, but rather to work alongside of them to be able to provide pollination to farmers who would otherwise have to wait their turn to pollinate their crops.

Automated pollination would eventually come to the modern world, it was just a matter of when. With CCD being mentioned everywhere, a solution had to be constructed. A semi-autonomous robotic pollinator is exactly the solution this problem needs. The current market for such a device is the agriculture department of our economy. Currently, farmers rely on the importation of bee colonies, where some have to wait for others before they can pollinate their own crops. This results in lower crop yield for the farmers without the access to bees, so pollination accessible to everyone would possibly help increase the economy.

With autonomy in place, the robot can work in places that natural pollinators have disappeared away from because of urbanization. The urban areas are interesting locations in today's age since our urbanization has caused things such as weather to change in its local area. There is a term such as "Urban Heat Island" that is used amongst meteorologists which refers to the change in weather in large cities. Studies on these heat islands have shown increase of perception of 50% compared to areas surrounding them. This makes these places ideal for growing crops since there would be less of a need to water on our own. Cities would be able to build gardens on their roofs as well as inside abandoned towers and buildings since the robotic pollinator would provide the pollination these plants need to produce crops.

Our robotic pollinator is heavily focused on the agriculture market of this world. We say the world because this robot has no limit to where it cannot go, with reasonable limitations of course. Facing extreme weather would limit this pollinator since it wasn't designed to face things like that. Since it is designed to be autonomous, extraterrestrial bodies such as Mars or the Moon are possible places where this robot could go. It could help pollinate plants where we could only rely on artificial pollination. This would help accelerate expansion to places that would otherwise seem impossible.

Aside from an autonomous pollinator being extremely versatile in where it can work, another projected outcome with such a pollinator is increased crop yield. While you might ask how, the answer is simple; complete pollination. We know that plants need to be pollinated to produce fruit, but a little-known fact is that a flower bud needs to be visited multiple times to be completely pollinated. Collecting pollen is not a bee's or other insect primary task, instead they focus on collecting nectar which is their source of food. The pollination process happens to be a byproduct of their foraging for food. Since the robotic pollinator is not interested in the nectar and its objective is only to pollinate flowers, it will reduce the amount of times it will need to visit the crops. It will be able to make multiple visits to the flower during the blooming phase, which will allow for the ovaries to be fully pollinated, thus producing better crops. Also, because all the flowers will be visited equally, it will allow for flowers that could otherwise have been neglected by bees to have been pollinated, thus increasing crop yield.

XI. Conclusion

This document has outlined our journey from the inception of our project, where we first decided on a societal problem and engineering solution, to its completion after two semesters. Our project was first inspired by the problem of colony collapse disorder. Team member Jason Smith had taken up vegetable gardening over the summer of 2018 before the first semester of the senior design project. On the Friday before the fall semester started, he was sitting outside watching the bees going about their business. This is when a quote attributed to Albert Einstein about honey bees popped into his head.

"If the bee disappeared off the face of the Earth, man would only have four years left to live."

Forming a team was not difficult as all five team members were enthusiastic about the idea of a robotic project that would contribute to a societal problem that is receiving more attention in the national news media. As the project moved forward, our overall understanding\ of colony collapse disorder changed in that we began to see colony collapse disorder as a contributing factor to a major larger problem; which is the overall availability of pollinators to farmers in agricultural areas. This change in understanding of the societal problem from colony collapse disorder itself to a much the much larger problem of pollinator availability stems from two factors. The first is that California, the nation's largest domesticated beekeeper with more than half the nation's bee colonies, still needs to import billions of bees every year to meet the state's pollination needs. The second came from a conversation from a local farmer who had trouble locking down his usual pollination supplier recently. Kevin Solari, a Stockton, California farmer spoke to us in January about his trouble. His blooms had started coming in and his usual suppliers were still occupied with their almond farming clients. This is not unusual in that almond farmers usually hold on to bees longer than other farmers. Around five or six weeks compared to other farmers who may only rent them for three or four weeks. This left Solari scrambling to find a new pollination supplier since, as he says, "When your blooms start coming in, you want to start pollinating." We started to see our project in a new light; Giving farmers the ability to pollinate at will.

The honey bee used to be the unsung hero of agriculture. In recent years we have heard beekeepers sound the alarm when their bee colonies started inexplicably dying off. This newfound coverage by the nation's media has helped to educate the public about just how valuable the honey bee is to our nation's food supply. Bees contribute a little more than ten percent to the nation's agricultural gross domestic product and it is estimated that pollinators such as bees are responsible for eighty-seven percent of all flowering plants species and sixty percent of the world's food supply. But colony collapse disorder, the problem receiving most of the media exposure when it comes to bees, is a contributing factor to the much larger problem of a growing population to feed and limited resources. One positive outcome from our project is that we hope a product such as ours will one day contribute to reducing the number of miles that bees travel each year to meet our farmers' pollination needs. We do not intend to replace the honey bee. The honey bee is the most efficient pollinator that exists today. We hope to augment the valuable contribution that bees make to our food supply.

Our proposal is to design and build a robotic pollinator that assists the pollination efforts of self-pollinating crops. The name "self-pollinator" is misleading. They still require a pollinator such as the honey bee to facilitate the fertilization process. Self-pollinators do not need their pollen to be transferred from one flower to another. The pollen of a self-pollinator can fertilize its own flower. We decided that this would reduce the amount of precision required as compared to what is needed for cross-pollinators. With self-pollinators our plan is to mimic hand-pollination by creating a disturbance to the bloom that loosens the pollen so that it falls into the flower's pistil. We chose the strawberry plant because it is a significant crop to California's economy, it grows in rows low to the ground, and is durable enough to survive the agricultural efforts of a bunch of engineering students.

We assigned six features for our robot, which would be named B.A.R.I.; short for Blossom Assisting Robotic Intelligence. Maneuverability, movable arm, path planning, rechargeable power supply, voice recognition (V.O.I.C.- Voice Operated Input Command), and led status indicators. The maneuverability is necessary for navigating the tight spaces between crop rows. The movable arm will be the pollinator for B.A.R.I. It will deploy horizontally over the crops as B.A.R.I. travels between rows. The rechargeable power supply allows for the farmer to charge the batteries in a timely manner so it can be in constant use for as many days as needed. Voice recognition allows the farmer ease of use with a few basic commands to stop and start the robot as well as a system override in case the user need to stop the robot mid-process. Status indicators give the user a visual display of what process the robot is currently in, and also allows the user to see if the robot is ready to take commands.

Aside from the six features that define our project, we also constructed a grow facility where we could test if our process of automated hand-pollination is viable. Our space was limited, but we were able to set up three short crop rows where we could mimic the pollination process by hand until B.A.R.I. is ready for deployment. Each row had four plants. The three crop rows were classified differently to test the viability of our pollination process. Row one was protected by a seed cloth that allowed sunlight in. The cloth was wrapped over a shelter to prevent insects from getting to the blossoms. Row one was pollinated by robotic simulation only. Row two was exposed to the outdoors and any wild pollinators in the area such birds, bees, wind, and other insects. Row two was also pollinated by our robotic pollination simulation. This row represented the most likely way our project would be used in the field. Row three was also exposed to the outdoors and natural pollinators, but it would not be pollinated by robotic simulation. We would compare results of the first two rows to the third row to see how the simulated pollination performed. It should be noted that the plants were surveyed every day and there were very few signs of wild pollinators like bees. Even with such small test groups, this would be a great opportunity to test the effectiveness of our pollination method where pollinators are hard to come by. The following observations were made over a six-week period starting March 11, 2019 and ending April 21, 2019: Over the first two weeks there was a large disparity with sample sizes of each row. By week six, the sample sizes of each row were roughly the same size. We found that over the first two weeks the pollination rates were similar. Row one was at 41.67%, row two was at 50%, and row three was at 50%. By week six, when the number of blossoms were comparable to each other, row one had a pollination rate of 93.75%, row two had a pollination rate of 94.12%, and row three had a pollination rate of 78.57%. These results should be taken with a lot of caution. The number of blossoms that each row is capable of producing is very small and we could not fully guarantee that row one was fully protected from natural pollination. A more in-depth study will need be performed with much larger crop rows. Our team still found the results to be promising and plan on pursuing more testing after graduation.

Our team believes in this project to the point that some of the team members plan on working together to improve the design and performance after graduation. We expect that the new design and testing process will take several years to complete, if we are to treat this project with the respect and dedication it warrants. The process of societal problem research, design idea research, market research, and the actual build itself has taught us the careful steps required for an acceptable project. Furthermore, we learned that we cannot take the testing and troubleshooting processes for granted. We can never assume that the most basic steps have been taken when troubleshooting. Always check the obvious first before a decision is made that will complicate the design more than it needs to be. Testing the various systems and their subsequent integration into the final build must also be treated as an ongoing process. Regardless of how thorough your testing is, there is a high probability that you have not accounted for every possible scenario that a final prototype may encounter. Every step we have taken over the last two semesters has helped to reinforce the basic skills needed to be productive in the engineering industry, helped to tell a story that will influence our decision making in the years to come.

REFERENCES

[1] Oldroyd, Benjamin P. (2007). "What's Killing American Honey Bees?". PLOS Biology. 5 (6): e168. doi : 10.1371/journal.pbio.0050168. PMC 1892840 . PMID 17564497

[2] "Colony Collapse Disorder | US EPA", US EPA, 2018. [Online]. Available: https://www.epa.gov/pollinator- protection/colony-collapse-disorder. [Accessed: 24- Sep- 2018].

[3] M. Casey, "40 percent of U.S. bee colonies died in past year", cbsnews.com, 2018. [Online]. Available: https://www.cbsnews.com/news/40-percent- of-u-s-bee-colonies-died-in-past-year. [Accessed: 24- Sep- 2018].

[4] "Report on the National Stakeholders Conference on Honey Bee Health" National Honey Bee Health Stakeholder Conference Steering Committee. https://www.usda.gov/sites/default/files/documents/ReportHoneyBeeHealth.pdf

[5] No author cited, bees.techno-science.ca, 2015, [Online]. Available: https://bees.techno-science.ca/english/bees/pollination/types-of-pollinators.php [Accessed 8-September- 2018]

[7]https://plants.usda.gov/pollinators/Native_Pollinators.pdf

[8] "Bio World Plant Reproduction - ANATOMY LABELLED", ANATOMY LABELLED - Human Anatomy Picture and Labelled, 2018. [Online]. Available: https://humananatomylibrary.co/photos/887984/bio-world-plant-reproduction-plant-reproduction.asp [Accessed: 22- Sep- 2018].

[9] "Self-Pollination and Cross-Pollination | Biology for Majors II", courses.lumenlearning.com, 2018. [Online]. Available: https://courses.lumenlearning.com/wm- biology2/chapter/self-pollination-and-cross- pollination/ [Accessed: 22- Sep- 2018].

[10] "Kinds of Plants That Are Self- Pollinated", Homeguides.sfgate.com, 2018. [Online]. Available: https://homeguides.sfgate.com/kinds-plants- selfpollinated-60532.html [Accessed: 22-Sep- 2018].

[11] "Self-pollination", Encyclopedia Britannica, 2018. [Online]. Available: https://www.britannica.com/science/self-pollination/media/533423/148671 [Accessed: 22- Sep-2018].

[12] "Cross Pollination vs Self Pollination - Difference and Comparison | Diffen", Diffen.com, 2018. [Online]. Available: https://www.diffen.com/difference/Cross_Pollination_vs_Self_Pollination [Accessed: 22- Sep- 2018].

[13] "Naturally Cross-Pollinated Flowers", Homeguides.sfgate.com, 2018. [Online]. Available:

https://homeguides.sfgate.com/naturally- crosspollinated-flowers-31505.html [Accessed: 22-Sep- 2018].

[14] "What Is Pollination in Plants? - Definition & Types - Video & Lesson Transcript | Study.com", Study.com, 2018. [Online]. Available: https://study.com/academy/lesson/what-is-pollination-in-plants-definition-types- quiz.html [Accessed: 24- Sep- 2018].

[15]"Cross-pollination", Encyclopedia Britannica, 2018. [Online]. Available: https://www.britannica.com/science/cross-pollination/media/144150/148672 [Accessed: 22-Sep- 2018].

[16] C. Brittain, J. Gibbs, R. Isaacs, I. Koh, E. Lonsdorf, T. Ricketts, and N. Williams, “Modeling the status, trends, and impacts of wild bee abundance in the United States,” PNAS, vol. 113 (1), pp. 140-145, December 22, 2015

[17] usda.mannlib.cornell.edu, 2018. [Online]. Available: .txt. http://usda.mannlib.cornell.edu/usda/current/ BeeColonies/BeeColonies-08-01-2018.txt [Accessed: 22- Sep- 2018].

[18]https://www.abfnet.org/page/PollinatorFacts [Accessed 8- September- 2018]

[19] R. Abcarian "How the honey bee crisis is affecting California’s almond growers", latimes.com, 2018. [Online]. Available: http://www.latimes.com/local/abcarian/la- me-abcarian-bees-almonds-20160226- column.html [Accessed: 22- Sep- 2018].

[20] usda.mannlib.cornell.edu, 2018. [Online]. Available: http://usda.mannlib.cornell.edu/usda/current/ CostPoll/CostPoll-12-21-2017.txt. [Accessed: 22- Sep- 2018].

[21] Sk Moquammel Haque, S. Paul, B. Ghosh, “High-frequency in vitro flowering, hand-pollination and fruit setting in ten different cultivars of Capsicum spp. (C. annum, C. chinense, and C. frutescens): an initial step towards in vitro hybrid production”, Plant Cell Tissue and Organ Culture (PCTOC), vol 127 (1), July 12, 2016. [online] Available: https://link- springer-com.proxy.lib.csus.edu/article/10.1007/s112 40-016-1039-9 [Accessed 8- September- 2018]

[22] Mission 2015: Bee Technology. [online] Available at: http://web.mit.edu/12.000/www/m2015/201 5/bee_tech.html [Accessed 10 Sep. 2018].

[23] Darnoud, G. (2018). Will human workers replace pollinating bees?. [online] Global Citizen. Available at: https://www.globalcitizen.org/en/content/life-without-bees-hand-human-pollination-rural-chi/ [Accessed 29 Sep. 2018].

[24] Individual Pictures, [Photo Taken By: *Pavel Boyko]*, [Date Taken: 05-December-2018]. Purpose: Displaying Progress/Material/ Dimensions

[25] Individual Pictures, [Photo Taken By: *Pavel Boyko]*, [Date Taken: 27-November-2018]. Purpose: Displaying Progress/Material/ Dimensions

[26] Cnbc, “Deadly California wildfire now 100% contained after scorching 154,000 acres,” *CNBC*, 26-Nov-2018. [Online]. Available: https://www.cnbc.com/2018/11/25/deadly-california-wildfire-now-100percent-contained.html. [Accessed: 27-Apr-2019].

[27] J. Masters, “America's Deadliest Wildfire in 100 Years: 56 Dead in Paradise, California by Dr. Jeff Masters | Category 6,” *Weather Underground*, 14-Nov-2018. [Online]. Available: https://www.wunderground.com/cat6/Americas-Deadliest-Wildfire-100-Years-48-Dead-Paradise-California. [Accessed: 27-Apr-2019].

[28] SuperDroid Robotics, “DC Carbon-brush motor,”IG-42CRGM 02 Type, 2018

[29] *“Ydlidar SDK Manual. (n.d.)”*. [Accessed: March 4, 2019]

[30] Individual Pictures, [Photo Taken By: *Pavel Boyko]*, [Date Taken: 20-October-2019]. Purpose: Displaying Progress/Material/ Dimensions

GLOSSARY

Anther - the part of a stamen that contains the pollen.

Apis mellifera - The western honey bee or European honey bee, is the most common of the 7–12 species of honey bee worldwide. The genus name Apis is Latin for "bee", and mellifera is the Latin for "honey-bearing", referring to the species' production of honey.

AWD – All Wheel Drive

B.A.R.I. - Blossom Assisting Robotic Intelligence

CCD - Colony collapse disorder

Cross-pollinators - The transfer of pollen from the male reproductive organ (an anther or a male cone) of one plant to the female reproductive organ (a stigma or a female cone) of another plant. Insects and wind are the main agents of cross pollination.

Hand pollination - Hand pollination, also known as mechanical pollination is a technique that can be used to pollinate plants when natural or open pollination is either undesirable or insufficient. This method of pollination is done by manually transferring pollen from the stamen of one plant to the pistil of another.

LED - A light-emitting diode (LED) is a semiconductor light source that emits light when current flows through it.

LIDAR - Light Detection and Ranging, a detection system which works on the principle of radar, but uses light from a laser.

Mitigate - Make less severe, serious, or painful.

Nectar - a sugary fluid secreted by plants, especially within flowers to encourage pollination by insects and other animals. It is collected by bees to make into honey

Pistil - the female organs of a flower, comprising the stigma, style, and ovary.

RWD – Rear Wheel Drive

Pollinators - An agent that pollinates flowers

Self-pollinating - the pollination of a flower by pollen from the same flower or from another flower on the same plant.

Spindle Hair - Hair like material

Stamen - the male fertilizing organ of a flower, typically consisting of a pollen-containing anther and a filament.

U.S.D.A. - The United States Department of Agriculture, the department of the United States government that manages various programs related to food, agriculture, natural resources, rural development and nutrition.

V.O.I.C.. - Voice Operated Input Command

Wind Pollination - pollination of plants by means of pollen carried on the wind.

APPENDIX A.

User Manual

IMPORTANT

READ THIS INSTRUCTION MANUAL CAREFULLY before attempting to operate the robot.

BEFORE OPERATION - ensure that the battery is fully charged, there are no visible cracks on the body, and no loose parts.

DO NOT EVER approach the robot while it is operating. The user can call out *"TERMINATE"* to cancel all functions of the robot.

1.0 GENERAL INFORMATION

General Information section explains in general terms the system and the purpose for which it is intended.

1.1 System Overview

B.A.R.I (Blossom Assisting Robotic Intelligence) is a robotic pollinator designed to operate in farming environments, assisting in the pollination of self-pollinating flowers. It has the ability to navigate down farm rows, whether it is in a farm environment or a tower farm in an urban environment. It has been designed to be a basic system with no computer or robotic knowledge necessary. The user will power on the robot and speak to it to begin its function. The given commands are explained in another section.

1.2 Organization of the Manual

The user manual consists of x sections: General Information, System Summary, Getting started, Using The System, and Troubleshooting.

General Information section explains in general terms the system and the purpose for what it is intended.

System Summary section provides a general overview of the system. The summary outlines the systems hardware, the systems configuration, and the user levels of access.

Getting Started section explains how to start the system and what the user needs to do prior to starting the pollinator.

Using the System section provides a detailed description of the systems functions.

Troubleshooting section briefly describes what to do if the system is not operating as intended.

2.0 General Information

This robotic system is designed to assist farmers and avid planters to pollinate self-pollinating flowers. This system was designed to help those who don't have access to bees or those who have to wait their turn to rent bees.

2.1 Features

Voice Recognition (V.O.I.C.): Voice Operated Input Control. This feature allows for the user to speak input commands to the robot to perform certain functions.

Status Indicator: Displays to the user what the robot is doing at its current moment. Different colored LEDs represent different functions.

Maneuverability: It was designed to fit between standard crop rows and has the ability to pollinated up to 1.5 ft/sec.

Moveable Arm: This is the primary function of the robot. It has the ability to rotate 180° horizontally and 120° in the vertical direction.

Path Planning: The robot scans its surrounding area and moves toward the crop row to begin pollinating.
Rechargeable Power Supply: The user is able to recharge the robot in under 6 hours and have a guaranteed 1.5 hours of operation time. During testing, 10 hours of operation was achieved.

3.0 System Summary

The robot was designed to handle the tough farm environment along with minimal user input and maintenance. In this section, the hardware and software will be reviewed.

3.1 Specifications

Body Dimensions
Length: 23”
Width: 20”
Height: 32.4”
Weight: 67 lbs.
Footprint Pressure: 11.17 lbs./sq.in.

Material Properties
Material: PVC Body, Aluminum Frame
Thickness: 0.25”
Color: Grey

Arm Properties
Pollinator: Horse Hair
Range of Motion:
Vertical Sweep: 120°
Horizontal Sweep: 180°

Other Specifications
Tires Pressure: 28 PSI
Battery Voltage: 24V
Operating System: Raspbian Linux
Language: Python
Voice Operation: English

4.0 Getting Started

Before powering the robot on, make sure it has been fully charged. To do that, make sure the power switch is in the off position. This ensures that only the charge system is active and no electronics will power on. There is a charging indicator on the top side of the robot. Red means it is still charging. It will turn green once the system is done charging. A fully charged system will read about 27V at the battery terminals.

4.1 Setup for Pollination

Once the system has been charged, verify that it is ready for operation. Check the tire pressure, observe for any possible fractures or anything that would prohibit proper operation. Verify that the pollinator is in good condition and there is no debris or material stuck in the pollinating hair that could potential damage the crops.

The robot is voice activated which means the user controls the basic functions of the robot using voice commands. The system is called V.O.I.C. which means **V**oice **O**perated **I**nput **C**ommand. Listed below is a description of what the LED’s represent and what voice commands activate tasks.

4.2 LED Functions

Yellow - The yellow LED is the system health light which shows the user the the system is operating.

Green - The green LED lights up once the code has been initialized and notifies the user that the microphone is listening for an input command.

Blue - The blue LED lights up once the input command “START” has been given to it and will turn off when its told to “STOP”.

Red - The red LED lights up once it hears the command "TERMINATE" or the robot encounters an error such as getting stuck.

4.3 Pollination Commands

START - The pollinator begins driving forward and once the planter is detected, it will begin the pollination process.

STOP - The pollinator stops its process and stands idle and will listen to the start command again.

TERMINATE - The pollinator stops all functions and will not operate. It will need to be reset after this.

5.0 Using The System

Once the setup is complete and all systems have been checked, the robot is ready for work. This robot was designed to have minimal user input. This is to prevent any unnecessary functions and so that the robot wouldn't be used for anything it wasn't designed to perform.

5.1 How To Use It

Once the user is familiar with all the functions, the self-pollination process is ready to begin.

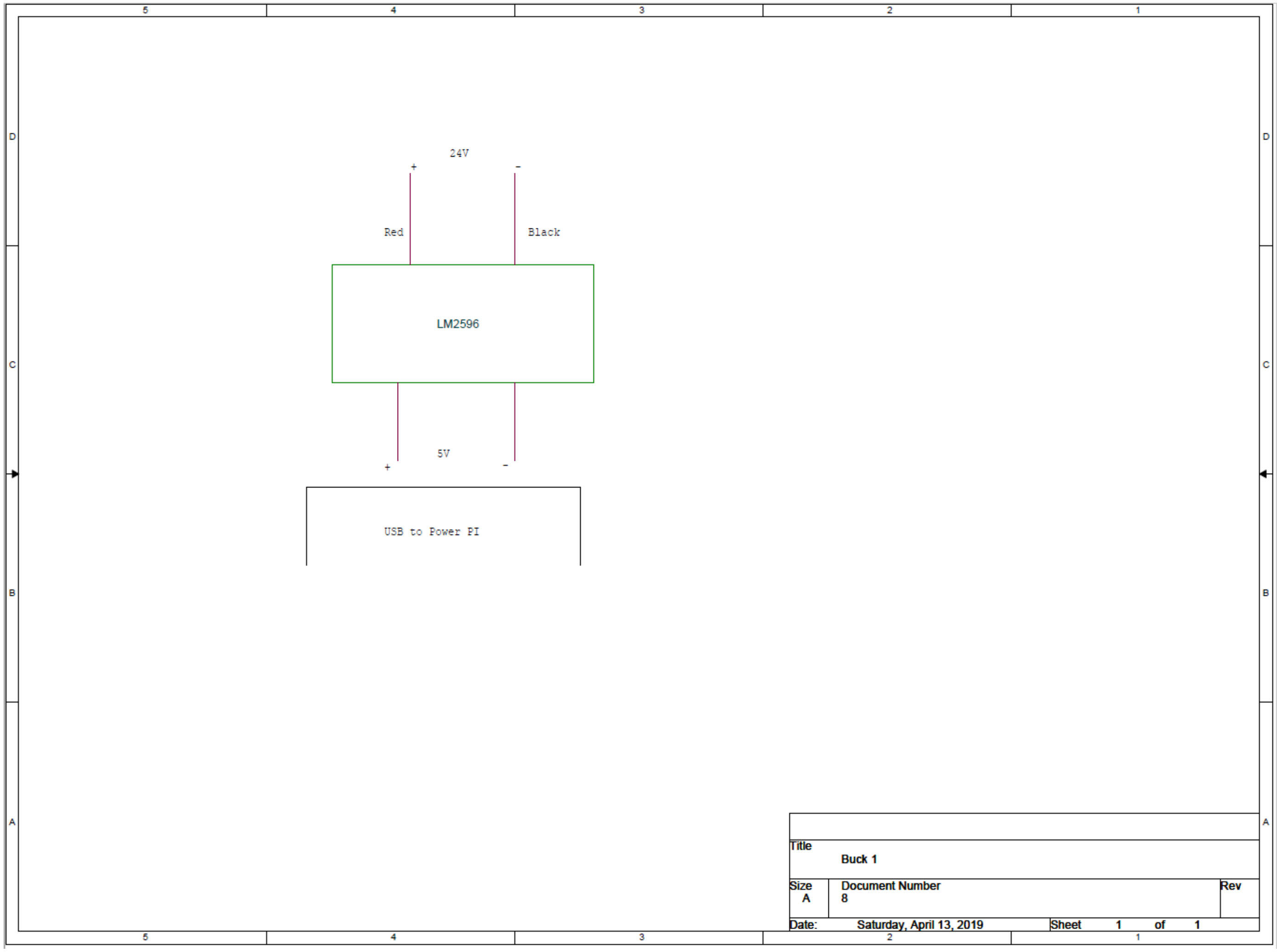
1. Place the robot parallel to the first row.
2. Turn on the robot and verify the yellow light is on.
3. Once the green light has been activated, there is about 3 seconds to give the *"START"* command.
4. Once the initial command is given, the robot will begin to operate.
5. Step away and let the robot do its work.

6.0 Troubleshooting

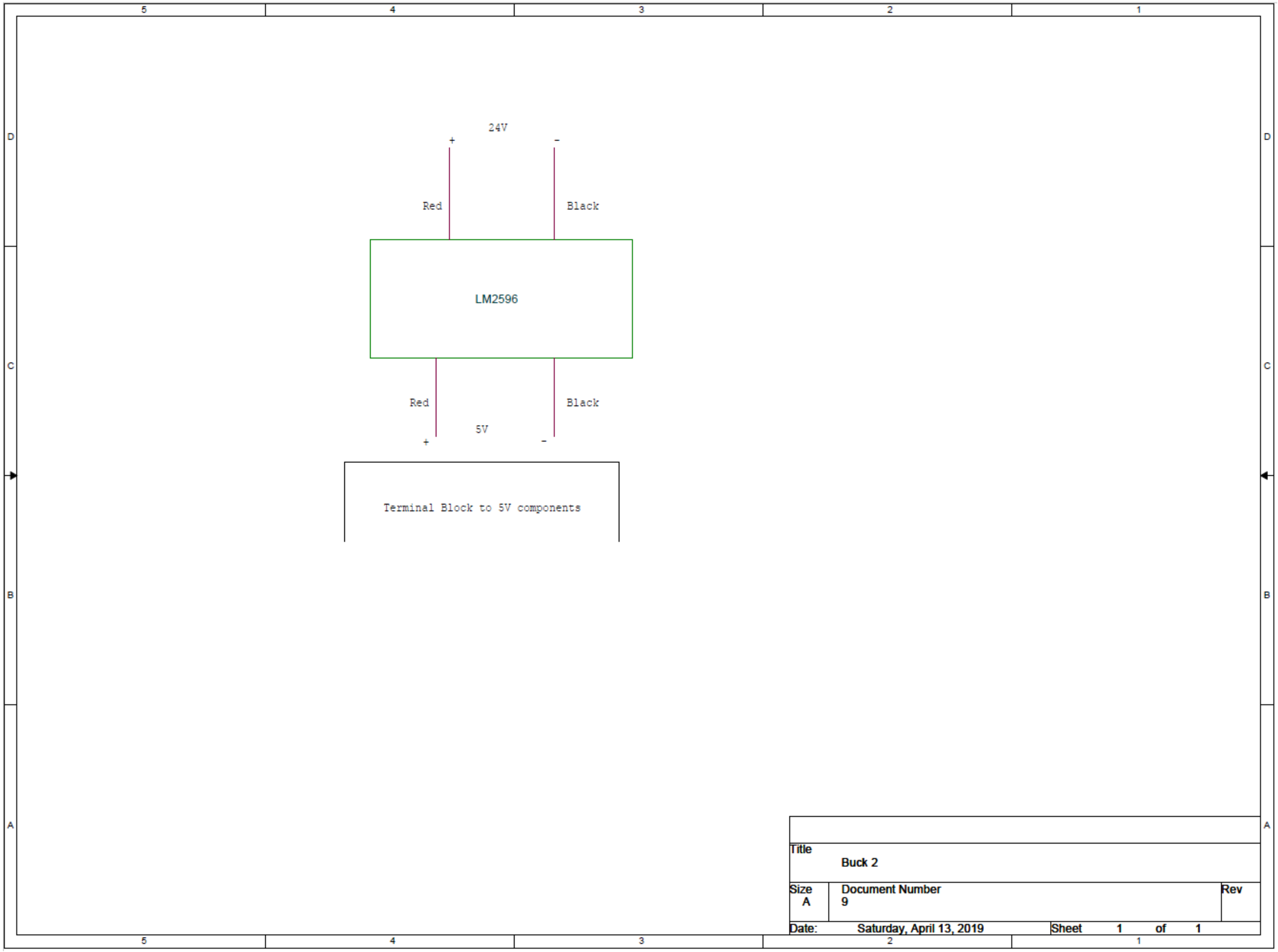
NO ACTION PERFORMED BY ROBOT- If the robot doesn't respond on the START Voice command, check if the yellow light is on. If it not, try turning off the main switch back on.

CHECKING IF ROBOT IS CHARGING – The robot should indicate the RED LED light as on, when charging. It should indicate green light once the batteries are fully charged.

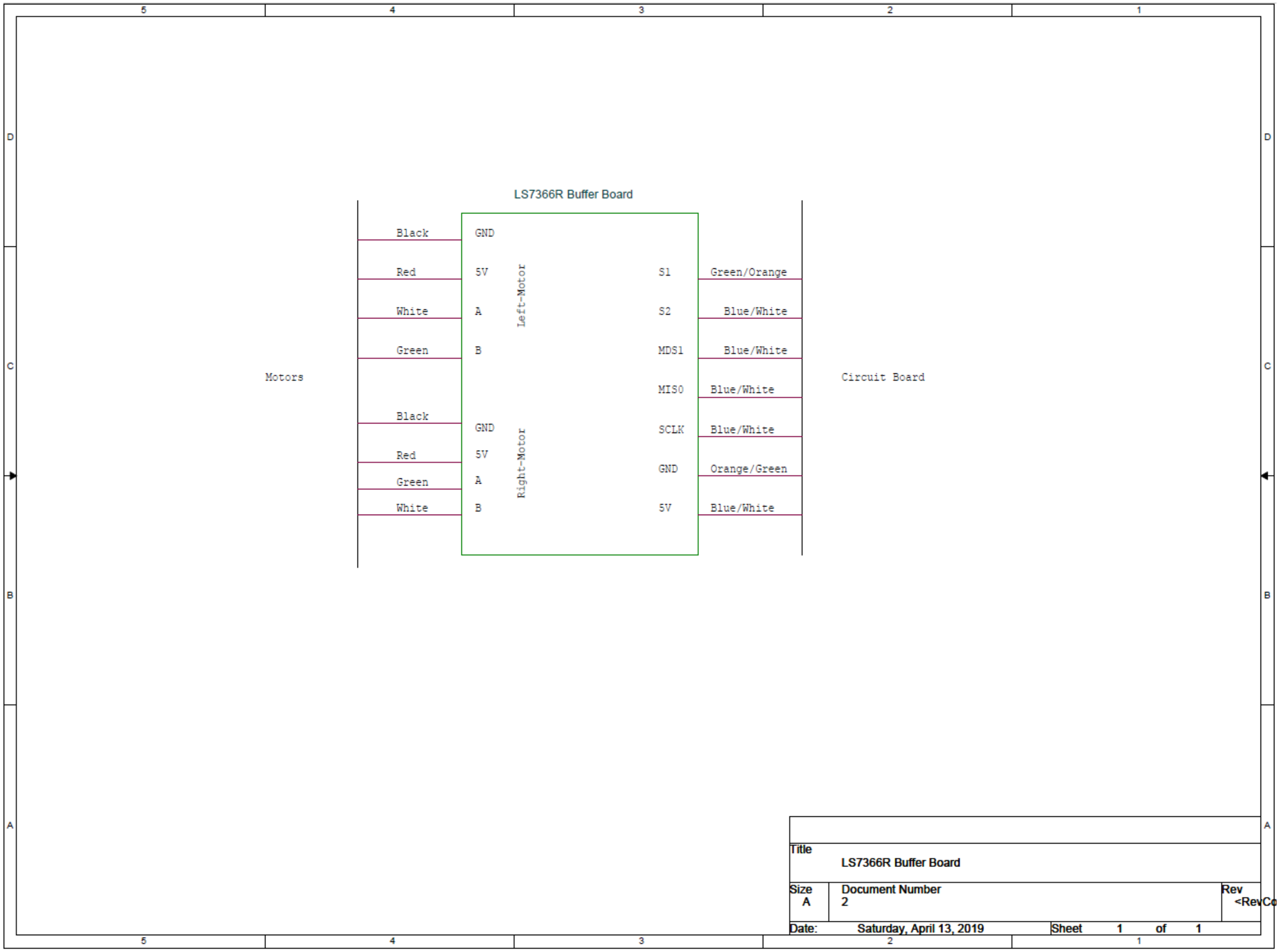
APPENDIX B.
Hardware



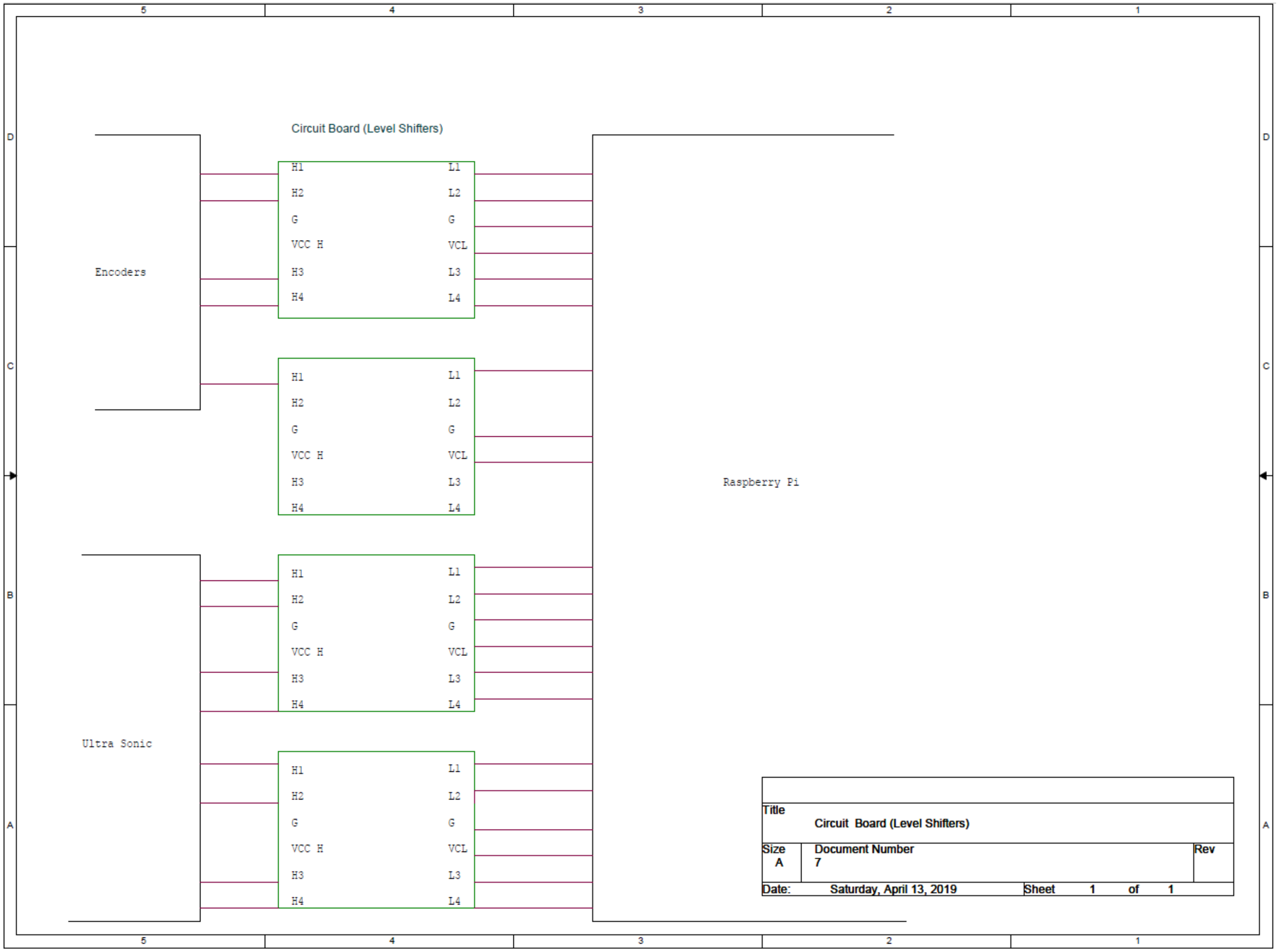
B-1. Wiring diagram schematic of a DC-DC buck converter stepping down 24 volts to 5 volts to power the Raspberry Pi.



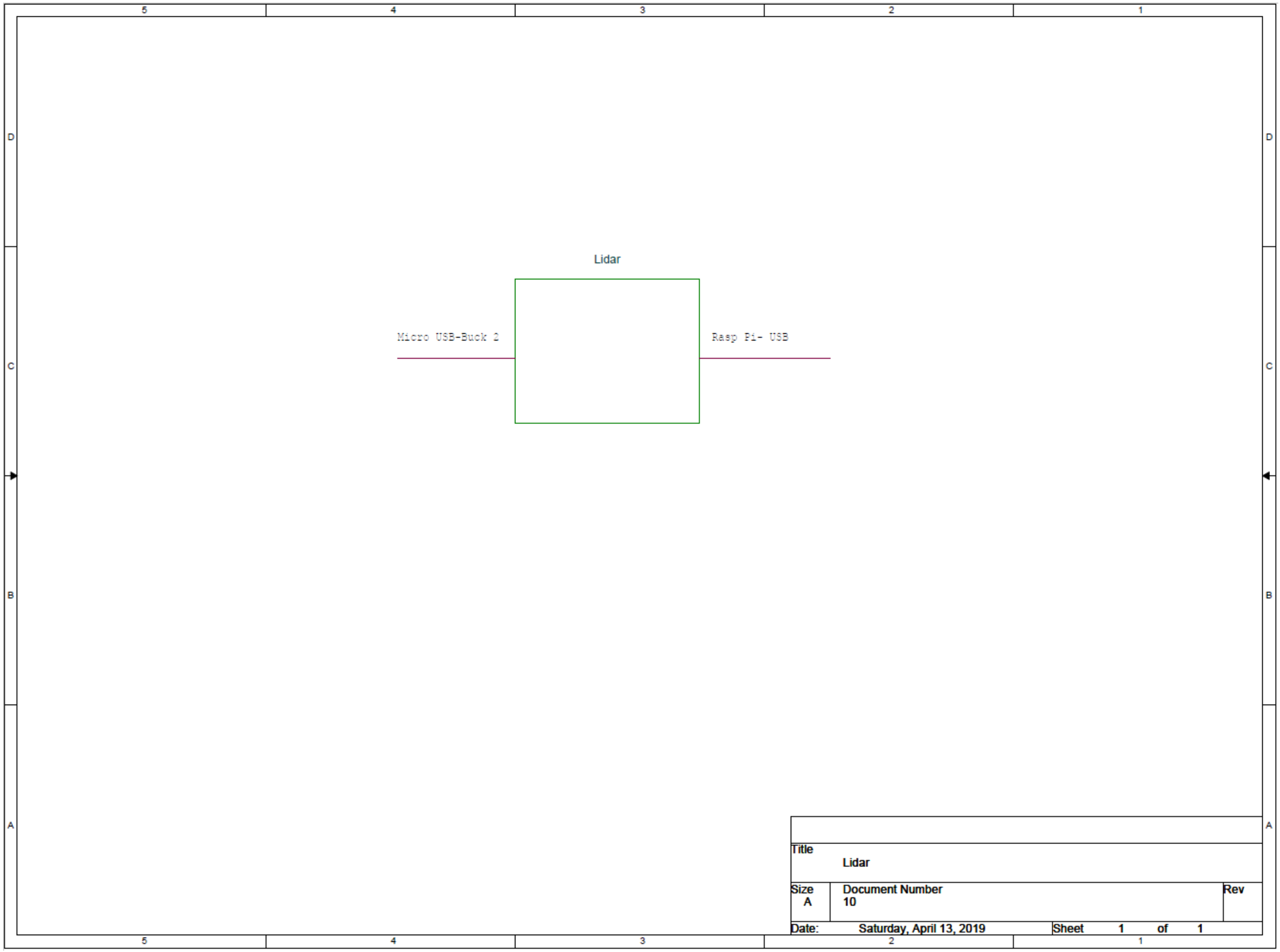
B-2. Wiring diagram schematic of a DC-DC buck converted stepping down 24 volts to a 5-volt terminal for use of the components.



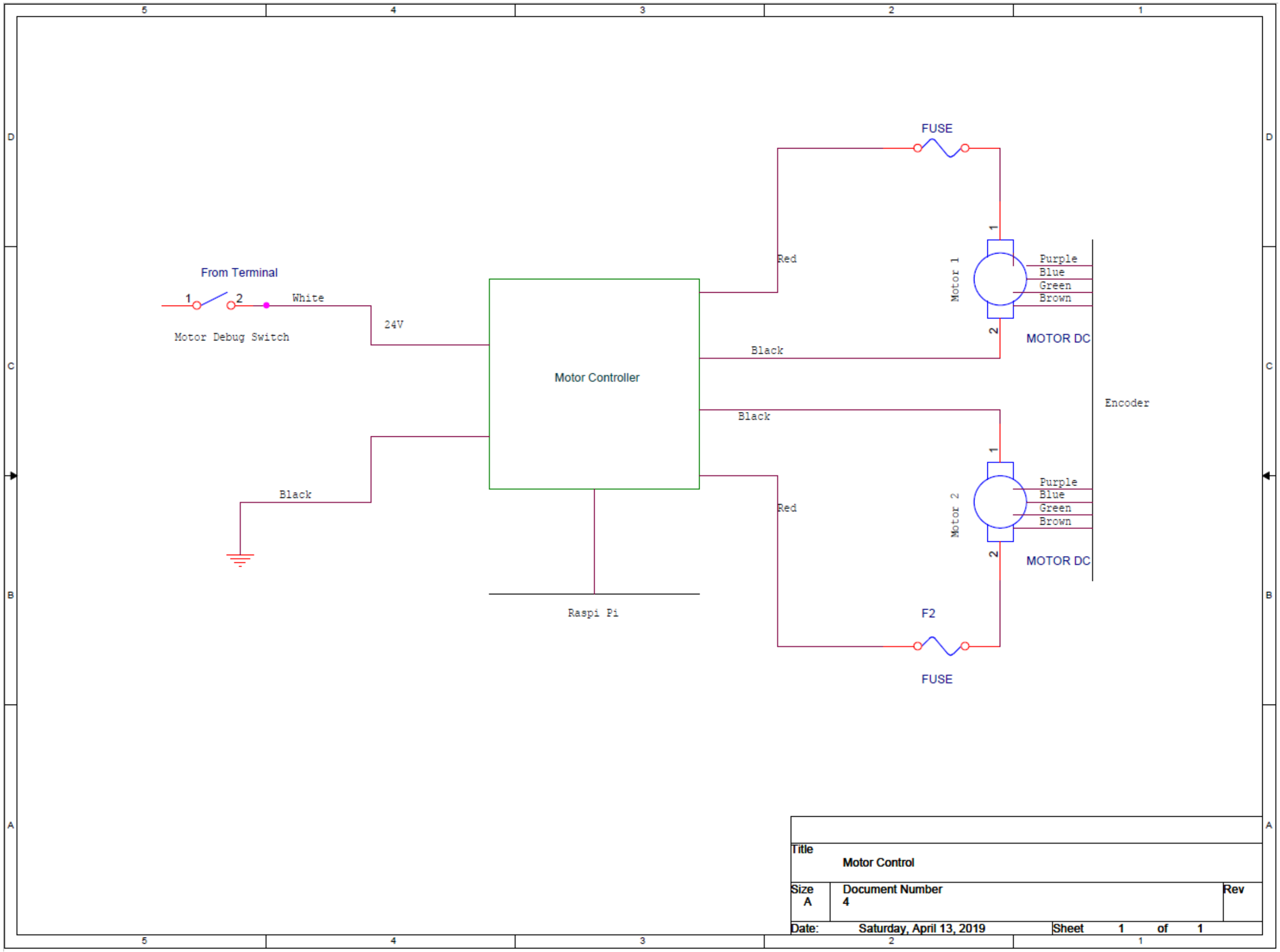
B-3. Schematic representation of the LS7366R Buffer Board wired to two motors with color coordinated wires going into the circuit board.



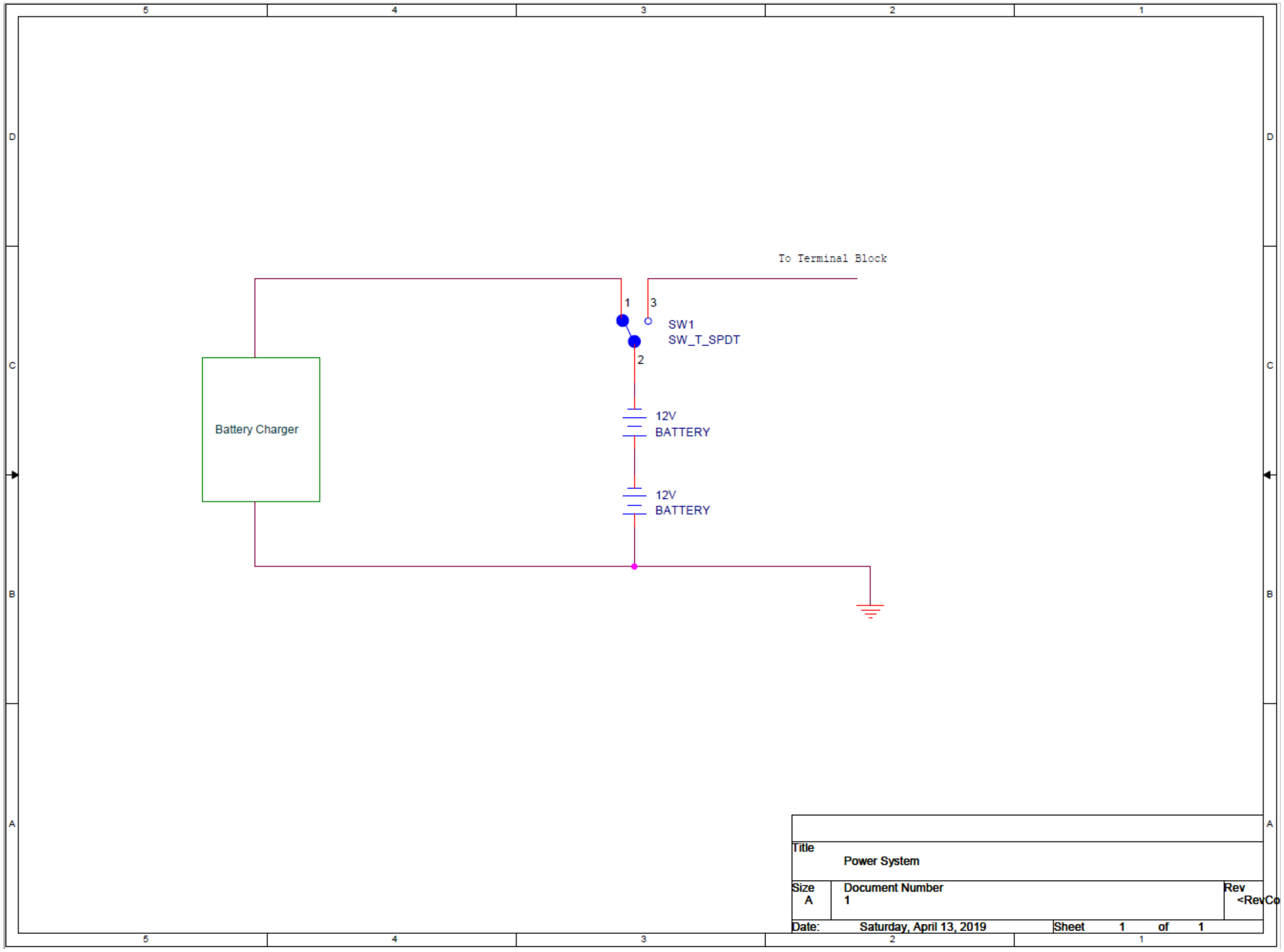
B-4. A representation of our circuit board schematic is illustrated with the wiring inputs of our electronic components.



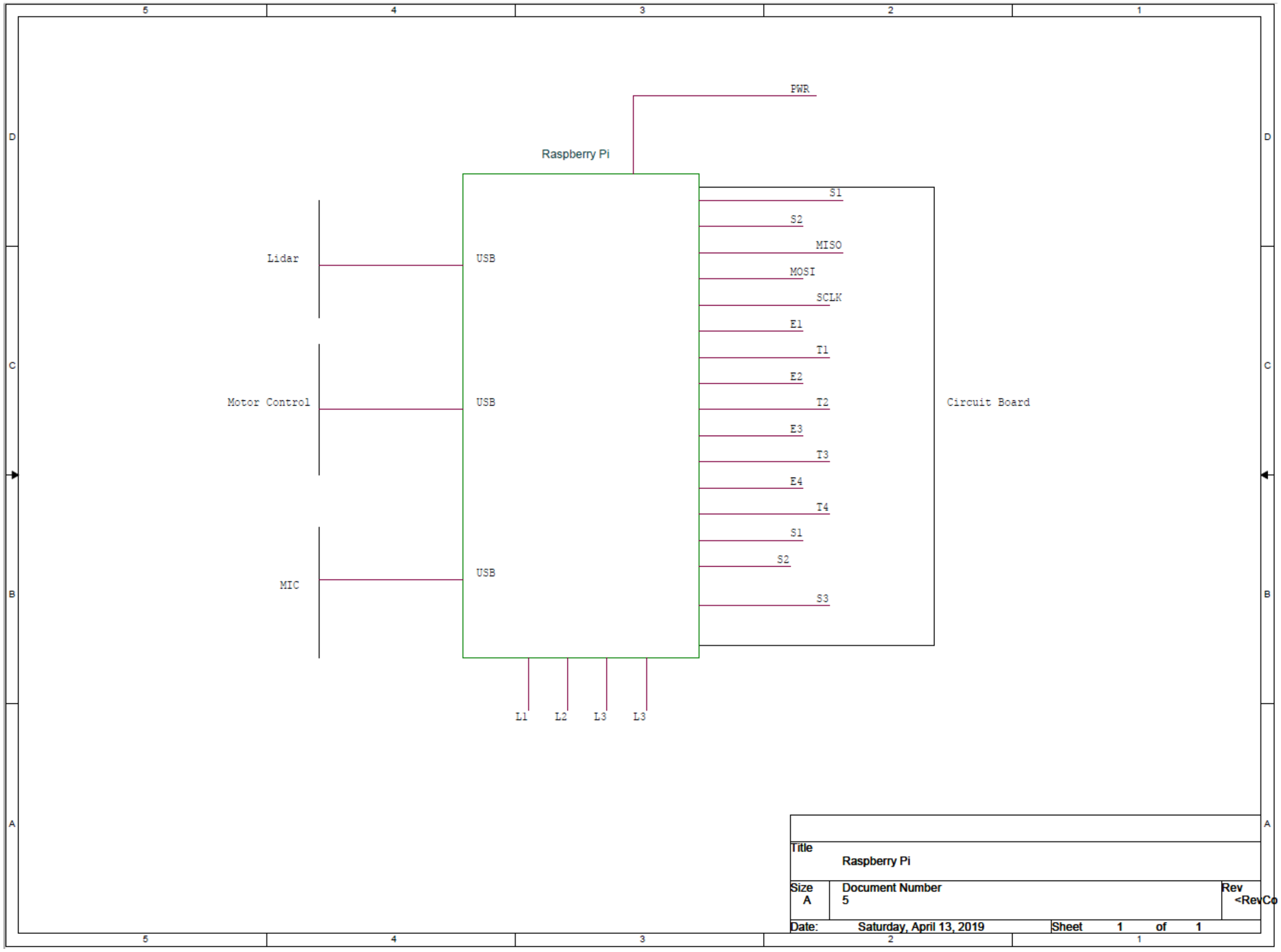
B-5. This Schematic demonstrates the wiring of the lidar connected to the raspberry pi through USB port being powered by a buck converter.



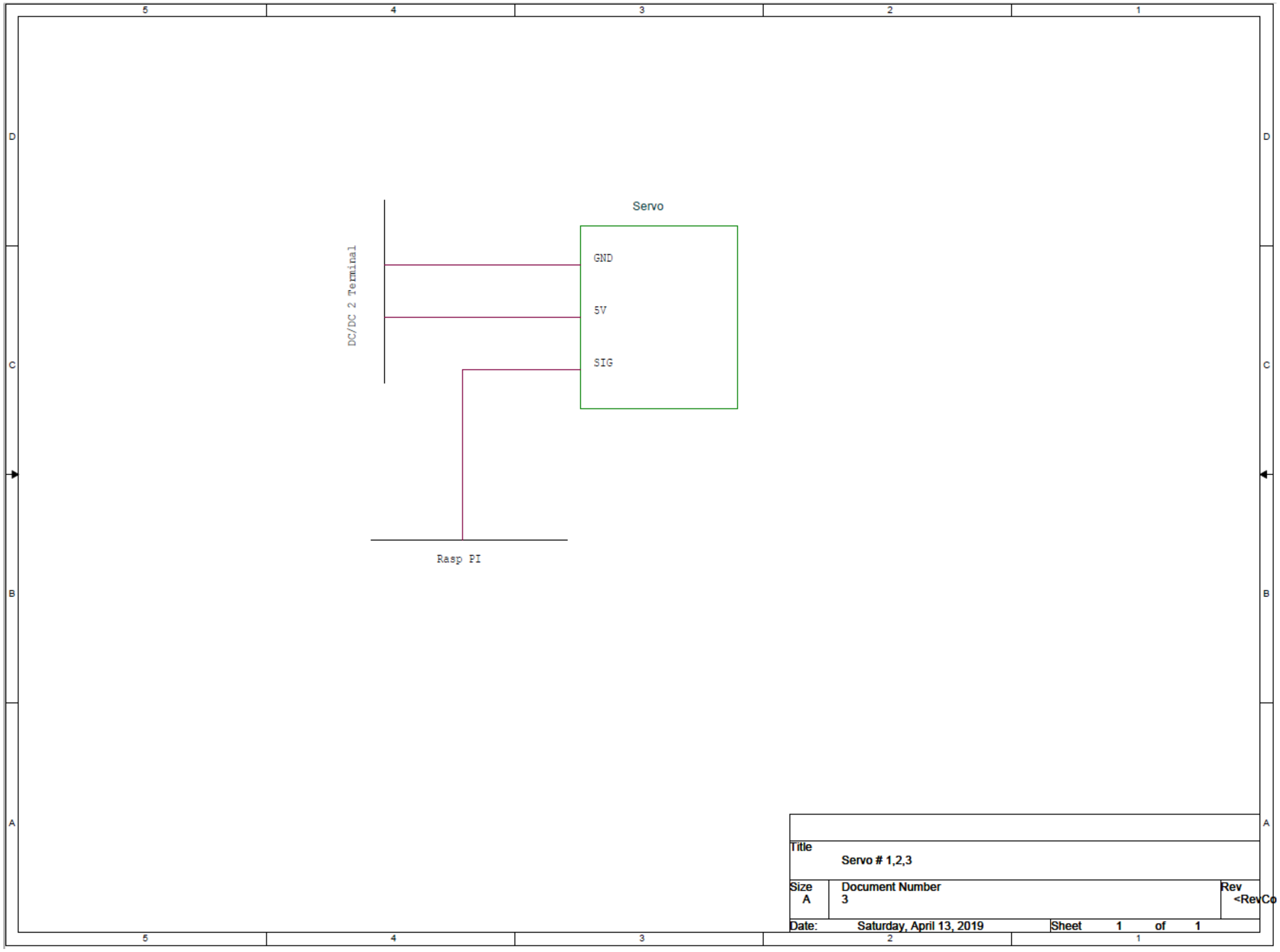
B-6. This schematic demonstrates the robots motor control system with operation of two DC motors with an inline fuse connection.



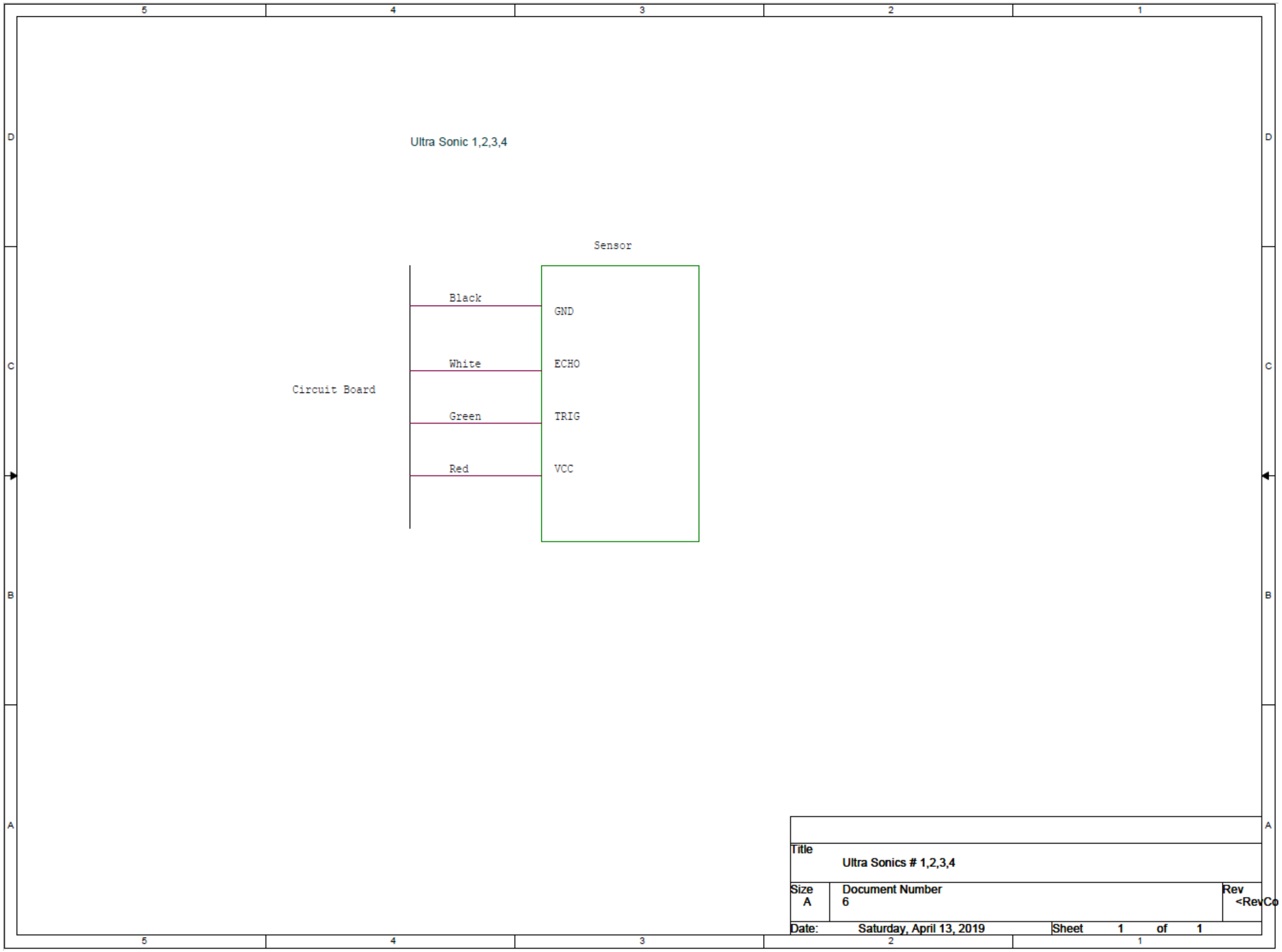
B-7. The schematic represents the wiring diagram of the charging block with a three-way switch to protect the components while in charging mode.



B-8. A representation of the microprocessor with the corresponded components wired to raspberry pi is shown in the schematic.



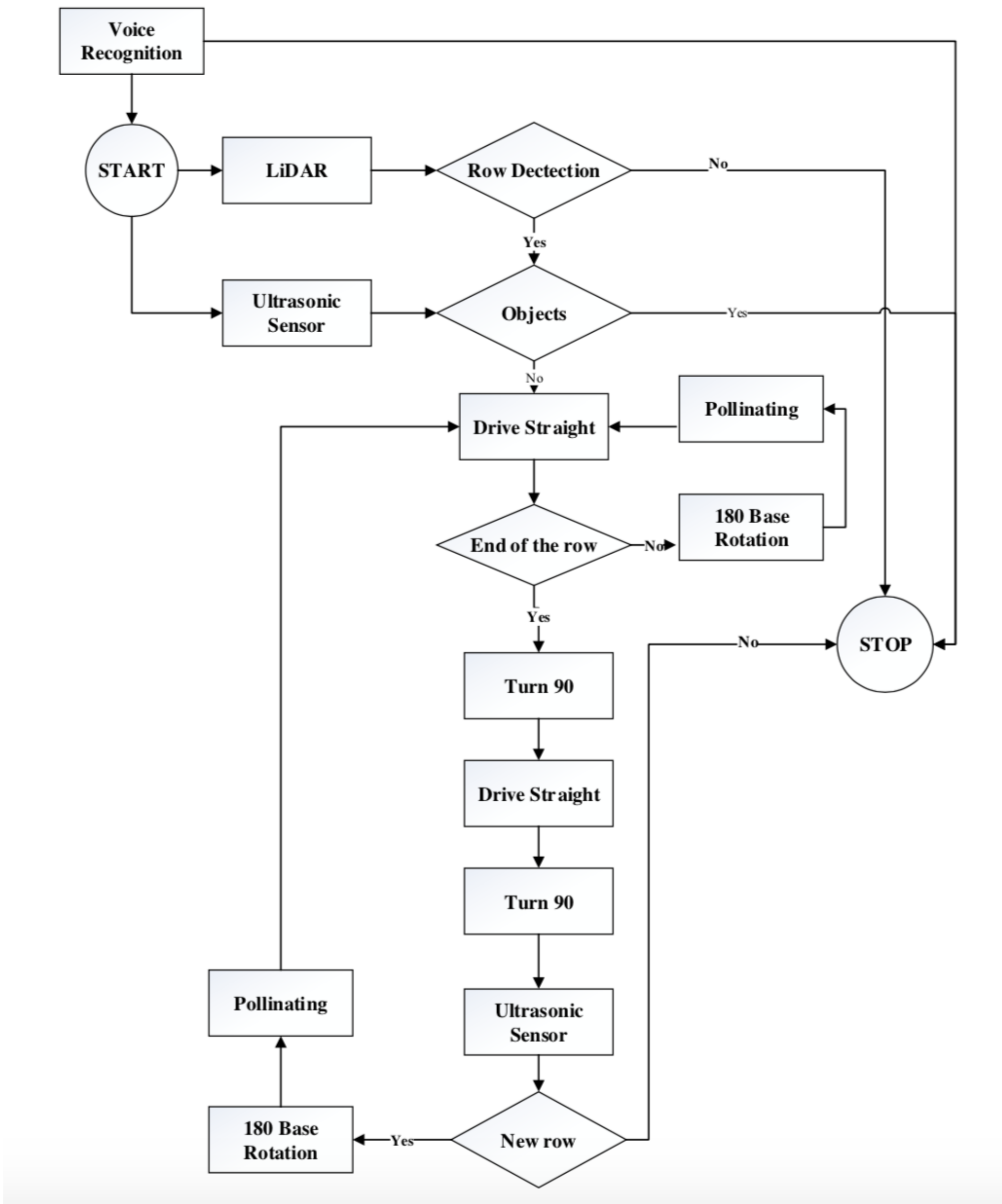
B-9. The robots uses three servos, all three are wired identical. A representation of the wiring is shown in the schematic.



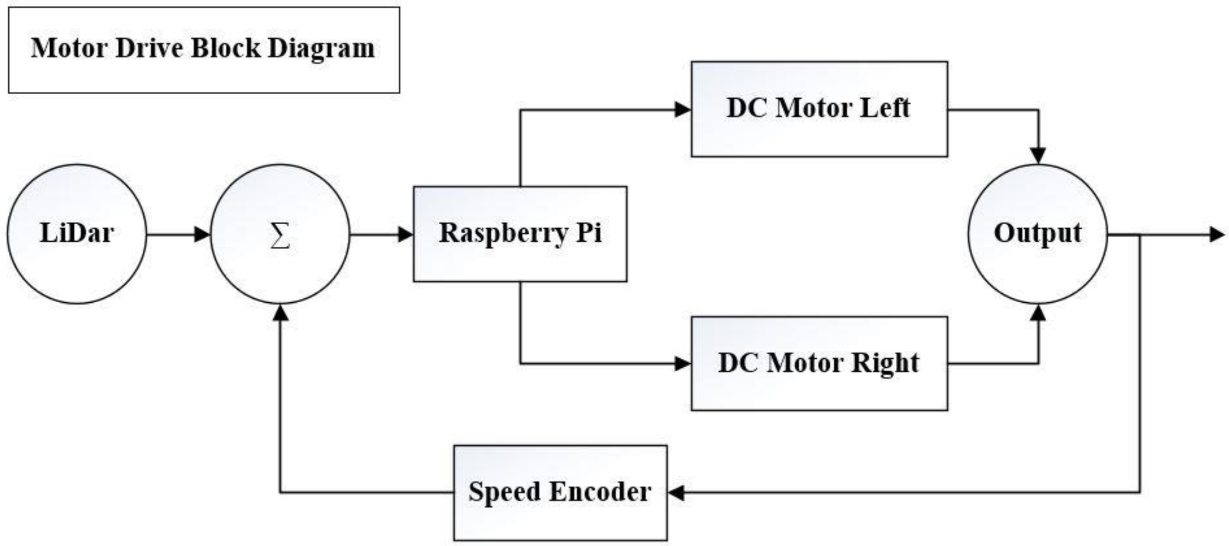
B-10. Four ultrasonic sensors are used all around, there wiring is identical among all four. A representation of their wiring is illustrated in the schematic.

APPENDIX C.
Software

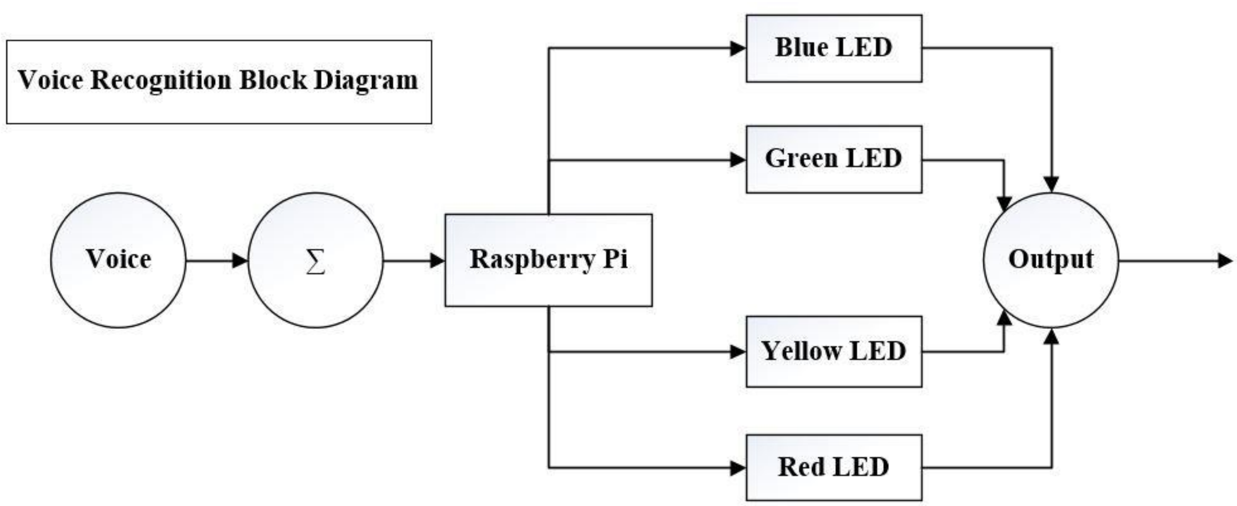
C-1. Overall Robotic Work Flow Chart.



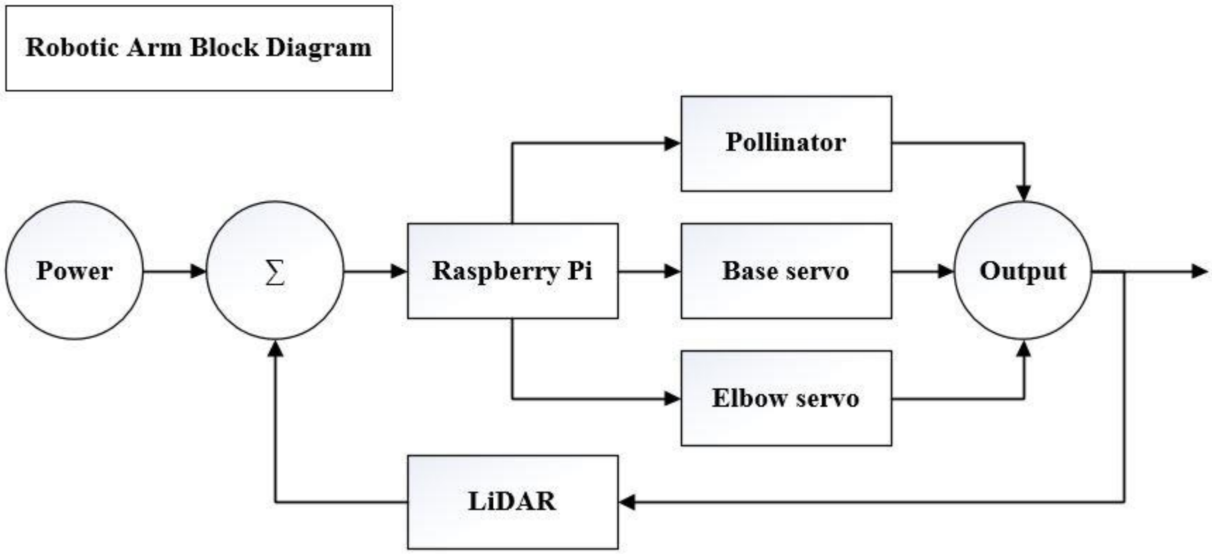
C-2. Motor Drive Block Diagram



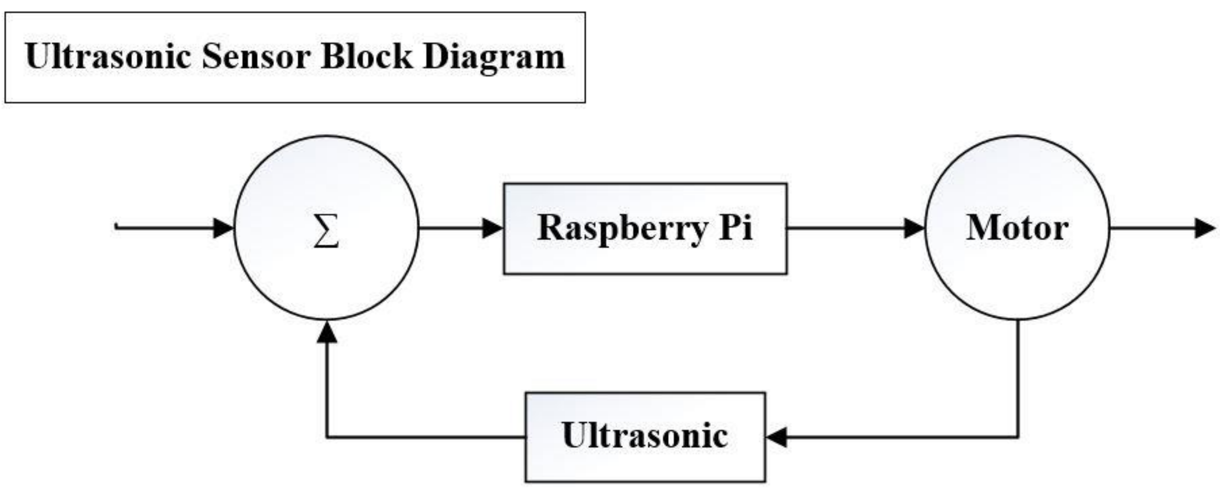
C-3. Voice Recognition Block Diagram.



C-4. Robotic Arm Block Diagram



C-5. Ultrasonic Sensor Block Diagram



Pseudo Code for the B.A.R.I. Software

Pseudo code for arm-:
If command from the main program to rotate arm
    Rotate the base servo to 180 degrees
If command from the main program to move the elbow servo
    Align the elbow servo to the preset height of plants
If command from the main program to pollinate
    Rotate the pollinator servo from 0 to 180 degrees back and forth in a while loop.

Pseudo code for motors-:
If command from the main program to move forward
    Run the function to move forward at the preset speed using straight line algorithm
    If the command from main program says to stop,
    Then stop
If command from the main program to rotate 90 degrees
    Using lidar data, align the robot to 90 degrees

Pseudo code for the lidar-:
    Run the driver to connect the lidar.
    Get the angle data and the distance data.
    Save it to the text file for reading.

Pseudo code for the ultrasonics-:
    Read the data from the ultra sonics.

Pseudo code for the voice recognition-:
    Record the voice command from the microphone.
    Convert the voice to text.

Pseudo code for the main program-:
    Read the converted text from sound.
    Do the process related to start, stop and terminate.
    If Start-:
        Look for the object using lidar data
        If no object in front of it, Keep moving the robot to the row.
        If row is detected, give command to arm to move the arm 180 degrees towards the row.
        Start the pollination and keep doing it while the row is still detected.
    If row is not detected-:
        If the row is not detected
            Give command to motors to make a 90 degree turn.
            Go straight while row is still detected.
            Make a 90 degree turn.
            Go to next row and start pollination again on the other row.
    If stop or terminate from voice command-:
        Stop the robot by stopping the python program.

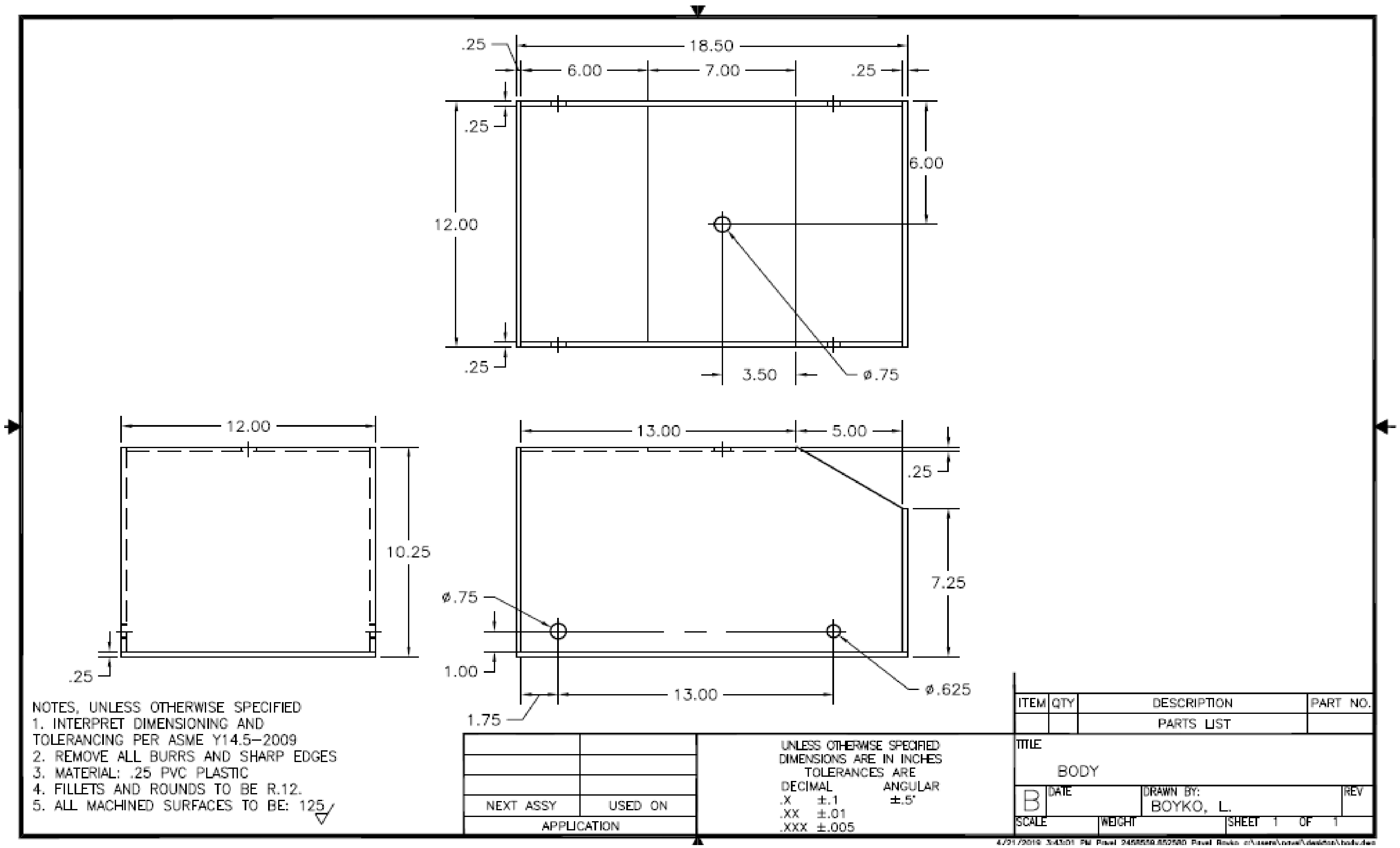
Software Test Plan

The robot consists of hardware parts that are dependent on software. The parts are motors, arm, path planning which includes the lidar and the ultrasonics sensors. This required the team to come up with a software test plan for each of the part. Each of the part was individually programmed and then tested before integrating into whole robot. The arm consists of three servos for which the code was separately written and then tested if they did what they were supposed to do. For example, the code for the base servo for the whole movement of the arm from 0 to 180 was written and then tested practically if the servo actually made a 180-degree angle. Similarly, the individual code was written for the other two servos. Once the individual results were achieved, the code for all the servos was integrated into one single python file. The whole program was tested again. However, it took the commands from user’s keyboard to verify the results. Similarly, the code for the motors was written. After, the motors were able to communicate and take commands from the user for the given power, the robot was tested by moving forward using the code for the given amount of time. The encoders, which work with the motors were also tested by letting the motors run freely. After getting the correct data from the encoders, the testing team became confident about the integration of motors and encoders together. Once, this was achieved, the motion of the robot was tested in the lab by letting the robot go in a line. After finding out that the robot doesn’t go in a straight line because of mechanical issues, the code to move the robot forward was modified. Now, this included integration of encoders and motors together in which encoders gave feedback to the motors about the motion. This was tested again. After the robot could go in a straight line, the code for lidar for path planning was integrated. This included the stopping the robot 4 feet from any object. When testing became successful, it corresponded that the lidar and motors were able to work together. After that, the code for detecting the rows was tested. This was tested by moving the arm for pollination when the row was detected. Once, this was achieved, the robot was integrated with the voice and LEDs. The voice was used to start the robot and turn on the corresponding lights. This was tested using voice commands. After recognizing the voice command, the robot started to move and detect a row. The arm moved after detecting a row and stopped at the end of the row. This was able to verify the testing plan.

Revisions made after the lab prototype

After the lab prototype was achieved, the success rate was high. However, the integration part of each feature was required. While integrating all the features together, software had to be modified. It had to be changed in a way that it could communicate with other features. For example, the program for the arm had to be changed to take commands from the main robot program. This required it to have global variables which made it possible to interact to the main program. Similarly, changes were made to the programs to start listening or take commands from the main program. Voice and LEDS worked depending on each other for the laboratory prototype. However, for the final integration of the robot, the voice and LED had to be called in from the main program to make it work. This again depended on the use of global variables and calling different functions. These were the major revisions made to the laboratory prototype to integrate all the features together.

APPENDIX D.
Mechanical



D-1. Mechanical drawing showing the actual body build of the robot.

APPENDIX E.
Vendor Contacts

Clark Pacific
40600 Co Rd 18C, Woodland, CA 95776
530-207-4100

The Home Depot
8000 Folsom Blvd, Sacramento, CA 95826
916-381-3181

SuperDroid Robots
244 Technology Lane, Fauqay-Varina, NC 27526
919-557-9162

Ace Hardware
Sacramento, CA
916-482-1900

Omni Duct
1650 Parkway Blvd, West Sacramento, CA 95691
916-492-89800

Frys Electronics
4100 Northgate Blvd, Sacramento, CA 95834
916-286-5800

Top Mobility
Hudson, FL 34667
1-888-364-3813

Tayda Electronics
167 Soi 28 Rama 6 RD
Samsennai, Payatai
Bangkok 10400 Thailand

Technician RK Ravuri
California State University Sacramento
6000 J Street, Sacramento California
Riverside Hall 3016A
916-278-7955

Amazon.com, Inc.
Customer service PO Box 81226 Seattle, WA 98108
1-888-280-4331

Harbor Freight Tools
Sacramento, CA
916-643-9640

APPENDIX F.
Resumes

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Pavel Boyko

Email: pablitoboykito@gmail.com

OBJECTIVE: To obtain a job in the electronic engineering field to enhance my skills and knowledge in this field.

EDUCATION:

***In Progress* Bachelor of Science, Electrical and Electronic Engineering;** CSU, Sacramento • Overall GPA: 3.510
Expected Graduation Date: Spring 2019

Associate of Science, Mathematics • Natural Science • Social & Behavioral Sciences; Sierra College Spring 2016

Related Courses:

Topics in Wireless Comm.	Introduction to Circuit Analysis	Probability and Random Signals
Antenna Theory & Design	Introduction to Computer Architecture	Product Design Project I &II
Applied Electromagnetics	Introduction to Logic Design	Programming Concepts
Communications Syst Adv ems Laboratory	Introduction to Microprocessors	Semiconductor Physics
Control Theory	Machine Vision	Signals & Systems
Electromechanical Conversion	Modern Comm. Systems	Technical Drafting I & II
Electronics I & II	Network Analysis	

SPECIALIZED KNOWLEDGE AND SKILLS:

Communication/Organization

- Skilled in written and oral communication developed through team projects and technical report writing.
- Developed strong organization and time management skills through work and team experiences.
- Bilingual: English/Ukrainian

Hardware: Oscilloscope, DMM, Function Generators, Spectrum Analyzer, Network Analyzer, Microcontrollers (Rasp Pi, ARM)

Languages: ● C ● MATLAB ● Python ● Assembly ● Java

Software: ● PSCAD 4.6.0 ● MATLAB R2017A ● PSPICE 15.7 ● Multisim 10.1 ● ANSYS 18.1 ● ADS ● Code::Block ● jGrasp ●MS Office/Visio ● AutoCAD 2017 ● Slic3r ● LineCalc ●

Additional Skills: Circuit analysis, logic design, reading schematics, soldering, PLC's, 3D printing, lathing.

PROJECTS:

Patch Antenna Project

I oversaw and lead a collaborative group project to produce a working patch antenna using impedance matching skills. We used programs such as Multisim and concepts like Smith charts to match the load and line impedances. Being the primary member with technical skills, I took on the role of manufacturing the antenna.

METeorological Station

I co-managed the production of a METeorological station (weather station) that had nine different sensors for data collection. A microcontroller gathered the data while a Raspberry Pi processed and stored that data. I worked directly also on second Raspberry Pi which acted as a remote server and used scheduled tasks to retrieve data from the primary Pi.

Robotic Bee Pollinator

My team had to plan, design, and produce a deployable prototype that addressed a current societal issue. With the growing rate of CCD (Colony Collapse Disorder), my team produced an autonomous robotic system capable of assisting plants with self-pollination. This robot has the ability to detect plant rows and capable of creating its own travel routes. I focused on managing the team and completing tasks before the deadlines. I assisted any team member that was struggling with their tasks while working on the control systems to make the vehicle autonomous.

Personal Projects

- Assembled a 3-D Printer
- Soldering and implementing an ECU to a project car

WORK EXPERIENCE:

Math Tutor Rocklin, CA — August 2012 – May 2016

- Provided individual and whole group tutoring.
- Worked with various students and their different learning styles, helped improve critical thinking skills.
- Presented and organized a new filing system to increase workflow of the Sierra College Tutoring Dpt.

Manufacturing Shop Assistant Loomis, CA — June 2016 – August 2018

- Provided technical skills to increase workflow in various departments.
- Implemented and provided training in task efficiency methods.
- Worked on a variety of tasks: machine operator, quality control, and product finishing

Jose G. Garcia

Email: ggjose19@gmail.com

OBJECTIVE: Motivated student seeking an internship opportunity where I can further enhance my abilities and apply my skills to better enhance the company's goals.

I. EDUCATION:

Bachelor of Science, Electrical and Electronic Engineering, Expected Fall 2019
California State University, Sacramento

II. SPECIALIZED KNOWLEDGE AND SKILLS:

A. Interpreting (English and Spanish)
B. Problem solving and critical thinking
C. Excellent communication skills
D. Self-motivated
E.
F. **Computer/Software**
G. AutoCAD – PSPICE – Python - MATLAB – Microsoft Excel – Multisim
H.

III. PROJECT Experience:

A. ***Product Design Project: Robotic Pollinator**,* our purpose was to design and create a laboratory prototype to assist and solve a societal issue. A robotic pollinator was created to assist in the demand for pollination where the robot will assist self-pollinating plants. This robotic system would have plant detection capabilities and the ability to create its own travel routes.

***PLC (Programming Logic Controller)**,* where the objective was to create a simulation of real-world application simulating a representation controller in which we set a variation of inputs and will then output a signal which will then be able to commence the task, for this lab I used a logic gate and a ladder to create a simulation of a push start car.

***Microchip Development System**,* the objective is focused on building a circuit based on the schematic provided. After building the circuit, we are then to run a code through MPLAB X which will monitor the input switches changing the output when the switch via a button is pushed. Furthermore, we are as well to troubleshoot the code and run two tasks to debug the code using breakpoints and watches. This allowed us to observe registers and variables when pushing the button in the circuit, program used MPLAB X.

IV. WORK EXPERIENCE

V. California State University, Sacramento January 2019 – Present
VI. *Student Technician Assistant*
VII. ● Assist faculty in the Electrical and Electronics Engineering department with setting up and fixing lab equipment for laboratory experiments. Calibrate equipment for accurate use. Assist students in approaching and solving laboratory projects.

Omni Duct System West Sacramento, CA 96691 January 2018-Present
Contractor Support Assistant

- Heating and air fabrication company where I help create 3D fabrication designs. Help sale representors confirm and close orders using Epicor program. Organize and manage sales data for best use using Excel spread sheets and DocuPeak Program.

Richter Brothers Inc Knights Landing, CA 95645 June 2014 – August 2017
Supervisor Assistant

- Led and oversaw a team of six to eight workers in a melon packaging plant during peak harvesting season, where I was in charge of inspecting and tying down pallets. Made sure environment was clean and sanitary and enforced safety protocol. Troubleshooting factory machinery such as electrical wiring, sensors, and bearings. English to Spanish interpreter when needed.

Staples Woodland, CA 95776 April 2012 – July 2012
Hardware Technician

- Technician in computer electronics department in charge of replacing hard drives, memory cards, and troubleshooting for both hardware and software malfunctions. Communicate with customers to diagnose computer problems.

Nick Pham | EIT

nphamlifestyle@gmail.com | linkedin.com/in/nick-pham

EDUCATION

California State University, Sacramento Graduation: Fall 2019
Bachelor of Science| Major: Electrical and Electronic Engineering | GPA: 4.0 Minor: Project Management

Associate of Science in Mathematics, Physics, and Natural Science | Sierra College | GPA: 3.5
Awards: President's List 14-17 | Dean's List 17-18 | 3 Sierra College Scholarships | 2 U.S. Army Awards
Licensure: 165700 CA, 2018 | International Tutor Training Program

RELEVANT COURSEWORK

Technical drafting	Circuit analysis	Feedback control systems	Microprocessors
Material science	Network analysis	Signal and systems	Electronics I and II
Engineering statics	Economic analysis	Applied electromagnetics	IC/ PCB design
Engineering statistics	Logic design	Electro-mechanical conversion	Project design

TECHNICAL SKILLS

Programming: Java, C, C++, Python, HTML, Verilog, MATLAB
Software: MS Office, Visio, Wolfram Alpha, AutoCAD, Altium, ADS LineCal, Quartus, PLC, PSpice,
Hardware: DMM, FPGA, CNC, Analog discovery, Raspberry Pi, oscilloscope, function generator
Language: English and Vietnamese
Additional: Work breakdown schedule, project planning, BOM, risk assessment, 3D modeling and printing, Circuit debug, logic analyzer, soldering, laser cutting, drill, lathe, indenters, force gauges

PROJECTS

- **Power Supply**: Design and test an adjustable 0~15V ADC power supply. Perform basic metalworking, electrical soldering including SMT, PCB schematic capture, board layout and design rule checking.
- **Robotic Arm:** Apply mechatronic principle to build pneumatic robotic arm that can grasp objects from 0° to 180° range using servos. Construct and evaluate control circuitry for electro-mechanical systems from schematics.
- **MET Station:** In a team of 4, design, build, and troubleshoot a compact weather station. Placed in charge of setting up and programming temperature, pressure, wind speed, irradiance sensors. Use data logger to poll station sensors via I^2C protocol. Store and send sensors data wirelessly to a remote server using Raspberry Pi.
- **Pulse Detector:** Implement the knowledge of active and non-active, low and high pass filter circuits. Design, troubleshoot and evaluate the pulse detector prototype using IR transmitter and LM741 amplifiers on breadboard
- **Robot Pollinator (in progress):** In at team of 5, design and produce a semi-autonomous vehicle that has a robotic arm that pollinates plants and vegetables. Placed in charge of team management, design, fabricating and controlling robotic arm. The goal is to achieve higher crops yield than conventional bee-pollinated crops in 2019.
- **Hornet Hyperloop (in progress):** In a team of 30, plan, draft, execute, and improve a safe, stable and energy efficient human-sized pod for Hyperloop competition IV sponsored by SpaceX. Placed in charge of designing feedback control system with stability, electrical parts listing and risk analysis.

EXPERIENCE

Math & Science Tutor, *California State University, Sacramento, CA* Fall 2017-Current
Explain scientific concepts, emphasize on strategic learning, critical thinking, and problem solving techniques

Lab Assistant, *Hacker Lab, Rocklin, CA* Spring 2015-2017
Organize maker space multiple times a week. Educate new members how to effectively and safely operate industrial machines such as 3D-printers, laser cutter, drill press, lathe, soldering iron

AFFILIATIONS

IEEE, *Member* Spring 2018-Current
Meet, learn and network with professionals from leading industries at events, competitions, and workshops

Tau Beta Pi, *Vice President* Spring 2018-Current
Volunteer at career fair and industry events and take tours to engineering firms, factories and testing facilities

Jason Smith

Email: jesmith262@gmail.com

OBJECTIVE: To gain employment in the electrical and electronic engineering field and to participate in design solutions for today's, and the future's, problems.

EDUCATION: Bachelor of Science, Electrical and Electronic Engineering; CSU, Sacramento (In Progress)
Expected Graduation Date: Spring 2019
Associate of Science, Electrical Engineering; Santa Barbara City College, Spring 2015
Associate of Science, Mathematics; Santa Barbara City College, Spring 2015
Associate of Science, Physics; Santa Barbara City College, Spring 2015

Related Courses:

Introduction to Circuit Analysis	Electromechanical Conversion	Semiconductor Physics
Introduction to Logic Design	Power Electronic Control Drives	Economics for Engineering
Introduction to C Programming	Applied Electromagnetics	Senior Design Thesis I & II
Introduction to Microprocessors	Robotics	
Introduction to Feedback Systems	Digital Control systems	
Signals and Linear Systems	Modern Communication Systems	
Network Analysis	MATLAB Programming for Engineers	
Electronics I & II	Probability and Random Signals	

SPECIALIZED KNOWLEDGE AND SKILLS:

Communication/Organization

- Written and oral communication developed through public presentations and technical writing
- Intermediate level Spanish, read and spoken

Hardware: Oscilloscope, DMM, Function Generators, Microcontrollers
Languages: ● C ● MATLAB ● Python ● Assembly (x86 processor) ●Verilog Hardware Definition Language
Software: ● MATLAB ● PSPICE ● Multisim ●MS Office/Visio
Related Skills: Soldering, wire crimping,

PROJECTS:

A. **Robotics**
Worked on a two-person team to design and build a robot that travelled to 5 pre-ordained G.P.S. coordinates using a compass and G.P.S. module. The robot was a four-wheeled vehicle that propelled itself with 2 DC motors controlled by an H-bridge, using pulse-width modulation. Ultrasonic sensors were used for object avoidance and a G.P.S. module was used to determine present position and intended path. A compass module was used for direction and integrated into real-time path planning along with the ultrasonic sensors.

B. **Robotics**
Designed a line-following robot that utilized a PID controller and infrared sensor array. The vehicle was a two-wheeled robot with DC motors controlled by an H-bridge.

C. **Robotics**
Worked in a two-person team to design and build a robotic arm that mirrors the movements of the user through flex sensors and a radio transmitter and receiver. The user wore a sleeve on one arm that was mounted with flex sensors on the shoulder, elbow, and wrist with two additional buttons mounted onto a glove. The buttons controlled a servo motor that rotated the base with a 360 degrees range of motion. The flex sensors on the shoulder, elbow, and wrist, controlled servo motors that allowed the arm to mimic the movements of a human arm.

D. **Senior Design Project**
Currently working on a five-person team to design and build an autonomous robot that pollinates crops. Features include lidar for environment mapping and path planning, ultrasonic sensors for near object avoidance, rotating arm controlled by servo motors, voice-operated user control, and rechargeable power supply.

WORK EXPERIENCE:
Work history and recommendations available upon request

E. Work history consists of over 20 years in the hospitality sector, primarily as a bartender and bar manager as well as 3 years in the music industry as a radio artist promoter for M.C.A. Records.
Highlights include: bartending at The Four Seasons for 5 years in Santa Barbara where I was responsible for attaining the top ranked service of all Four Seasons properties in the Americas. Top radio artist promoter in the United States for M.C.A. Records.

KANWARDEEP SINGH WALIA

Sacramento, CA 95835 •kanwarsinghwalia@gmail.com

OBJECTIVE

To obtain an internship with Intel in the field of Computer Engineering.

EDUCATION

Bachelor of Science, Computer Engineering — Expected: **December 2019**

California State University, Sacramento, CA

Dean's Honor Roll: Fall 2017, Fall 2016 - Fall 2015

Related Course Work:

Data Structures and Algorithm Analysis	Computer Hardware Design	Discrete Structures for Computer Science
Computer Interfacing	Network Analysis	Signals and Systems
Systems Programming in UNIX	Differential Equations	Programming Concepts and Methodology
Assembly Level Computer Architecture (Intel)	Circuit Analysis	Advanced Logic Design

SKILLS

Hardware Description Language:	Verilog, VHDL
Scripting/Programming Languages:	C, C++, R Programming, Python, Java, Assembly Language, MATLAB
Engineering Tools:	Vim, Nano, Altera Quartus, Xilinx
Tools/Packages:	LaTex, Microsoft Excel, Microsoft Office 2016, Model Sim, Multisim
Platforms/Systems:	UNIX, Linux (Ubuntu), Windows (10, 07, Vista, XP, Me, 2k), Mac OS
Language Skills:	Trilingual in English, Hindi, Punjabi
Organization and Communication:	Strong technical report writing and attention to details, commended on ability to communicate with teammates and members of the public, proven leadership qualities, ability to adapt to new environments quickly, strong at developing interpersonal relationships, professional at managing time and prioritizing tasks, problem-solving and multi-tasking skills.

RELATED PROJECTS

Building Computer Programs and Debugging

- OmegaRon AI: Created a virtual personal assistant like Google assistant, engaged in a two-way conversation. The project uses python programming language to analyze voice input data, converts voice commands to text, analyzes data and replies in the form of speech and text. The tasks executed using voice commands include searching temperature of any city, playing music and displaying pictures.
- Program to search in the Database System: Currently working on a C programming project to search for people or objects from the given database matching the criteria provided by the user.
- UNIX Shell: Constructed a C Program using system calls to create a shell program supporting I/O re-direction commands and using debugging techniques for any programing logic issue.

Computer Logic Design

- State Machine for Car Remote Unlocking System: Designed and simulated by developing State Machine diagram, K-maps and programmed it using Verilog on the FPGA. It involved the data transfer between user inputs and system's logic to lock, unlock and open to boot space of the car.

Research Project Presentation

- Internet of Things: Proposed the steps to prevent hacking of the Internet connected devices (presented during the STRONG 2017 event at CSUS). The project discussed the solutions such as improving the network security system of the computer machines to prevent the hackers from manipulating and accessing data from the connected devices.
- Self-Driving Cars: Participated in the STRONG 2016 event held at CSUS and presented the Research Project to the Intel and the Sacramento Kings. Project proposed the ways to deal with civil laws to bring the Self Driving Cars in the market and explained the need of the communication between the Self-driving cars to validate them as safe.

WORK EXPERIENCE

Event Supervisor, University Union at CSUS	Jan 2018 – Present
Event Setup Assistant, University Union at CSUS	August 2017 – December 2017
Volunteer, UNIQUE at CSUS	Jan 2016 – May 2017

PROFESSIONAL ACTIVITIES AND ASSOCIATION

Member of Institute of Electrical and Electronics Engineers (IEEE)	March 2018 – Present
Hardware Technology Officer at HackState Club, CSUS	January 2018 - Present
Member of Tau Beta Pi Engineering Honor Society	December 2017 - Present
Member of Association for Computing Machinery (ACM)	Feb 2016 – Present

APPENDIX G.

Bill of Materials

Item	Amount	Cost	Total	Supplier
Raspberry Pi 3 B+	2	$32.18	$64.36	Fry's Electronics
Raspberry Pi 3 B+ Case	1	$8.99	$8.99	Amazon / iUniker Pi
Sabertooth Motor Controller	1	$124.99	$124.99	SuperDroid Robots
IG42 24VDC Right Angle 122 RPM Gear Motor with Encoder	2	$92.65	$185.30	SuperDroid Robots
24V 5AH LI-ION Battery Charger	1	$48.00	$48.00	TopMobility.com
12V DC Battery	2	$44.99	$89.98	Amazon / Mighty Max Battery
Dual LS7366R Quadrature Encoder Buffer Board	1	$45.68	$45.68	SuperDroid Robots
Logic level shifter	10	$0.75	$7.50	Amazon
DC-DC 1.23V-30V LM2596 Step Down Buck Converter	5	$3.99	$19.95	Amazon/ Texas Instruments
YDLIDAR F4PRO	1	$169.00	$169.00	Robotshop.com
Ultrasonic Sensor HC - SR04	10	$1.49	$14.90	Amazon/ LGDeHome
Yellow LED w/Bezel	3	$0.19	$0.57	Tayda Electronics
Green LED w/Bezel	3	$0.19	$0.57	Tayda Electronics
Red LED w/Bezel	3	$0.19	$0.57	Tayda Electronics
Blue LED w/Bezel	3	$0.19	$0.57	Tayda Electronics
Hitec HS-425BB Standard Servo	1	$14.94	$14.94	Amazon/ Hitec RCD Inc.
Hitec HS-5645MG Digital Servo	1	$38.65	$38.65	Amazon/ Hitec RCD Inc.
Hitec HS-805BB Mega 1/4 Servo	2	$39.89	$79.78	Amazon/ Hitec RCD Inc.
Aluminum Thin L Bar (18 in)	2	$1.50	$3.00	Home Depot
White PVC Tube (4 ft)	1	$5.99	$5.99	Home Depot
Half-Inch Aluminum Hollow Rod	1	$9.99	$9.99	Home Depot
(⅝ -½ in) Zinc-Plated Extension Spring	1	$4.93	$4.93	Home Depot/ Everbilt
(7/16 -½ in) Zinc-Plated Extension Spring	1	$3.84	$3.84	Home Depot/ Everbilt
U-Shape Primary Shaft Cover Flange*	2	$0.00	$0.00	Donated by
U-shape 3D Printed Servo Cover*	2	$0.00	$0.00	CSUS 3D Printing Lab
Pollinating Rod*	1	$0.00	$0.00	Donated by Pavel Boyko
Silver Grey Horse Hair Pack (¼ lbs)	1	$18.40	$18.40	Amazon/ CrazyCow
Genuine Leather Brown Bundle Pack	1	$9.99	$9.99	Michaels
Body PVC ¼ in. thick sheets	0	$0.00	$0.00	Donated by Clark Pacific
⅞ in. Alum. Rod for Axle	1	$15.95	$15.95	Big R Metals
Robot Wheels	4	$6.99	$27.96	Harbor Freight
Metal Washers Pack	4	$1.78	$7.12	Home Depot

Bolts Pack	10	$1.58	$15.8	Home Depot
Metal Nuts Pack	3	$1.76	$5.28	Home Depot
Aluminum Medium L Bar	1	$10.53	$21.06	Home Depot
Set of Door Hatch	1	$3.27	$3.27	Home Depot
In-Line Fuse Holder	2	$0.18	$0.36	Tayda Electronics
Fuse Glass Fast-Acting, 3A 5x20	2	$0.18	$0.36	Tayda Electronics
PCB Wiring Board	1	$9.99	$9.99	Fry's Electronics
Micro USB Cable	2	$4.99	$9.98	RK's office
Micro USB Cable	2	$2.50	$5.00	
Wire Connectors Pack	1	$20.00	$20.00	
Electrical Wires Bundle Pack	1	$15.95	$15.95	The Home Depot
Electrical Tape	1	$12.93	$12.93	The Home Depot
Planters	4	$13.60	$54.40	Walmart
Wood Handle Cultivator	1	$4.50	$4.50	Green Acres
Wood Handle Trowel	1	$4.50	$4.50	Green Acres
Watering Can	1	$16.50	$16.50	Green Acres
Soil Mix Bag	6	$9.75	$58.50	Green Acres
Strawberry plant	2	$4.50	$9.00	Green Acres
Seed Blanket	1	$17.50	$17.50	Green Acres
Pollinator Mix	1	$12.00	$12.00	Green Acres
Planting Mix	1	$19.50	$19.50	Green Acres
Plant Food	1	$4.50	$4.50	Green Acres
EB Stone Sure Start	1	$4.50	$4.50	Green Acres
		TOTAL:	$1,346.85	

APPENDIX H.

Field Testing and Pollination Simulation

We constructed a grow facility to test our method of hand-pollination simulation. Our space was limited, so we were only able to set up three rows containing four strawberry plants each. Each row would be pollinated differently. Row one is protected by a seed cloth to keep insects from getting to the blossoms. This row would be pollinated by the robot only. Row two is outside and would be pollinated by the robot and with natural pollinators like bees, wind and other insects. Row three will be pollinated by natural pollinators only. It should be noted that the small sample sizes mean that these promising results should be taken with caution. Furthermore, we could not fully guarantee that insects were prevented from getting to the strawberry plants in row one. We planted the strawberries on March 11, 2019 and the table below reflects week two survey results and week six survey results. Early results were not very reliable as the sample sizes were varied and not very large. By week 6 the rows caught up with each other and were more suitable for comparison. The plants were cared for and surveyed every day. Of important note is that very few bees or other insects were observed in the grow area. This was fortuitous, as we could measure results in area devoid of plentiful pollinators. By the end of week 6, the rows that were treated with simulated hand-pollination had a much better pollination rate than row one.

TABLE H-1.
DAILY PLANT SURVEY RESULTS

	Pollination Rate and Week #					
Crop Row Designation	Wk.1	Wk.2	Wk.3	Wk.4	Wk.5	Wk.6
Row One	12	5	41.67%	16	15	93.75%
Row Two	2	1	50%	17	16	94.12%
Row Three	6	3	50%	14	11	78.57%