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Adaptive Robotic Chassis (ARC): RoboCrop A Smart Agricultural Robot Toolset

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ENTITLED

Adaptive Robotic Chassis (ARC): RoboCrop
A Smart Agricultural Robot Toolset

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By

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Abstract

RoboCrop is a payload system that attaches to an existing modular drivetrain to support the agriculture industry with their primary challenge of labor shortages. ARC: RoboCrop features three degrees of freedom as an XYZ Cartesian robot and is intended specifically for pruning strawberry flowers. The image bay camera attached to RoboCrop's frame identifies the strawberry flowers, communicates their XYZ coordinates, and then the Cartesian robot moves to the desired locations. The snipping toolhead is interfaced at the bottom of the Z-stroke and performs the snipping process. RoboCrop has a proven success rate of at least 70% of flowers pruned in a single workspace.

Acknowledgements

We would like to thank Dr. Christopher Kitts and Dr. Manoj Sharma for their continued guidance and support on this project. We would also like to thank James “JT” Tipton of California Giant for sharing his knowledge of strawberry farming with our team and Santa Clara University’s School of Engineering and SCU’s Center for Food Innovation and Entrepreneurship for providing funding for our project.

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List of Acronyms

ARC	Adaptive Robotic Chassis
CAD	Computer-Aided Design
CNC	Computerized Numerical Control
DOF	Degrees of Freedom
FEA	Finite Element Analysis
FOV	Field of View
HSV	Hue Saturation Value
LED	Light Emitting Diode
NPL	National Physical Laboratory
RGB	Red Green Blue
ROS	Robot Operating System

1. Project Introduction and Field Research

1.1 Introduction

From the healthcare system to education to social interactions, the COVID-19 pandemic has negatively impacted the quality of life for many. Before the virus, the world was already experiencing an alarming food shortage that has only been exacerbated by the prevention of in-person work; the amount of people suffering from unreliable food sources continues to grow. In 2016, 108 million people were in danger of malnutrition. In 2019, that number increased to 135 million people[1]. Not only has the virus "exposed the weaknesses of a food system which prioritizes the profits of big food and agriculture companies over the needs of food producers and workers"[2], it has also reduced the global capacity to satisfy food demands. Where workers are faced with the moral dilemma of going to work and risking exposing their families to COVID-19, companies struggle to maintain food production levels due to labor shortages. The UN estimates that there will be an extra "2-3 billion mouths to feed by 2050"[3], and as such, food production must increase by 60% in order to meet the world's food demands[4]. Globally, there is an apparent food and labor shortage that not only harms the agricultural sector, but also threatens to destabilize the world's food supply.

The United States is no stranger to this phenomenon, as agriculture is one of its largest industries. As the primary source of raw materials, the agriculture industry is integral to America's international trade and economic success. Most importantly, it supplies the population with a necessary resource: food. Due to the large demand for food products, the Agriculture, Food, and Related industries sector of the American economy contributed $1.109 trillion towards the U.S's GDP; farms alone contributed $136.7 billion of that amount in 2019[5]. This number is only projected to grow as the national, as well as global, population levels are steadily increasing; more demand calls for more supply. These rising numbers also pose the threat of

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[1] "Global Report on Food Crises." *Global Report on Food Crises - 2020*, Food Security and Insecurity Network, 2020, www.fsinplatform.org/report/global-report-food-crises-2020/.

[2] Deen, Thalif. "UN Warns of an Impending Famine With Millions in Danger of Starvation." *Inter Press Service*, Inter Press Service New Agency , 30 Nov. 2020, www.ipsnews.net/2020/11/un-warns-impending-famine-millions-danger-starvation/?utm_source=rss&utm_medium=rss&utm_campaign=un-warns-impending-famine-millions-danger-starvation.

[3] Dickson, Ben. "Will Technology Prevent the next Food Shortage Crisis?" *TechCrunch*, TechCrunch, 25 Dec. 2016, techcrunch.com/2016/12/25/will-technology-prevent-the-next-food-shortage-crisis/.

[4] FAO "Global agriculture towards 2050" High Level Expert Forum http://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf

[5] Jared , George. "Ag Industry Set to Boom during the next Century." *Talk Business & Politics*, Talk Business & Politics, 26 Feb. 2020, talkbusiness.net/2019/04/ag-industry-set-to-boom-during-the-next-century/.

climate change. Unfortunately, higher levels of pollution have drastically reduced the volume of arable land available for farm production. With growing demands, limited land availability, and the presence of climate change, farmers must take drastic measures to protect their livelihood and the agriculture industry. As such, it is imperative that farms maximize their plant yield without increasing their input and develop sustainable farming practices to protect the integrity of independent farming and agriculture as a whole.

1.2 Environmental Impact

The rapidly-growing population of the US has significantly impacted the environment, as the main source of pollution derives from human activities. Starting in the 1800s, the Industrial Revolution ignited a global shift in production and consumerism that has only been amplified. As such, the use of fossil fuels, incorrect disposal of waste, and general overuse and depletion of natural resources are the main contributors to climate change. The agriculture industry is significantly affected because of this, as “billions of dollars in profits are lost each year…because of the effects of climate change”[6]. Monetary value is only half of the issue. The Earth’s gradual temperature increase also causes soil degradation and dead zones (oxygen-depleted zones)[7] which eliminate the very foundation of agriculture, both literally and figuratively. Without help from government regulations to preserve the environment, the responsibility falls on the individual farmer to ensure that their fields are prepared for the season, their crops are of high yield, and they are able to produce a profit. With the average US farm spanning 444 acres, it is nearly impossible for small farmers to monitor and maintain this size of land without significant hired help[8].

1.3 Labor Shortage

Despite the agriculture industry providing 21.6 million jobs to working Americans, farmers are still faced with labor shortages[5]. Workers are expected to comb through hundreds of

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[6] Ag Solutions Group. “Top 5 Issues Affecting Agriculture in 2020 - Ag Solutions Group, LLC: The Midwest's Leading Distributor of Farming Equipment.” *Ag Solutions Group, LLC | The Midwest's Leading Distributor of Farming Equipment*, Ag Solutions Group, LLC , 11 Dec. 2019, www.agsolutionsgroup.com/top-5-issues-affecting-agriculture-in-2020/.
[7] Sauer, Amanda, and Suzie Greenhalgh. “Awakening the Dead Zone.” *World Resources Institute*, World Resources Institute, 26 Sept. 2018, www.wri.org/publication/awakening-dead-zone.
[8] “PERCENTAGE OF SMALL MEDIUM AND LARGE FARMS IN THE U.S.” *2.5 Million Farmers & Ranchers Leads To Grow Your Business. Grow Your Sales With This Powerful Farmers & Ranchers Leads*, www.usfarmdata.com/percentage-of-small-medium-and-large-farms-in-the-us.

acres of fields to plant, weed, and harvest the crops in often extreme temperatures. Even with the amount of workers employed, farmers don't have enough manpower to properly maintain their fields and the workforce that is available is more expensive than it was previously. Consequently, farms lose necessary profits as they already operate on thin margins. To combat these rising costs, farmers are forced to downsize their farms leading to lower yields and less profits and ultimately, a smaller supply of food that is of depreciating quality.

California, one of the major contributors to the agriculture industry in the US, is no stranger to this. California grows "more than 400 commodities at a value of $50 billion"[9]. Given its substantial presence, it is imperative to investigate the major shortfalls that California farms face. According to the California Farm Bureau Federation, over 50 percent of farmers have "failed to find the required number of workers for the last five years"[10]. In 2018, an anonymous California strawberry farmer reported that his farm had to reduce their acreage from 80 to 17 because of the lack of labor[11]. This shortage can be attributed to the continued increase in minimum wage, lack of employee benefits, as well as the anti-immigration rhetoric encouraged by the previous administration.

California's minimum wage is one of the highest in the nation and it continues to increase yearly. Workers typically work long hours in intense conditions which has resulted in laborers leaving the agriculture industry in favor of jobs in construction, landscaping, or food service. The need for stability in the form of health insurance is becoming increasingly important to the average worker and unfortunately, the agriculture industry can't always provide that[12]. Despite farms paying their workers more, their compensation isn't healthy enough to sustain the high cost of living in California and their payments are without benefits. Because of this, smaller farms have deviated from high-labor crops such as vine-ripe tomatoes, in favor of those that are low-maintenance, such as garlic and onions. In addition, agriculture workers have historically mostly consisted of undocumented immigrants. With the previous administration's harsh

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[9] Washburn, Kaitlin. "In California Farm Country, Growers Struggle with Labor Shortage." *USA Today*, Gannett Satellite Information Network, 6 Apr. 2020, www.usatoday.com/story/opinion/2020/04/06/california-growers-struggle-labor-shortage-other-challenges-column/2941779001/.

[10] Neuburger, Bruce. "California's Migrant Farmworkers." Monthly Review, Monthlyreview.org, 1 May 2019, monthlyreview.org/2019/05/01/californias-migrant-farmworkers/.

[11] Barringer, Felicity, and Geoff McGhee. "A 'Climate of Fear' Accelerates Existing Labor Shortages on California's Farms." *The Bill Lane Center for the American West*, Stanford University , 11 Sept. 2019, west.stanford.edu/news/blogs/and-the-west-blog/2019/climate-fear-accelerates-existing-labor-shortages-california-s-farms.

[12] Semuels, Alana. *American Farmers Are in Crisis. Here's Why*. 27 Nov. 2019, time.com/5736789/small-american-farmers-debt-crisis-extinction/.

crackdown on undocumented labor, farms have had to look for other means of labor which comes at a higher price[13].

1.4 Specialized Industry

Strawberries are a huge market for farmers located in Northern California, such as Watsonville and the Valley, as they are one of California's largest cash crops grossing $3.4 billion in 2018[14]. The strawberry industry is no different than the agriculture industry. Government regulations that are designed to protect workers and the environment ultimately make the process operationally more demanding and are a financial burden on growers[15]. After speaking with James Tipton (JT), the district manager at California Giant Berries, it was clear that labor shortage is the main issue faced in industry. The majority of California Giant's workforce is now retired and the newer generation of workers aren't consistent and require greater compensation. Given that growing and harvesting strawberries is nearly a year long process spanning from January to November, it requires extensive labor and detailed attention in order to yield high quality strawberries in large batches. One acre per year costs roughly $70,000 for the entire year of maintenance and nearly $3,000 of that accounts just for pruning the strawberry plants. Additionally crops such as berries are difficult to pick via automated machinery. As a result, farmers either submit to receiving lower yields for the season, reduce their acreage, or switch their crops to low-maintenance produce such as walnuts[16]. California Giant, a family run business, is looking for a solution that supplements the current labor required to cut white strawberry flowers in order to continue serving its fresh strawberries to local communities.

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[13] Smith, Stacey Vanek, and Cardiff Garcia. "Worker Shortage Hurts California's Agriculture Industry." *NPR*, NPR, 3 May 2018, www.npr.org/2018/05/03/607996811/worker-shortage-hurts-californias-agriculture-industry.
[14] Hyman, Jordy. "Strawberry Growers Face New Challenges." *Good Times Santa Cruz*, Good Times Santa Cruz, 4 Mar. 2020, goodtimes.sc/cover-stories/strawberry-growers-new-challenges/.
[15] Guan, Zhengfei, et al. "Top Challenges Facing the Florida Strawberry Industry: Insights from a Comprehensive Industry Survey." *IFAS Extension*, University of Florida, Nov. 2015, edis.ifas.ufl.edu/pdffiles/FE/FE97200.pdf.
[16] Garcia, Sierra. "A 'Climate of Fear' Accelerates Existing Labor Shortages on California's Farms." *Elemental Reports*, Bill Lane Center for the West, 14 Nov. 2019, elementalreports.com/urbanization/2019/09/15/a-climate-of-fear-accelerates-existing-labor-shortages-on-californias-farms/.

1.5 Existing Solutions

According to JT, although robotics are slowly being introduced into the agriculture industry, they haven't made a mark in the Watsonville area. This can be attributed to the high buy-in price of robots and the fact that none have been customized to meet the direct need of their specific farm. From in depth-research, our team has concluded that the majority of agriculture robots are still in the beta stages of development; none have been permanently implemented into the daily activities of a farm. However, improvements are being made that automate certain processes such as spraying herbicides on crops, picking weeds, and harvesting the fruit itself. For example, the Berry 5 Robot from Harvest Croo Robotics, detailed in Table 2.1, is a large system that can pick strawberries from 5 rows of strawberry beds, averaging 8 seconds to pick one berry. Unfortunately, this robot design is exclusively available in the UK. In fact, all but one of the major agriculture robots on the market are headquartered and used internationally. Whereas vertical farming has gained traction in the US, automated solutions that include a robot traversing the fields have not yet been developed. Given the ample opportunities for robots in the US, our team identified a drastic need for automated processes that will help eliminate the need for labor and decrease farm costs overall.

1.6 Customer Needs

James Tipton (JT) from California Giant Berries is the main partner and contact for this project. After visiting California Giant's fields and speaking with JT and his field specialist, Rick, it became clear that CalGiant has a desperate need to cut labor costs through cheaper and more readily available solutions. To provide perspective on how much California Giant's fields cost to operate, it costs $70,000 to maintain just one acre per year, and pruning flowers accounts for roughly $3,000 per acre. Given that California Giant has 180 acres, JT spends significant funds each year just to ensure the bare minimum of maintenance is covered. In this application, robustness and reliability are extremely important as labor downtime and delays result in high costs for the farm — costs farms can barely afford. After learning more about the long strawberry harvest, the need for a robot that can prune white flowers and work during the majority of the year became apparent. Investing in a high cost robot means that the robot has to perform up to standards in order to be a viable, realistic solution for farmers. JT and Rick also expressed interest in a weatherproofed system that requires little maintenance to ensure that costs are minimized.

This project is working in conjunction with a current initiative through the Robotics Systems Laboratory, the Ag Robot II. Our system is attached to the existing agricultural robotic rover via a removable frame that contains our payload. After speaking with Dr. Kitts and Manoj Sharma, the leads on the Ag Robot II project, modularity became a focal point in our discussion. Our team confirmed that we needed to design our system in a modular, independent manner in order to best interface with the existing design. In doing so, our attachment increased the functionality and flexibility of the overall system.

In order to learn more about the agriculture industry's other needs, we spoke to Will Marten of Ag & Water where we learned about issues regarding agriculture irrigation systems. Ag & Water focuses on the irrigation networks of farms and works to find solutions to water treatment methods. Closely working with various nut and almond growing companies, Will shone light on issues that many of their partners face, as well as issues faced by his own agriculture irrigation company. In regards to where robotic automation could help almond farms, Will suggested a robot with the ability to identify and potentially fix broken irrigation lines. Rats chewing pipelines and general animal travel breaking sprinkler heads are common issues in this industry. Will also suggested that a robot that collects data regarding the location and status of the repair needed would be a huge benefiting factor within his company. Given that one person takes 1-2 days to check the system, and this task must be performed every three days, an automated robot could allow farms to dedicate their manpower to more complex tasks. This information helped refine our project goals to fit the needs of a client who is looking to make a process more time and cost efficient.

Figure 1.1: Image of the strawberry rows in full bloom at California Giant's fields.

1.7 Project Objectives

The agriculture industry is suffering and there is a pressing need to alleviate the underlying problem: labor shortages. By supplementing its workforce, farms have the potential to produce large, profitable yields while not increasing the amount of input into their farm to continue putting good, quality food on our tables. It also provides the opportunity for farms to invest more time into their workers and capitalize on their talents in more human-centric roles.

In order to supplement the labor force, robotics can be used to automate the more tedious tasks involved in farming processes. The objective of this project is to develop a vision-guided manipulation system for integration with an existing agriculture rover. The robot, titled RoboCrop, has a specific focus on pruning flowers on strawberry plants. Our team designed three integrated subsystems which form the foundation of RoboCrop. These include an image camera bay to capture bird's eye view images of the strawberries, a cartesian robot with three degrees of freedom in the XYZ axes to move to the desired flower in the outlined workspace, and a snipping tool head that is attached to the Cartesian robot and prunes the flower. As a proof of concept that automation in agriculture can effectively increase the productivity and output of a farm, our team focused specifically on the strawberry industry and hoped to test RoboCrop in California Giant's fields.

2. Proposed Solution

2.1 Existing Solutions and Benchmarked Results

To further understand the market and customer need for agricultural robots, benchmarking of current products and robotic integrations in the industry was performed. Scientists at the National Physical Laboratory (NPL) in London have been developing an image processing robot that can reliably identify the ripeness of strawberries. Because strawberries have a high sugar content, the technology uses microwave, radiowave, and infrared waves to identify the fruit's ripeness[17]. As one of the first labs to develop this form of technology, one of the largest obstacles for NPL included achieving performance consistency both inside and outside the laboratory due to changing and imperfect conditions encountered in the field. The team's primary focus has been on producing reliable, clear imaging. Their secondary focus is to add mechanical arms to the robot in order to pick the determined ripe fruit. Even though the team has proof of concept for their design, NPL's shift to a commercial system has presented challenges and setbacks. Despite this, the team, specifically member Richard Dudley, is optimistic that the robot will be able to pick at the same rate as a human, if not faster, and that it undoubtedly has great potential.

In addition to NPL's strawberry robots, image processing and computer vision processing are emerging technologies within the agriculture industry specifically because of their innate abilities to identify nutrient and water levels, weeds, product quality, and perform product sorting and packing[18]. The increasing use of image processing "reduces the human labor intensity, and improves the productivity of mankind"[17]. In reference to the manual work required to identify plant nutrient levels, a scientist must take, or alter, images in specific RGB (red, green, blue) filters and then compare those with grayscale images of the same workspace. Through these filtered images, and also with inputted texture parameters, nutrient deficient leaves are able to be found in plants. Instead of using a human to perform this laborious task, a company in China was able to accurately detect phosphorus deficiency 100% of the time and had an overall accurate diagnostic rate of 87.5%[17]. Humans are prone to error, specifically in regards to subjective photo

[17] Eddy, David. "Robot Strawberry Picker." *American Vegetable Grower*, vol. 61, no. 9, 2013, pp. 16-17. *ProQuest*, https://login.libproxy.scu.edu/login?qurl=https%3A%2F%2Fwww.proquest.com%2Fdocview%2F1441327567%3Faccountid%3D13679.

[18] Huang, Ximei, et al. "Application of Computer Vision Technology in Agriculture." *Agricultural Science & Technology*, vol. 18, no. 11, 2017, pp. 2158-2162. *ProQuest*, https://login.libproxy.scu.edu/login?qurl=https%3A%2F%2Fwww.proquest.com%2Fdocview%2F2201630322%3Faccountid%3D13679.

comparison. The image processing unit not only eliminates this error, but automates an otherwise time-intensive process. In terms of plant water retention, other methods are being developed using Photoshop and MATLAB that use prediction modeling, grayscale imaging, and imaging under different light sources in order to reliably detect the water content in the leaves. For weeding, binary and grayscale images were originally used to distinguish between crop and intercrop weeds. The initial tests had an identification rate of 86%, however after tweaking the image processing model, adding noise filtering, and a neural network, the accuracy reached 98.3%[17]. Finally for picking and sorting, "the agricultural robot plays an irreplaceable role in the process of picking fruits and vegetables"[17], as it improves productivity, reduces the cost of picking produce, ensures better picking quality, and ultimately plays a significant role in agricultural production.

From these two products, our team was able to learn how these technologies could be harnessed to our advantage and how to limit project setbacks. Additionally, to get a better understanding of available products, and identify any deficiencies, our team also performed extensive market research detailed in Table 2.1. Although there are a variety of agriculture robots, our team quickly discovered that few are affordable and based in the US. Because small farms already operate on thin margins, our robot is inexpensive and is a more viable option in comparison to other automated solutions.

Table 2.1: Existing Products on the Market

Robot Name	***Berry 5***	***Agrobot E-Series***	***Scout System***	***Avo Weeding Robot***
Company	Harvest Croo Robotics	Agrobot	American Robotics	Ecorobotix
Headquarters	UK	Spain	Massachusetts	Sweden
Service or Purchase?	Service	Service	RaaS: Robot-as-a-Service	Service
Purpose	Autonomous machine that scans, selects, and picks three strawberries every 10 seconds with 16 robotic heads	Identifies and harvest ripe strawberries using 24 independent robotic arms	Drones that "run missions autonomously, collecting, processing, and analyzing data" intended for the agriculture industry.	Autonomous weeding operations. Using machine learning, the robot detects and selectively sprays weeds with a micro-dose of herbicide
Weight	N/A	N/A	N/A	750 kg
Material	N/A	Stainless Steel and military grade Aluminum	N/A	N/A

Table 2.1: Existing Products on the Market (continued)

Max Speed	8 seconds to pick one strawberry plant and 1.5 seconds to move to next plant	N/A	N/A	1 m/s
Throughput	Takes 20 hours to pick what 30 harvesters to in one day	N/A	1000 acres / day	10 hectares / day
Price ($US)	N/A	~ $250,000	N/A	N/A
Power Source	N/A	N/A	Charges in waterproof station (box)	Solar Power (1150 W) – 3x 48 V removable batteries (75 Ah per battery) at robot front
Adaptability	Adaptable, has variety of robotic heads	Not adaptable	Yes, can be used for variety of applications	Adjustable wheel spacing
Remote Controlled?	No	No	No - self piloted	Controlled via smartphone or tablet (Also can be self-piloted)
Environmentally Sustainable?	Yes - only picks ripe strawberries, maximized picking	Yes - doesn't damage strawberries, only picks ripe ones	Yes	Yes - 95% less herbicide used
Portable?	No	No - huge mechanism, would need more than a tractor to transport	Yes	Yes - can be transported via a tractor / trailer
Autonomous	Yes	Yes	Yes	Yes
Navigate Tough Terrain	Yes	Yes	Yes	Yes - 4WD Suitable for slightly sloped terrain (10%)
Weather Tolerant	Yes	Yes	No (Charging station is weatherproof. Not drone)	Yes
GPS	Yes	Yes	Yes	Yes
DoF	3	3-4	0	1
Sensors	N/A	Color and infrared depth sensors LiDAR sensors	N/A	LiDAR and ultrasound sensors
Safety Features	N/A	Virtual perimeter stops the robot	Precision Landing	Safety bumper that activates automatic stoppage
Cameras	N/A	No	Yes	Yes - row tracking camera

2.2 Patent Disclosure

Due to the increasing popularity of robotics in agriculture, our team researched current patents to ensure that our product was innovative and new. We also identified a key component of our robot that has the potential to be patented: the snipping toolhead, also known as the Quick Snipper. During our research, it became apparent that many agriculture robots target the harvesting process, instead of the planting or growing process, and the patents are for entire robots instead of individual subsystems. Based on the patents listed in Table 2.2, the Quick Snipper is clearly a new and innovative idea in the agriculture space. Instead of harvesting crops, the Quick Snipper's sole responsibility is to prune and cut the stems of strawberry flowers. Although a few patents detail a similar idea, most products on the market feature some form of claw mechanism with various other capabilities, such as multiple jointed arms for weeding and measuring crops. Although they are impressive, the engineering behind this development is not only complex and expensive, but also requires maintenance from trained professionals. To create a product with an affordable price tag for farmers, our team kept the design of the Quick Snipper simple yet effective. With the primary focus of pruning strawberry flowers, independent farmers have access to a robot that is both cost efficient and requires significantly less maintenance.

Table 2.2: Relevant Agricultural Device Patents on the Market

Title & Hyperlink	Description	Patent No.	Date
Agricultural Robot System and Method	An agricultural robot that harvests, prunes, culls, weeds, measures and manages crops. Uses cameras that identify and locate the fruit on each tree and points on a vine to prune.	US 2006/0213167 A1	September 28, 2006
Agricultural Robot System and Method	An agricultural robot with autonomous and semi-autonomous features that can be utilized to measure agricultural parameters or aid in managing resources.	WO 2006/063314 A3	June 15, 2006
A Robotic Harvester	Automates the process of harvesting high value crops via a crop picking end effector.	WO 2017/152224 A1	September 14, 2017

End Effector for Robot Harvesting	A fruit harvesting system that includes a vacuum generating subsystem connected to an end effector. The end effector suctions the piece of fruit to harvest.	WO 2016/090012 A1	June 9, 2016
Robotic Systems, Methods, and End Effectors for Harvesting Produce	Robotic system and specialized end-effector to automate harvesting of produce such as apples. Uses 4-axis arm and friction grip end effector.	US 2017/0105346 A1	April 20, 2017

2.3 System Requirements

Table 2.3 details RoboCrop's system requirements which were created using the considerations of California Giant's needs as well as the constraints of the Ag Robot II initiative. Serving as benchmarks of success depending on the subsystem, RoboCrop was forecasted to be able to perform to the following specifications.

Table 2.3: System Requirements

Cartesian Robot	Have programmable X, Y and Z movement
	Have 1 mm level accuracy in all directions
	Self correcting system to account of any kinds of unexpected arm movement from rover
	Create contained system to withstand weather, environmental factors, dust, water etc
Tool Head	Pluck/remove the flower as close to stem as possible
	Move the flower away from the stem to remove to side of the flower bed
	The system toolhead will have interchangeable tool heads for different purposes
	Create a sturdy casing to withstand the environment and constant movement
Image Bay	Accurately extract the flowers from the image with an accuracy >70% correct identification
	Create closed loop system of verifying the flower has been properly removed
	Be able to get XYZ coordinate from 2D image and stereo depth camera
Entire System	Systems subsystems will be able to work independently and communicate across each other and with other rover components
	Shall be easily interchangeable within the core base of the existing rover
	Have operating speed of ~90 seconds per workspace
	Be powered by the existing rovers battery

2.4 Proposed Solution

The robotic chassis consists of a 770 x 700 mm workspace area that is designed for a payload to be added according to the task assigned to the robot software. The main function of the robotic system is to navigate its way through the rows of strawberry fields and successfully remove the white flower head from the strawberry plants. The subfunctions of the robotic system include image capturing to optically locate the white flower head among the leaves of the strawberry plant, moving a robotic arm element to the flower, and cutting off the flower head to be left in the adjacent furrows.

The input of the system is electricity, powered from a 24V charged battery to match that of Ag Robot II. The outputs of the system are electrical signals, sent from a computer to the mechanical, robotic arm elements and shearing mechanism to power the cutting of the flower. The initial concept of operations is itemized in the diagram below in Figures 2.1 and 2.2.

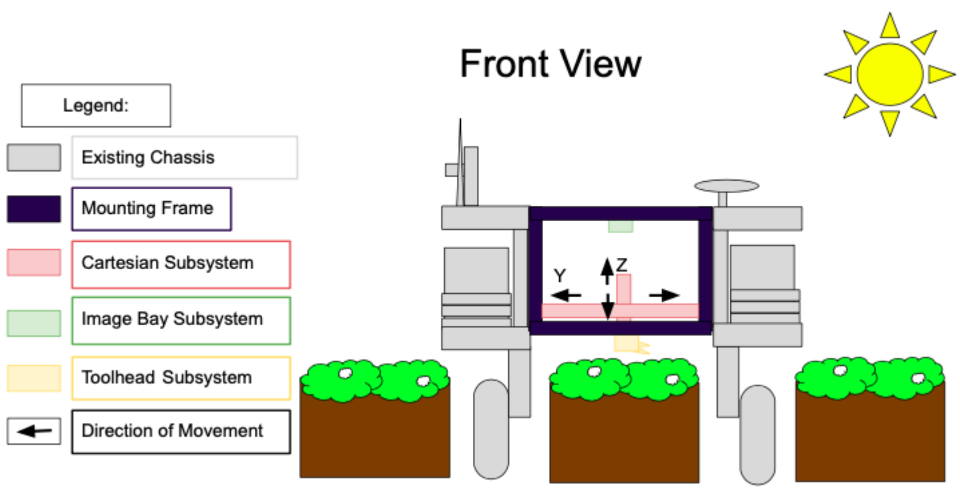


Figure 2.1: Front View of Concept of Operations

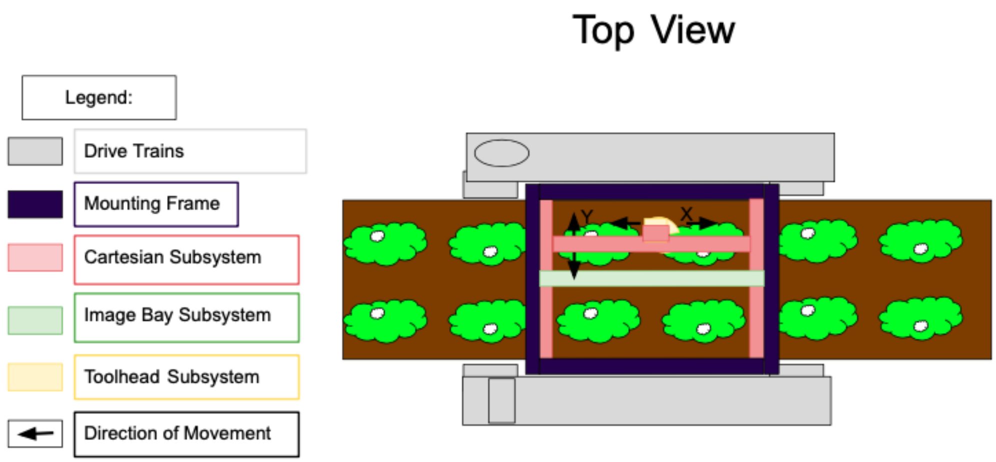


Figure 2.2: Top View of Concept of Operations

The concept of operations diagrams shown in Figures 2.2 to 2.3 are how the RoboCrop payload system looks in the field once attached to the existing Ag Robot II. The payload system is pictured in dark blue and is situated in between the two drive train units, shown in grey. RoboCrop is responsible for identifying and pruning the strawberry flowers one row at a time and the entire system moves in sequences of workspaces. These workspaces were determined based on California Giant's bed dimensions, and each was calculated to have four strawberry plants within the workspace.

Figure 2.3 outlines the three main subsystems and the electrical components within them. The robot's specific electronics are discussed in further detail in each of the subsystem chapters.

In terms of movement through the fields, the Ag Robot II utilizes a hard-coded step motion, stopping a set distance of approximately 1000mm, and stops once a single workspace is within the camera's FOV. At this point, the image bay subsystem will take a picture of the underlying bed and extrapolate the XYZ coordinates for the flowers of interest. These coordinates will be sent to the Cartesian subsystem via the onboard computer which then commands the robot to move to the correct location. Once positioned, the snipping tool head is actuated, cutting the flowers from the plant. The camera then surveys the underlying bed another time to confirm that all flowers within the workspace have been successfully pruned. The onboard computer then communicates with Ag Robot II, which moves its next set distance and the process is repeated. The software flow chart that also outlines the main sequence of operations can be found in Figure 2.5.

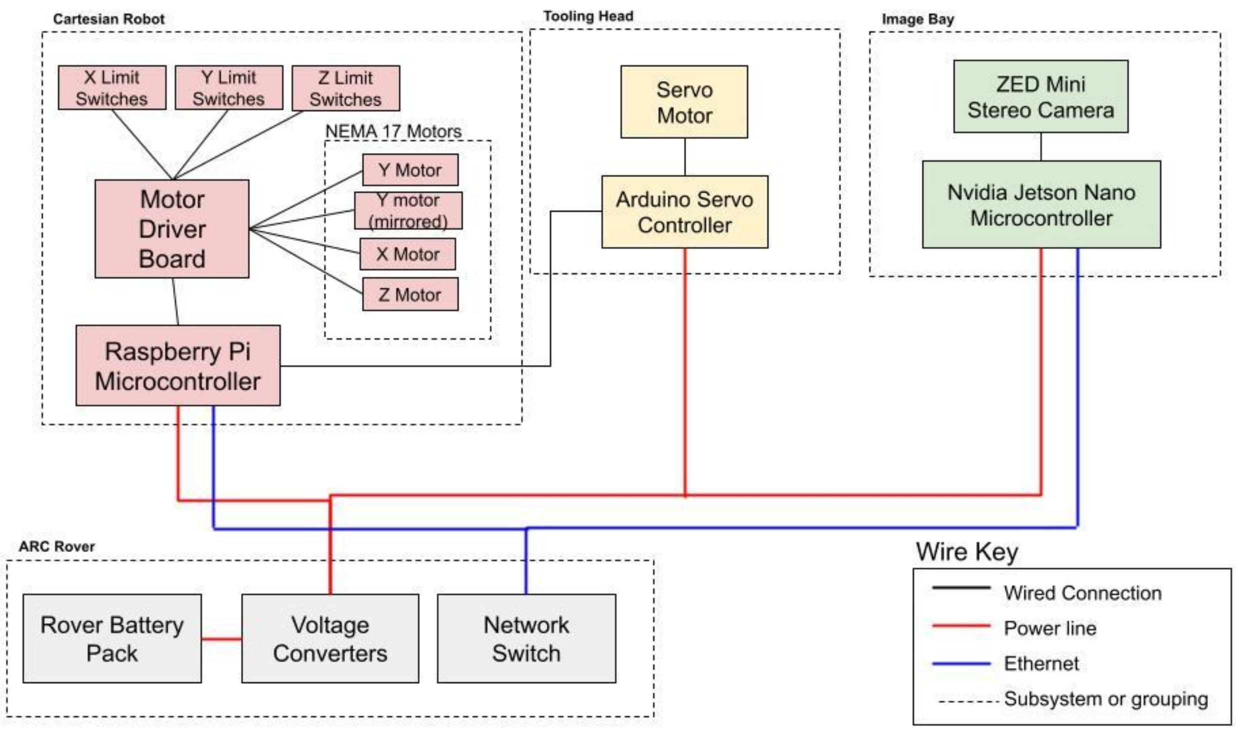


Figure 2.3: Component Block Diagram

2.5 Subsystem Breakdown

2.5.1 Cartesian Subsystem

The Cartesian subsystem is responsible for the movement of the entire payload system and must correctly and reliably position the tool head in order to successfully prune the flowers. The Cartesian subsystem has three degrees of freedom and demonstrates the ability to move in one axis, meaning isolated movement in one direction, or in multiple axes at the same time. For speed and precision purposes, RoboCrop was programmed using the latter, with the XY gantry and Z-stroke moving in conjunction with each other. The payload is mounted 19 inches from the bottom of the superstructure frame, which clears the furrow by 2 inches, in order to prevent collision between the retractable Z-stroke and the mounted camera at the top of the frame. All axes utilize NEMA 17 motors to drive the motion as well as a combination of belt driven and lead screw actuators to position the tool head in the workspace.

The Cartesian subsystem also contains the superstructure frame, which is a specially designed frame to allow for seamless mounting with the existing drive trains of Ag Robot II, explicitly shown in Figure 2.4. The frame also allows for the width to be adjusted with respect to the drive trains in order to accommodate different bed and furrow widths depending on the crop and farmer preferences. As a modular system, RoboCrop can accommodate multiple farms that have different dimensions for their strawberry crops.

Figure 2.4 : Mechanical configuration of RoboCrop and Ag Robot II.

2.5.2 Tool Head Subsystem

The toolhead subsystem must successfully remove the head of the white flower of the strawberry plant after it is identified using the image bay. The Cartesian robotic frame brings the toolhead to the correct location of the flower and the toolhead then removes the flower head. This requires the toolhead to interface with the bottom of the downward z-arm attachment of the Cartesian frame, operate using its own computer, communicate with the Raspberry Pi, and encompass all snipping, electronic, and interfacing components.

Initial system specifications include a pair of shears which have the ability to sever the head of the flower and a motor to operate the cutting motion of these blades. Alternatively, a method to expose the flower stem and/or discard the severed head was explored to also interface with the Cartesian Z-stroke. All electronics and blades are housed in order to keep away debris of the severed flower head, dirt, or any other surrounding environmental variables that might damage the electronic system or build up over length of use. This component was prototyped by 3D printing and designed to eventually be machine-manufactured for prolonged use.

2.5.3 Image Bay Subsystem

The Image Bay subsystem must be able to successfully identify the flowers within the workspace below the camera. This subsystem acts as the main source of information of where the flowers lay within the space and confirms their successful removal.

2.5.4 Software Architecture Subsystem

Since there are many different physical subsystems, the software architecture was designed in a way that allows each of the subsystems to act independently. Each subsystem has its own microcontroller and thus needs a software architecture that makes the interfacing among subsystems seamless and easy. See Figure 2.5 for a full breakdown of the software flowchart.

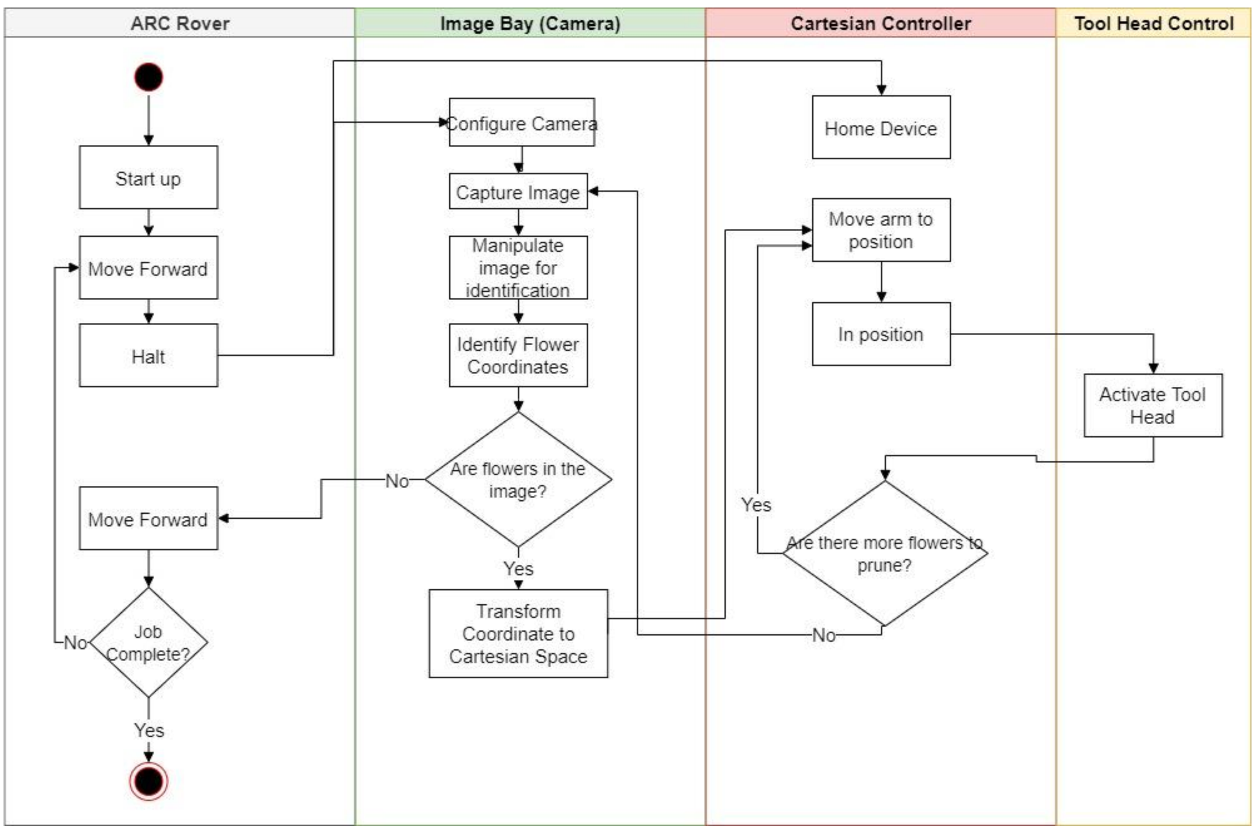


Figure 2.5: Software Flow Chart

3. Cartesian Robot Subsystem

3.1 Introduction

The objective of the Cartesian robot is to successfully navigate to the flower from the extrapolated XYZ coordinates and accurately position the tool head for flower removal. At a simplified level, the Cartestian robot is responsible for the XYZ movement, the stability and connection with the toolhead, and the attachment of the payload system to the existing drive train units of Ag Robot II. Key features of the design include a timing-belt driven XY movement, a lead screw driven Z-stroke, and a superstructure frame constructed with Aluminum 40x40 V-slots. The system has dimensions of 770 mm x 700 mm x 350 mm and has safety features in the form of limit switches at the end of each travel distance of the XYZ axes to prevent the damaging of parts.

The dimensions of both the XY gantry and the Z-stroke were constrained by the height of the Ag Robot II and the size of the strawberry beds. Figure 3.1 illustrates the plant spacing and placement at California Giant that served as constraints within our calculations and design process. In order to be compatible with the Ag Robot II and the strawberry beds, our team cut the aluminum extrusions to fit the bed dimensions, seen in Figure 3.1. The team also cut the height of the frame to prevent collision with the bed furrow and machined new plates, spacers, and end mounts which will be discussed further in the following sections.

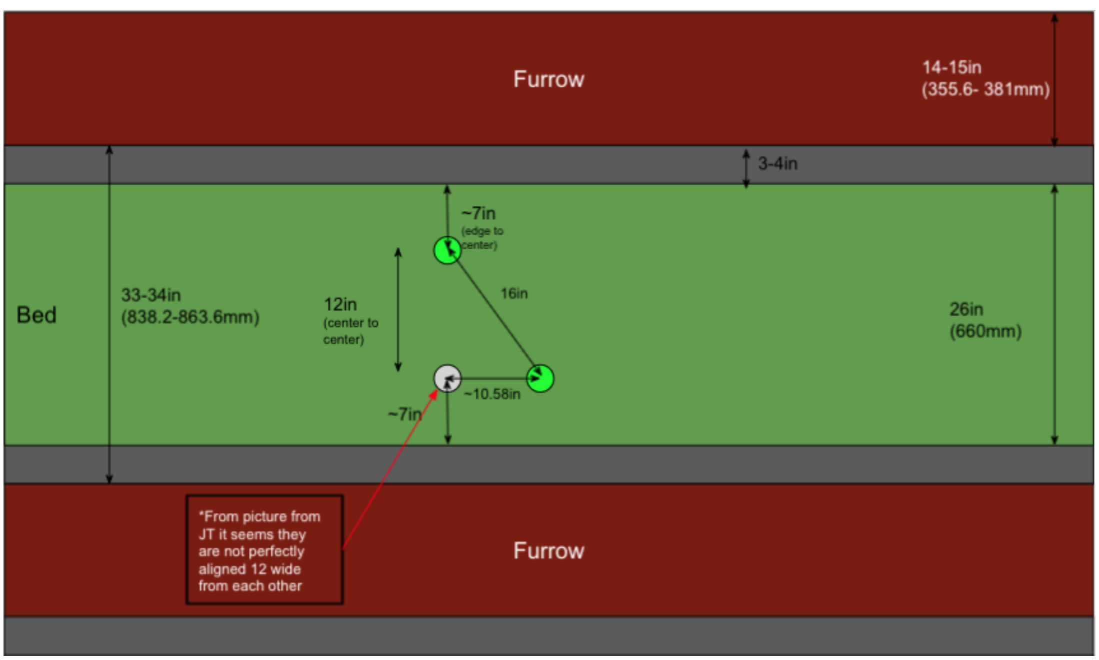


Figure 3.1: Flower bed dimensions with 48in spacing between bed centers.

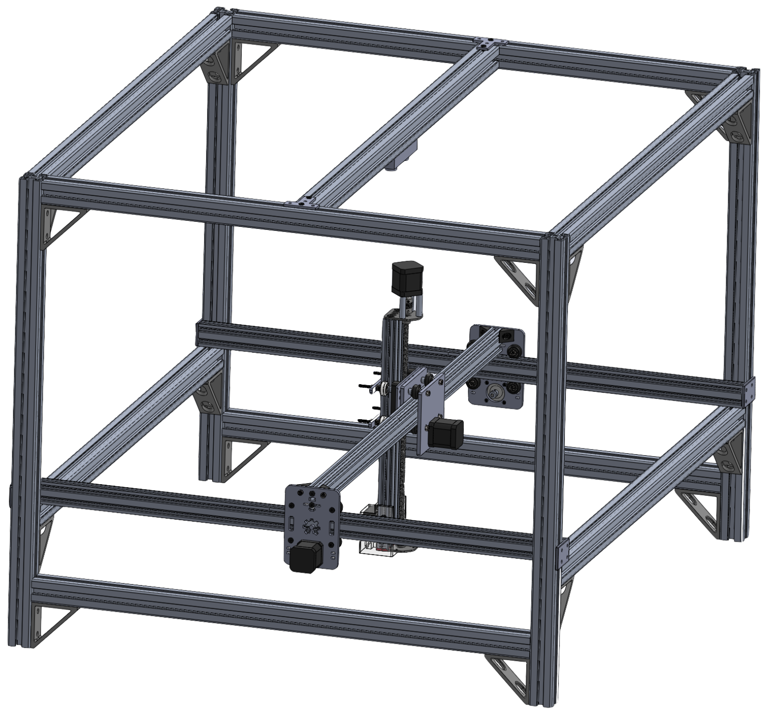


Figure 3.2: Cartesian Subsystem

3.2 Design Process

Before we decided on the Cartesian robot design, our team also researched SCARA robots, 6-axis robots, and dual arm robots. We ultimately decided on a Cartesian robot because it was affordable, economical, easier to not only assemble but also to program, and because it was the least complex system that had the most potential to be up and running by our deadline. Having proof of concept was an important benchmark for our team. Additionally, due to the time constraints of the senior design project as well as the severe restrictions imposed due the pandemic, both of the XY and Z components were built from purchased kits which are shown in Figure 3.3. The kits served as the foundation of the payload system but allowed our team the flexibility to modify and change the pre-existing design to fit our needs. Many parts included in the kits closely resembled what our team would have designed independently, such as Nema 17 motors, a lead screw actuator, and mounting plates.

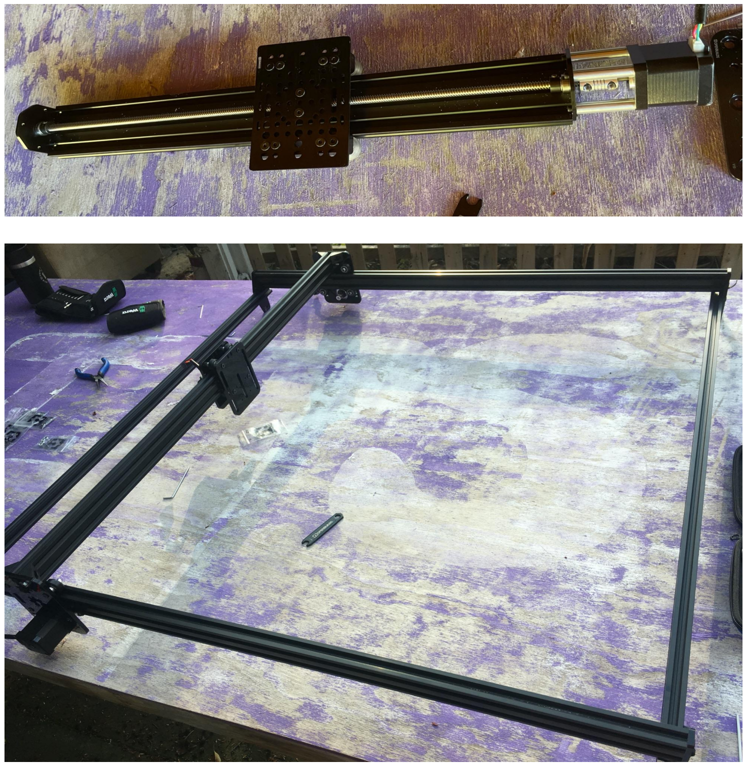


Figure 3.3: Initial Z-stroke (Top). Initial XY gantry (Bottom)

After receiving and assembling the kit, our team had concerns that the existing plates, seen in Figure 3.4, wouldn't be able to hold the load of the Z-stroke and that the y-axis bar would deform due to rotation of the plate assembly. To test these concerns, we performed physical weight testing using individual 1 lb weighted bags mounted to one side of the plate to simulate the location of the Z-stroke. The weights were placed on a platform in five pound increments up to the amount of 15 pounds; 15 pounds was based on the combined maximum weight of the Z-stroke and tool head. To verify any form of deflection or deformation, the effects of the weights were observed statically and dynamically. The weight testing allowed our team to proceed with the selected Z-stroke kit but also brought attention to three areas of concerns. First, because the plates were made of acrylic, a brittle material known to crack under stress, they deformed under the tested load. Second, there was rotational deflection about the x-axis due to both the clearance holes for the wheels being too long, as well as the uneven weight distribution of the Z-stroke; the weight is only loaded on one side of the aluminum extrusion. This prevented the bottom wheels from making sufficient, stable contact with the V-slot aluminum extrusion.

The final problem involved the Z-stroke interface. The plates from the kit didn't have enough surface area to connect to the Z-stroke. Therefore, our team designed and machined new plates made out of Aluminum. Aluminum was selected for its corrosion resistance, low cost and weight, and for the purpose of material continuity throughout the project. To verify that the y-bar itself would not be affected by the Z-stroke weight, we also performed FEA analysis assuming a 15 pound distributed load. This analysis showed that the stress and displacement were not a cause for concern. As a result, only the y-plates were redesigned.

Figure 3.4 : Original Acrylic Plates

The new y-plates, shown in Figure 3.5, were machined out of Aluminum, designed to be thicker, and had updated wheel dimensions that allowed them to make solid contact on all sides of the V-slot. This eliminated both the rotational deflection and the jitter experienced during motion. The new y-plates also featured new clearance holes that seamlessly interfaced with the Z-stroke design. As a result of the redesign, there were no longer concerns that these plates would fail during application.

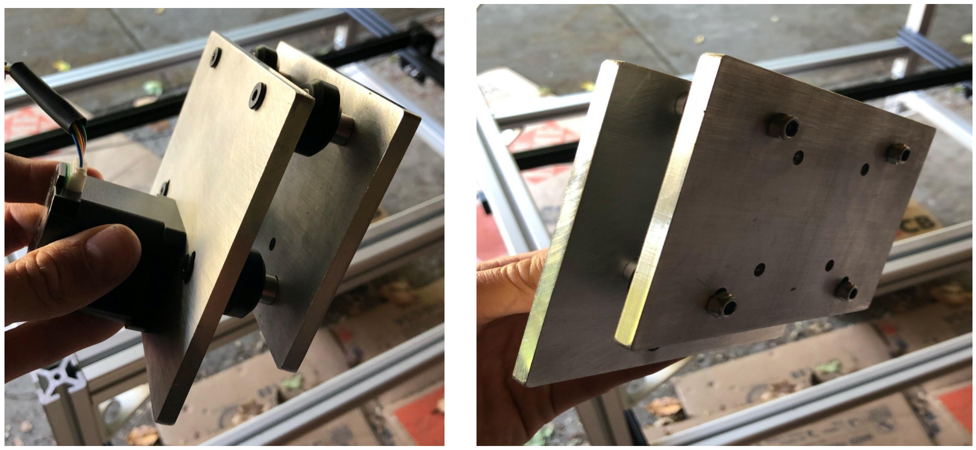


Figure 3.5: New Machined Aluminum Plates

Other design changes made to the system involved the fabrication and machining of Aluminum end mounts. Because the XYZ gantry sits within the frame, end mounting brackets were required to provide a flush finish between the gantry system and the frame. Keeping the XYZ gantry flush against the frame was important not only for accuracy, but also to prevent boring and other unneeded stresses on the Aluminum extrusions. If the XYZ gantry was not flush against the frame, the wheels moving the plates along the track would be bent and not make sufficient contact with the surface. This would put stress on the motors and the screws which could lead to system deterioration and result in the robot needing frequent maintenance. As a result, the plates shown in Figure 3.5 were machined in order to fit both within the 40x40 Aluminum slot and also within the clearance holes already created at the end of the XY gantry Aluminum slots.

The Aluminum bars were designed to sit behind the wheels of the Z-stroke and their purpose was to hit the limit switches during the Z-stroke's travel so that it did not over extend and damage the motor or other parts of the design. Figures 3.6 and 3.7 show the implementation of both the designed end mounts and aluminum bars.

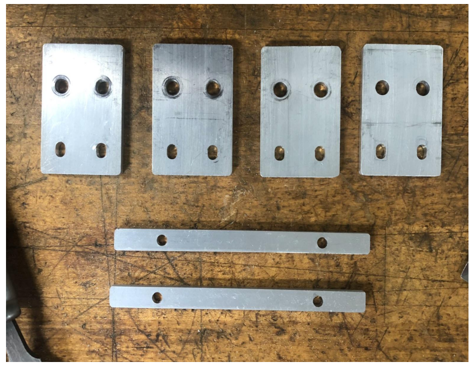


Figure 3.6: Machined Aluminum End Mounts and Bars

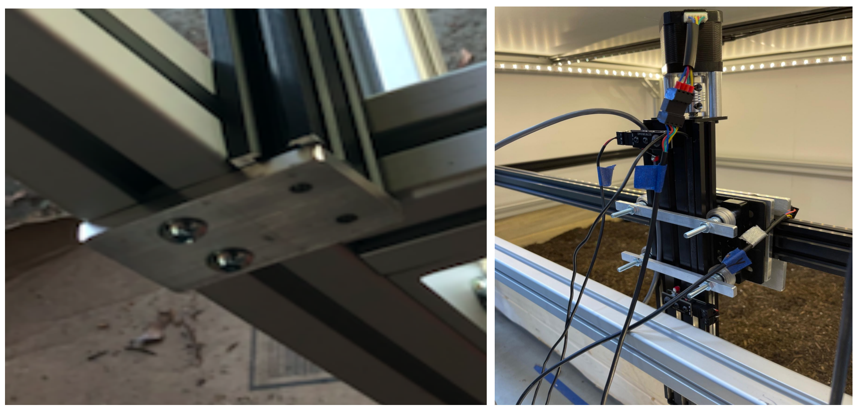


Figure 3.7: End Mount Implementation (Left). Aluminum Bar Implementation (Right)

3.3 Expected System Requirements

To ensure that customer needs were met, our team devised a list of system requirements, seen in Table 3.1, specific to the Cartesian subsystem. These requirements served as benchmarks of success at the conclusion of building to ensure accuracy and reliability.

Table 3.1: System Requirements

Category	**Requirement**
Weight	< 120 kg
Degrees of Freedom	3
Workspace Width	770 mm
Workspace Height	350 mm
Positional Accuracy	1 mm

Homing	System must home to origin before starting on each workspace
Protection	Closed environment for controlled lighting and shielding from weather and debris
Safety	Limit switches to prevent damage to parts

3.4 Initial Design Alternatives and Tradeoffs

The Cartesian subsystem is the main subsystem responsible for the movement of the tool head to the flowers. To provide the best functionality and accurate control, our team was deciding between either 2 or 3 degrees of freedom (DOF) as the minimum requirement of our subsystem. For 2 DOF, movement in the Y and Z would be part of the Cartesian's responsibility, while the X movement would be accounted for as the rover moves linearly over the strawberry beds. For 3 DOF, the system would have the same Y and Z movement, but would now have an added movement in the X direction that is independent of the moving rover. This would allow the Cartesian system to reposition the head attachment if the Ag Robot II were to overshoot the flower, or encountered rough terrain where it couldn't stop as precisely. Ultimately, we decided on the 3 DOF minimum requirement for the Cartesian subsystem because of the uncertainty associated with relying on the rover to position the head correctly in the X direction. This extra DOF also allowed the rover to move independently of the chassis, within its workspace, which allows its application to be more precise and accurate in its movements.

Another key issue is the modularity of the system design and how it will be mounted onto the rover currently being built and tested by Dr. Manoj Sharma. Because there aren't any industry standards for strawberry beds, different farms have different dimensions with regards to bed and furrow width, crops per bed, and crop spacing. With this in mind it was important to create a modifiable design to accommodate multiple field sizes and bed dimensions. In having multiple applications, the robot has the potential to assist a larger network of farmers. With the ability to be extended physically through the use of longer Aluminum extrusions, the Cartesian robot can accommodate larger bed widths. The Cartesian subsystem is also mounted to its own superstructure frame which eliminates any dependence on the Ag Robot II. The frame also allows users to easily attach and detach the payload from the drive train units. With this independent frame, our team is not constrained to a set wheel width and can adjust our design accordingly.

After these initial design constraints were placed onto the Cartesian subsystem, a tradeoff analysis of different design options was performed to ensure optimal efficiency. Our three main design options were to buy pre-made linear track actuators and linear servos, to buy build kits of a specified track design, or to build and design the Cartesian system from scratch. We ultimately went against buying a pre-made linear track and servo because many of the designs were too costly and restrictive in the dimensions of both the stroke length and overall size including the motor and mounts.

Table 3.2: C-Beam Design Options

	C-Beam	C-Beam XL	C-Beam Double Wide
Force	26 lb (115 N)	26 lb (115 N)	26 lb (115 N)
Speed	0.13 m/s	0.13 m/s	0.13 m/s
Accuracy Positioning	0.091 mm	0.026 mm	0.091 mm
Accuracy	0.05 mm - 0.10 mm	0.05 mm - 0.10 mm	0.05 mm - 0.10 mm
Travel Distance	900 mm (for 1000mm option)	885 mm (for 1000mm option)	830 mm (for 1000mm option)
Price	$189.99 (for 1000 mm, no shield, normal stepper)	$203.99 (for 1000 mm, no shield, normal stepper)	$227.99 (for 1000 mm, no shield, normal stepper)
Motor Options	NEMA 23 normal stepper	NEMA 23 normal stepper. NEMA 23 stepper high torque series	NEMA 23 normal stepper. NEMA 23 stepper high torque series
Shield Option Available	Yes (250 mm, 500 mm)	No (purchase separately)	Yes (250 mm, 500 mm)

Our research ultimately led us to begin looking at Aluminum T-slots, V-slots, and C-beams with a motor and gantry plate where we would either buy a kit or build from scratch. Many of the kits leave room for design changes where we were able to change the motors, plates, or the length of the beam to better accommodate our design dimensions. Building the Cartesian system from scratch would yield a design similar to one if we simply used a build kit. We would have slightly more freedom in which individual parts we use in our design, however, the build kits are fairly flexible and allow us to change parts and dimensions easily while giving us a complete physical framework to work with. Furthermore, with our goal of showing proof of concept by the conference date, and COVID affecting our team's ability to machine new parts, obtain access to equipment, and work together in the lab space, a build-kit was the best option to have a preliminary design up and running the fastest. This, in turn, allowed us to begin testing while also making design modifications. For these reasons, our team proceeded with a build-kit for the Cartesian subsystem with the intention of customizing its features to fit our specific needs.

Table 3.3: V-Slot Design Options

	NEMA 23 V-Slot	NEMA 17 V-Slot
Force	26 lb (115 N)	13.5 lb (60 N)
Speed	0.13 m/s	0.18 m/s
Accuracy Positioning	0.091 mm	0.075 mm
Accuracy	0.05 mm - 0.10 mm	0.05 mm - 0.10 mm
Travel Distance	900 mm (for 1000mm option)	900 mm (for 1000mm option)
Price	$203.99 (for 1000 mm, no shield, normal stepper)	$168.99 (for 1000 mm, normal stepper)
Motor Options	NEMA 23 stepper	NEMA 17 stepper

Once we decided on purchasing a kit for the Cartesian system, more consideration was needed into what kit would be best. The two types of tracks offered were either V-slots or C-beams, and the two types of motion were either belt driven or lead screw driven. Tables 3.2 and 3.3 outline the different options for both the C-beam and V-slot actuators with consideration to price, motor options, and size being the main points of interest. Outside of these kits there was also an XY gantry system which would only require an additional purchase of the Z-stroke. A table listing the XY gantry system;s size, price, and specifications is shown in Table 3.4.

For the Z-Stroke, our team considered both a lead screw and a ball screw linear actuator but quickly settled on the lead screw design. Known to be optimal in vertical applications, lead screw linear actuators don't require braking mechanisms, are lightweight, and don't produce backdrive that could harm the system and lead to increased maintenance. Additionally, lead screws are significantly less expensive than ball screws. With the purpose of designing a cost effective robot, our team solidified our design with the selection of a lead screw linear actuator.

After careful thought and further calculations informing the selected system requirements, it was decided that the XY gantry system would be purchased as the initial design for the XY, and a NEMA 17 V-Slot actuator would be purchased as the initial design for the Z-stroke. Both of these kits provided a solid framework for our design that allowed for sooner testing while still giving us flexibility in design modifications.

Table 3.4: XY Gantry System Specs

	XY Gantry
Workspace Dimensions	300x300mm (20x20in total dimension) 800x800mm (40x40in) 300x800mm (20x40in)
Positioning Accuracy	0.10mm~0.20mm
Max Load	Testing Required
Max Speed	Variable
Price	$289.99 - $627.97
Motor options	NEMA 17 Stepper Motors

After the kits were ordered, further trade offs of motors were needed in order to select the motor that not only provided the correct speed and torque necessary to efficiently prune flowers, but also to be reliable and accurate. Servo, stepper, and brushless DC motors were all considered as viable options that were able to be implemented in our design. Table 3.5 outlines their different features.

Table 3.5: Motor Selection Matrix

	Servo	**Stepper**	**Brushless DC**
Torque	Low (unless buying expensive one)	High holding torque	
Total Load	Low (unless buying expensive one)		
Accuracy	High	High	
Speed	High		

Heating (of motor)	Only for long run times or for heavy loads. No problem under normal use within spec range	Potential Problem	
Lifespan / Maintenance level	Ideal conditions 20+ years. Extreme conditions 1 year.	Around 5 years if used everyday for 8 hours. (10,000 hours)	Long (10,000 hours) / low maintenance
Control	Easy and accurate. Send pulse commands	Easy and Precise	More difficult (check model and specs)
Cost	Inexpensive	Not too expensive but more than servo price	Most expensive but still very reasonable
ROM	Limited (typically only 180 deg.) (check specs)(some are 360)	Full 360 degrees reversible. Check step count for degrees per movement	Full 360 degrees reversible. Check step count for degrees per movement
Efficiency	Efficient	Low efficiency	High/Efficient
Other	Might have jitter	Might skip steps at high loads	

Servo motors were quickly eliminated from consideration as many of the servos only have a range of motion of 180 degrees, and it proved to be a costly solution as the servo motors would need to be adjusted to achieve the required torque and load requirements. Brushless DC motors, which provided the best efficiency and lifespan, were also eliminated due to their increased cost and more complex control process. Stepper motors were the only motors left, however, several options for this type of motor were still on the market and needed to be explored deeper.

Looking at Table 3.6 below, three different types of stepper motors were considered with their specs shown. Looking at our design requirements, our entire system would not be holding a significant amount of weight, with the heaviest load on the motor not exceeding 15 lbs. Therefore, our team did not need extremely high torque. The Cartetsian robot also required a motor able to move our system at a speed such that our payload could complete the pruning of one workspace, 4 plants, at roughly the same speed as a human worker. The final consideration was in price; our team needed to purchase the cheapest motor that fulfilled all necessary requirements in order to save on cost to be able to allocate funds to other aspects of our design. For example, the image bay system required significant funds to purchase the Jetson computer.

Through design analysis and with our financial budget design, our team selected NEMA 17 stepper motors for our application. Known to be an industry standard motor, NEMA 17 motors were included with the ordered kits.

Table 3.6: Motor Considerations for different steppers

	NEMA 23Stepper	**NEMA 23 Stepper High Torque**	**NEMA 17 Stepper**
Shaft Size	0.009 mm	0.009 mm	5 mm
Torque	175 oz*in (1.23 N*m)	345 oz*in (2.43 N*m)	76 oz*in (0.53 N*m)
Step Angle	1.8	1.8	1.8
Volts	12-48 VDC	24-48 VDC	12-24 VDC
Peak Current	2.8 A/phase		1.68 A/phase
Price	$27.99	$43.99	$17.99

3.5 Analysis and Design Considerations

Previously mentioned in our design process, the first test performed on the XYZ gantry system was static and dynamic weight testing using 1 lb bags mounted to one side of the y-plates. To test the deflection of both the bar and the mounting plate, we purchased ankle weights with insertable 1lb bags and two mounting brackets to provide a platform on the mounting plate. From there, we tested weight in increments of five pounds, both statically and dynamically. To test weight dynamically, the speed of the XY was set to an acceleration of 2,000 mm/min. The Cartesian robot was then moved in the Y-direction in increments of 100 and 500 mm. It was concluded that weight did not impact the performance, such as speed, of the robot which eliminated our design constraints of the Z-stroke. After each addition of weight in the static test, photos were taken of the deflection in the mounting plate and measurements of the deflection were noted. It was concluded that the addition of weight up to 15lbs caused the same amount of deflection of the mounting plate, in the amount of 11.34mm. The test setup is shown in Figure 3.8, as well as the deflection.

Figure 3.8: Test setup and deflection of y-plates during testing.

Deflection or deformation was not present in the V-slot, however our team still wanted to perform FEA stress analysis to determine if the V-slot would need to be reinforced. For the FEA, a study was run on the 40x20 Aluminum Extrusion which is responsible for holding the weight of the Z-stroke, Z-Can, and the tool head. Because these components are mounted on only the faces of the Aluminum V-slots, it was determined that a simulated study was necessary to ensure the bar could support the weight of these components without failure. Since the components being mounted are critical to the robot's success and are expensive and costly, confirmation that the bar would be stable before mounting any of the physical components onto the existing XY gantry was necessary. This avoided future system failure and ordering of more parts, which would be expensive and delay our scheduled lead time. To determine the displacement, stress, and strain that the bar would experience under loading, a stress-strain study was run. Similar to physical testing, a maximum load of 15 lbs was assumed. This 15 lbs was treated as a uniformly distributed load over a length of 127 mm, which is the length of the plate that the Z-stroke is mounted to on the 40x20 Aluminum extrusion. As an assumption, the bar was treated as fixed on both ends since it is firmly mounted to the X-plates on either side. Finally, a mesh was created over the bar and the study was run. The results are pictured below in Figures 3.9, 3.10, and 3.11 and a table with all of the maximum values can be found in Table 3.7.

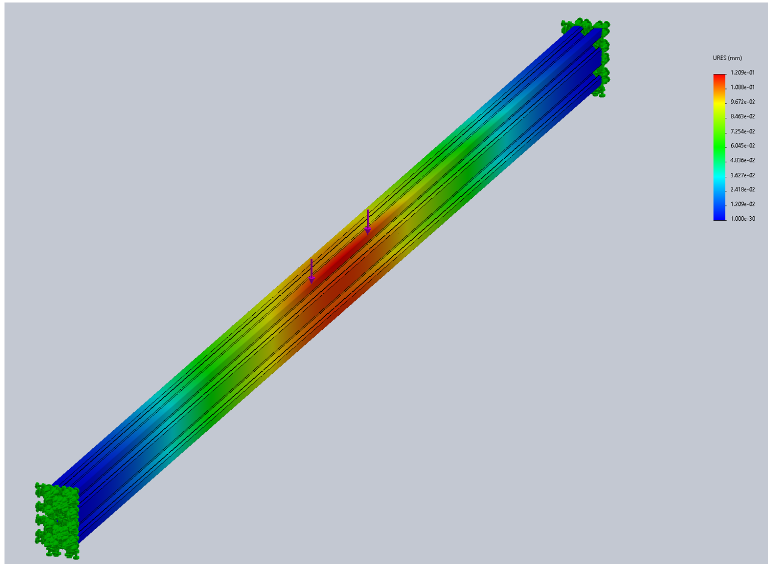


Figure 3.9: Displacement (mm); Scale on right hand side (blue to red): 1.00e+30 to 1.29e+01

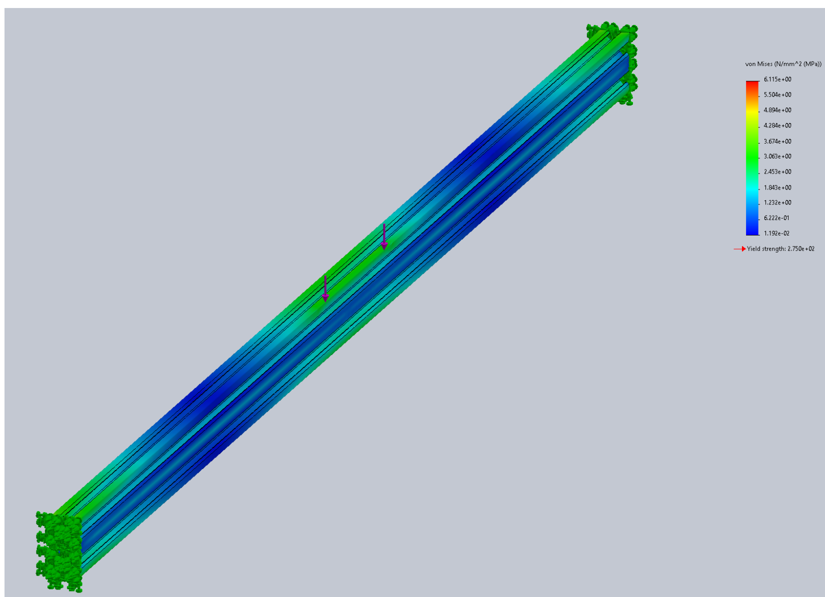


Figure 3.10: Stress (N/mm); Scale on right hand side (blue to red): 1.192e-02 to 6.115e-00

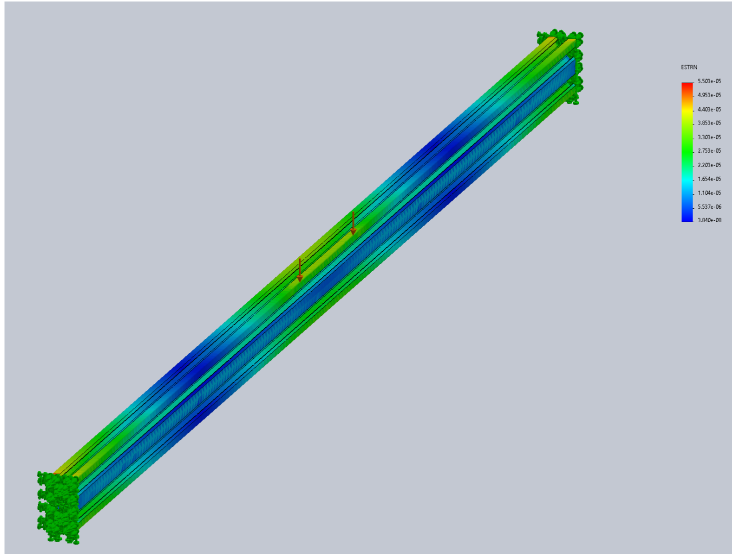


Figure 3.11: Strain; Scale on right hand side (blue to red): 3.840e-08 to 5.500e-05

Table 3.7: FEA Analysis Results

FEA Test	Results
Stress	$3.036\ \frac{N}{mm^2}$
Strain	$4.403\text{x}10^{-5}$
Displacement	0.1209 mm

As evidenced in the images and table above, the Aluminum extrusion did not experience significant displacement, stress, and strain for the bar to deform; the experiment passed and the y-bar is able to successfully carry the expected maximum weight of all the mounted components. The maximum displacement and stress were both at the locations where the load was applied, which is to be expected, and the maximum displacement is at a value of 0.1209 mm, which is not significant enough to cause concern. Also with the assumption of the maximum load applied in this study, the true load carried by the bar will likely be less and therefore the displacement in the beam will also be less than this value. The maximum stress on the bar was 3.036 N/mm^2 which is significantly less than the yield strength of the bar at 275 N/mm^2 which is also not significant enough to warrant any design changes. Finally, the maximum strain on the bar was experienced at the location of loading, but also at either end where the bar was fixed. The maximum value of the strain however was at $4.403 * 10^{-5}$ which is practically negligible and not a cause for concern. The results of this study were as expected and reaffirmed the previous hypothesis that the 40x20 Aluminum extrusion would be capable of holding the necessary weight.

3.6 Final Design

Figure 3.12: Final Cartesian Subsystem

The final Cartesian design is shown in Figure 3.12. Table 3.8 below highlights the various parameters and requirements met such as speed, weight, and safety. Overall, the subsystem has three degrees of freedom: the XY movement utilizes belt driven actuators while the Z-stroke utilizes a lead screw actuator. Both the travel speed and homing speed are variable and able to be changed within the operational capabilities of the motors, however all three directions were set to move at a speed of 83 mm/sec and the homing speed was set to 41 mm/sec. This speed was determined through testing of the movement and accuracy of the system. At low speeds, the timing belt skipped steps causing inaccuracy in the system positioning, and proved to be extremely inefficient due to the long completion time of a single workspace. The homing speed is also half of the travel speed to ensure that the system starts precisely at the origin each time. Our system was able to successfully home, receive the XYZ coordinates from the onboard computer, and repeatedly move within 1 mm of the desired location. Our system also weighs a total of 11 kg, which is well below the weight limit of the existing chassy, which is 120 kg.

Table 3.8: System Specifications

Specifications	**Parameters**	
	Value	**Units**
XYZ Speed	83	mm/sec
Homing Speed	41	mm/sec
Repeatability	1	mm
Z-Stroke Travel	350	mm
Weight	11	kg
Safety Limit Switches	3	Pairs

4. Tool Head Subsystem

4.1 Introduction

The toolhead is the subsystem attached to the end of the Z-stroke in the Cartesian subsystem. The attachment removes white flowers that grow on the strawberry plants by snipping the stem. From going to the farm and analyzing the location and orientation of the flowers, a design that would be able to access and accurately cut the stem was designed. Key aspects of the design include blades and a motor which drives the blades and forces the cutting action. A microcontroller, an Arduino Uno, is used to initiate the motor as well as communicate with the overall system software.

4.2 Design

The flowers are currently removed by pruning shears operated by human workers that walk the fields and manually pick the flower head off of the strawberry plants. In Figure 4.1, the stem and flower plant can be seen as it would be planted in its bed of soil in the bottom most image, and the manually removed stems lie above the plant. During the removal process, the bottom of the stem is exposed and then cut by the workers, the procedure which our team designed to mimic. The toolhead component was designed to receive an input from the main Jetson computer, signaling the initiation of the Arduino Uno which then controls a servo to close a pair of clippers to sever the head of white strawberry flowers. As can be seen in Figure 4.1, more than just the top of the flowers are currently being manually cut in the field. However, after discussion with Cal Giant, the discrepancy between the robotic toolhead and manual extraction of the flower was deemed acceptable because the most important aspect of the flower removal, as iterated by the company, is solely that the head of the flower is snipped.

Figure 4.1: Extracted flowers by human workers.

4.3 Expected System Requirements

The toolhead system attaches to the end of the z-stroke Cartesian frame and must encompass its own modular components such as electronics, motors, and snipping tool. As the severed flower heads are discarded manually after they are severed by field workers, alternative design goals were explored to optionally have the ability to sever the flower head closer to the stem. It was considered to induce this capability by pulling the plant taut or vacuuming the plant to expose the stem, then potentially discard the flower. Each explored requirement listed in Table 4.1 was expected of the toolhead cutting mechanism and subsequently ranked according to its priority in order to reach our goal of successfully removing the white flower head; especially given the resource, time, and lab restrictions brought upon the team due to COVID-19.

Table 4.1: Tool Head System Requirements

Toolhead System Requirements	**Priority**
The software architecture had to be compatible and able to communicate with the software of the overall system.	HIGH
The casing had to be able to attach to the end of the Z-stroke	HIGH
The motor had to produce enough torque to cut the stem	HIGH
The clippers had to be able to close around the flower stem.	HIGH
The toolhead must discard the severed flower head/expose the stem for adequate cutting	LOW
Components must be entirely enclosed to prevent dirt/debris from damaging electronic components	MEDIUM

4.4 Alternatives and Tradeoffs

After brainstorming and producing sketches of possible designs, a selection matrix was created to weigh the different options, as seen in Table 4.2. The criteria that was used to evaluate the designs included aspects of being able to complete the cutting action, such as efficiency, precision and safety. Criteria that were considered in reference to the ability to create the design considered included aspects such as manufacturability and low cost for the early prototyping and later machining of the toolhead. It was also examined how a design would be incorporated into the larger system, such as ease of integration and repair on a commercial level.

Each design included aspects of a component to induce a taut stem and/or a method to remove the flower head off of the plant, either by brute force or blade. Sketches pertaining to each option exploration can be referenced to in Appendix D in more detail. This detail entails tradeoff options for each design option.

Table 4.2: Design Selection Matrix

	Weight	**3-Prong Claw**	**Motorized Scissors**	**2-Prong Claw**	**Rake & Scissor**	**Cigar Cutter**	**Open Blade**
Efficiency	**.5**	2	4	2	4	2	4
Safety	**1**	5	3	5	3	4	1
Ease of Repair	**.5**	2	4	2	3	2	2
Low Cost	**.5**	1	5	2	3	3	3
Manufacturability	**1**	2	4	2	3	2	3
Ease of Integration	**1**	2	4	2	3	2	3
Precision/Accuracy	**2**	4	2	3	4	4	1
Final Score		**19.5**	**21.5**	**18**	**22**	**19.5**	**13.5**

After weighing these options within the matrix, it was clear that the scissors and raking combination scored the highest, with the motorized scissors a close second. With this in mind, the scissor and raking mechanism was pursued. Once the design concept was frozen, the raking design was further explored. As iterated previously, the purpose of the raking mechanism was to expose the stem and thus create an ease of access for the clipping configuration to come in secondly and perform the snipping action. In addition to rakes powered by linear actuators, different ways of inducing pressurized air to force a gust and move the covering leaves was considered for the same purpose.

4.5 Analysis and Design Considerations

Initially, methods in order to pull the stem taut and discard the severed flower head were explored. As previously discussed, raking and vacuum mechanisms were considered to fulfill these two requirements, and their experimental set up can be seen in Figure 4.2.

Figure 4.2: Concept of Raking and Linear Actuator Integration.

In order to fully analyze the method in which the toolhead component would interact with the strawberry plant, the amount of force required to sever a flower steam was investigated. This force calculation was required in order to accurately design a rake and linear actuator combination, or vacuum attachment. Retention force testing was performed to collect a small sample size of data to give the team an idea of what amount of force would be required. The raw data from these experiments can be seen in Tables 4.3 and 4.4. Testing was performed using an Instron to determine the stems' ultimate tensile strength.

Table 4.3: Raw data of retention force testing for purple pansies.

Purple Pansys					
	Serial #	Inserter	Maximum Load	Load at 3mm	Ten. Ext. at Max Load
			(lbf)	(lbf)	(mm)
1	1	Purple Primrose	2.14	2.06	2.63
2	2	Purple Pansy	1.03	0.26	0.00
3	3	Purple Pansy	1.80	0.45	0.37
4	4	Purple Pansy	0.95	0.92	3.55
5	5	Purple Pansy	0.98	0.15	39.12
6	6	Purple Pansy	0.89	0.26	20.00
7	7	Purple Pansy	2.27	0.57	0.00
AVG MAX LOAD =	**1.44**	lbf			
AVG Tensile Extension =	**9.38**	mm			
AVG Load Overall =	**1.68**	lbf			

Table 4.4: Raw data of retention force testing for white primrose.

White Primrose						
	Serial #	Flower	Maximum Load (lbf)	Load at 3mm (lbf)	Ten. Ext. at Max (mm)	Notes
	1	White Primrose	0.67	0.15	5.34	Snapped at stem
	2	White Primrose	1.00	0.01	22.75	Snapped At Stem
	3	White Primrose	2.80	0.00	0.00	Snapped at stem
	4	White Primrose	2.20	1.14	1.70	Snapped at stem
	5	White Primrose	2.57	0.53	0.76	Snapped at head
	6	White Primrose	1.73	1.18	1.57	snapped at stem
	7	White Primrose	1.57	0.01	1.43	snapped at stem
	8	White Primrose	1.80	1.44	1.57	snapped at stem
	9	White Primrose	3.05	0.23	0.62	snapped at stem
AVG MAX LOAD =	**1.93**	lbf				
AVG Tensile Extension =	**1.62**	mm				
AVG Load Overall =	**1.69**					

After observing the data above, it was determined that the >2lbf of retention force was not statistically significant to the purpose of the project, thus, the concept was placed lower in the priority list. Through observation, the exposure of the flower stem and discarding of the flower's severed head was not deemed a necessity for Cal Giant and thus efforts were refocused on the cutting aspect of the subsystem.

As far as the blade configuration that would be used in conjunction with the mechanism to expose the stems, it was initially considered to have two blades, each driven by an individual servo. These blades would work in unison to cut the stems, replicating the physical operation of cutting shears. This configuration can be seen in Figure 4.3.

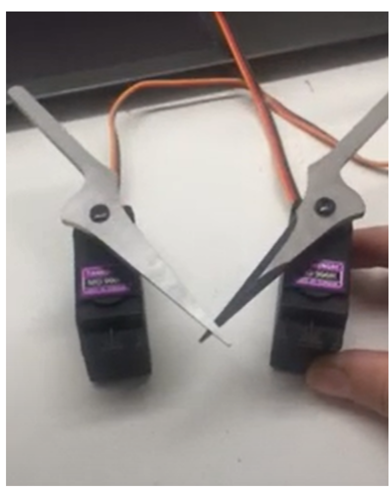


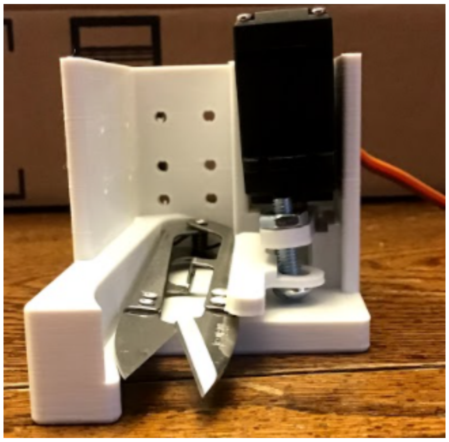
Figure 4.3: Preliminary Snipping Design

An issue that was found with this configuration was that the scissors were not able to induce enough torque to cut the stem. After running into this problem, it was decided to hold off on the raking/blowing mechanism and instead focus on being able perform the cutting action in order to save resources and time constraints surrounding restricted lab access due to COVID-19 regulations.

Torque testing was used to identify how much torque would be required to cut the stem with the already purchased shears. From that testing it was found that 7lbs of force was required to close the shears, equating to 172 oz-in of torque required. This justifies why the original configuration did not induce enough torque because the servos originally selected were only able to produce 150 oz-in of torque. It was then decided to upgrade and purchase a servo to one which produced 500 oz-in of torque. It was also during this time that it was decided to opt for a more sleek design that would be integrated into the z-stroke, which could be found to be in a new pair of shears that ultimately took less force to close. These new shears were yarn clippers that were found to only require 3lbs of force to close, translating to require 185 oz-in of torque, which was still in the range of the new servo procured. The yarn snippers selected may be viewed in Figure 4.4.

Figure 4.4: Yarm Snippers

With the new elements of the design obtained, a casing to encompass the components was designed in Solidworks to be 3D printed. The new design was to have the servo lever arm, controlled by the Arduino Uno, come into contact with the cutters as a point force to induce the closing action of the blades. Thus, the casing was required to hold all components in place while allowing ample space for the lever arm to perform its task without scraping the bottom of the housing unit and also operating within the same datum plane as the snippers. An initial configuration of the housing unit and first prototype can be seen in Figure 4.5.



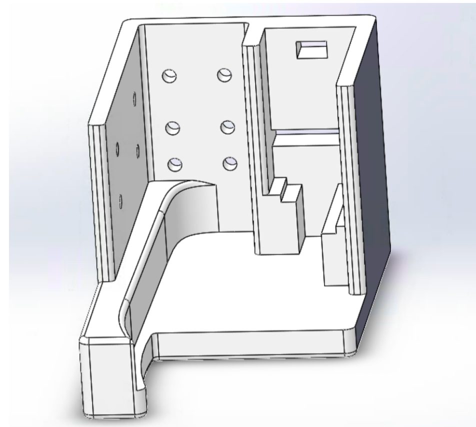


Figure 4.5: Initial 3D Printed Case

An issue found with this configuration was that the lever arm of the servo was not in the same plane as that of the snippers. This prohibited the ability for the servo to run into the snippers and perform the cutting action. In an attempt to solve this problem, putty was used to raise the shears so that they were in the same plane as the lever arm, however, this was only a quick fix for prototyping until the corrections could be made to the design of the housing unit and be printed.

Figure 4.6: Putty to Raise Clippers

The next design change focused on how the case was to interface with the Z-stroke extension of the cartesian frame. Originally, the back of the case contained clearance holes to attach the case extruding out of the side of the Z-stroke using M5 screws see in figure 4.6. After design analysis, in efforts to better secure the clippers to the housing unit and accommodate for user-friendly removal/reattachments, the design was refined to create a ceiling over the clippers and altered interfacing walls for the Z-stroke arm. This design change can be viewed in Figure 4.7.

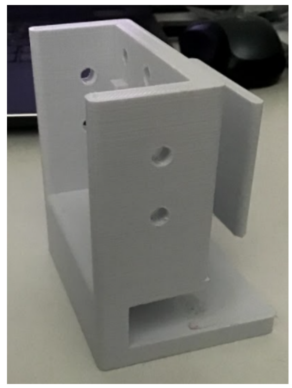


Figure 4.7: Condensed Z-stroke Attachment

With the overall design of the casing fairly set, the servo and clippers were added into the design to test functionality. As seen in the following image, the servo was able to successfully rotate into the clippers to close them. This was performed by the Arduino Uno microcontroller communicating through to the servo. An issue that was overcome with this process was that the Arduino automatically functions in a specific pulse width. However, the new, more powerful servo operated in a pulse width that did not align with that of the Arduino. This required the operating pulse width of the Arduino to be manually changed to coordinate with the servo. As far as the casing was concerned, the only issues that came were keeping the servo secure in the casing, as there was some slight deflection in the wall as the servo rotated into the shears.

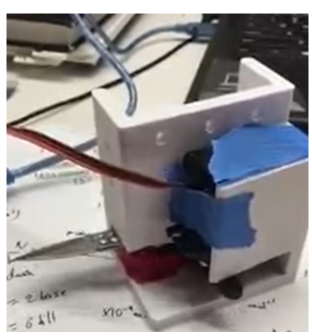


Figure 4.8: Toolhead Design Functionality Test

4.6 Final Design

The final design of the toolhead lowered and thickened the outerwall to keep the servo secure and eliminate any deflection. Due to time constraints, the final design was not able to be machined, so in keeping unity with the Z-stroke, the PLA 3D printed material was changed to black. M5 screws were used to attach the casing to the extension and the toolhead was fully functional to perform its cutting task. A red tray was integrated into the design to secure the yarn snippers. This also raised the datum plane of the snippers allowing them to interface with the lever arm of the servo which performed the sweeping, cutting motion for the snippers. The servo fits into the housing model at a precise pressed-fit. The final CAD assembly and design in conjunction with the final prototype can be seen in Figure 4.9.

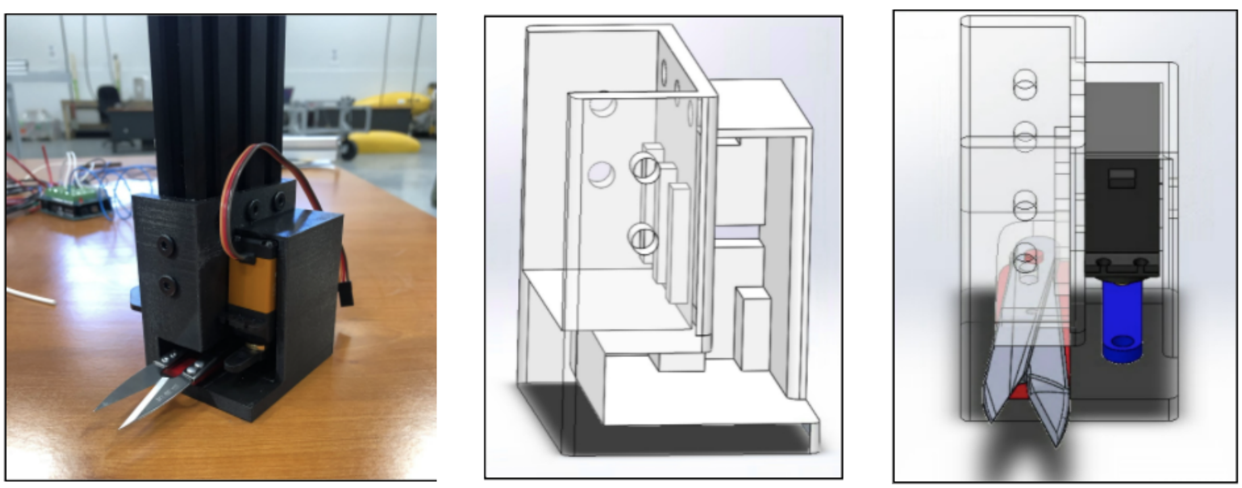


Figure 4.9: Final Toolhead Design

5. Image Bay Subsystem

5.1 Introduction

The image bay acts as the main vision component of the system and is how we are actually able to identify the strawberry plants and their subsequent locations. There is a single stereo camera positioned in the center top plane of the frame system that can capture high resolution 2D images as well as millimeter precision depth. The stereo camera's dual lens capability allows for it to use binocular vision to be able to perceive depth through the overlap of the images and the angle of intersection. Ultimately with the 2D image captured and the subsequent matrix of millimeter depths per pixel, an exact location of the flower can be identified. Our initial design for the image bay can be seen in Figure 5.1.

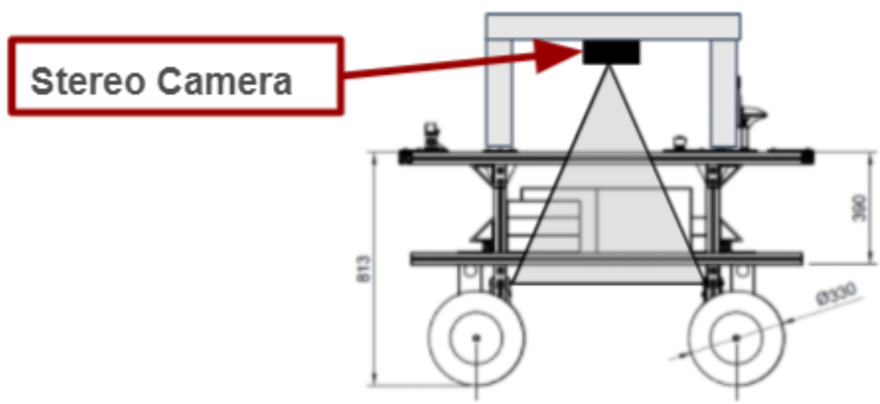


Figure 5.1: Initial Image Bay placement

5.2 Design

5.2.1 Image Processing Algorithm

The first main function of the image bay is to actually be able to identify the flowers within the work bed beneath. In order to do this, we created an image processing algorithm that can manipulate a picture of the workbed to find the flowers based on their high contrasting white color. Below is the outlined sequence of operations used to achieve a desired flower extraction accuracy and Figure 5.2 has each of the steps visualized.

1. Convert the RGB image to HSV (Hue Saturation Value) Space in order to be able to filter out specific range of the white color
2. Create a mask of the image that contains only specific white range of pixels

3. Use morphological transformation on the black and white image of extracted white images
    a. Opening algorithm to get rid of smaller spare pixels of white
    b. Closing algorithm to close the flower circle better
4. Use built in findContours function to extract blobs of contrasting pixels
5. Return the pixel location in form of top right corner X and Y position and the width and height of the bounding box around the contour

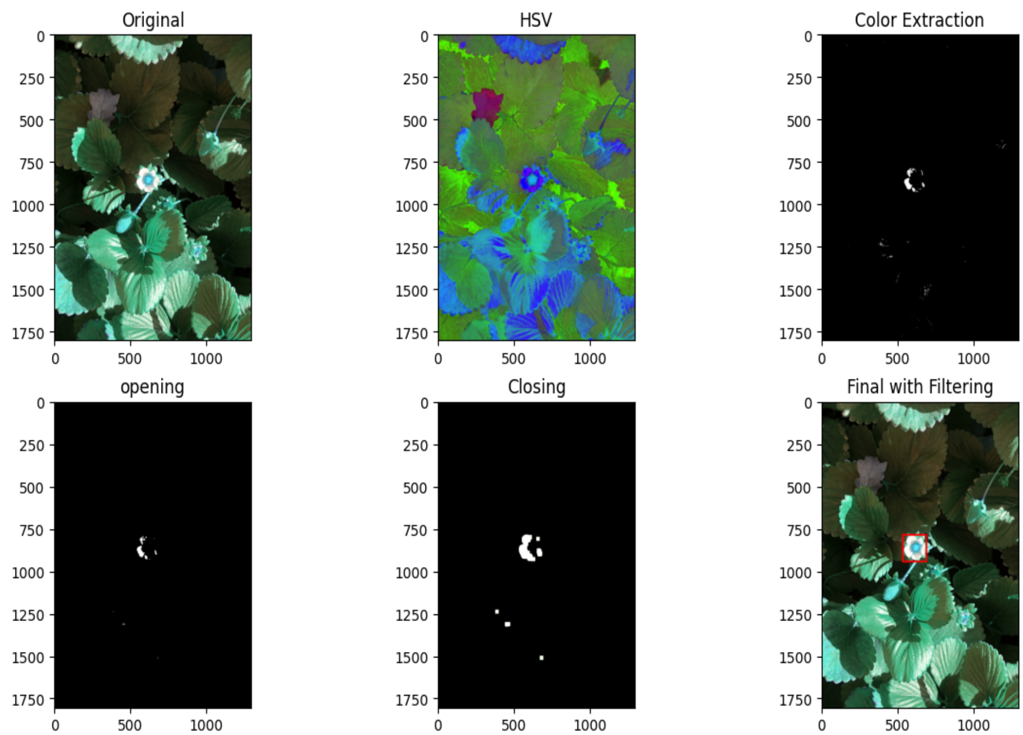


Figure 5.2: Image Processing Sequence Visualization

Another problem we encountered was lighting. During one of our visits to the farm we immediately noticed how washed out the flowers looked like in the sun and how the sun reflected off of the black plastic covering. Below in Figure 5.3 is the image taken at the farm that shows this.

Figure 5.3: Washed out flower photo taken at the farm

In order to address this problem, we decided to create a controlled lighting solution with an enclosed covering. We did this by making a foam board enclosure around the frame which can be seen in Figure 5.4. We then purchased an LED light strip with different brightness and hue settings in order for us to get the best lighting possible for our image processing algorithm.

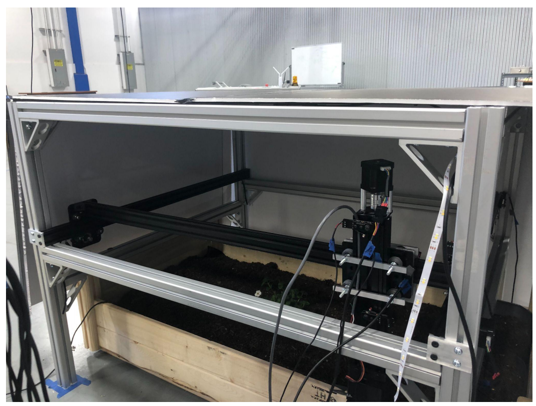


Figure 5.4: Foam board enclosure created around the frame

Final finishing touches came from filtering out additional noise based on the area of the contours found. This involved simply creating a minimum and maximum area threshold of the counties and only using the ones that are the typical strawberry flower size. Prefiltering image can be seen in Figure 5.5 and post filtering can be found in Figure 5.6.

5.2.2 Location Extraction

The next main function of the image bay is the location extraction of the previously identified flowers. The location is used as the main commands for the Cartesian robot subsystem so that the Cartesian arm can traverse to the flower and the tool head can then cut it. In order to get the location, we are able to take the centroid of the bounding box of the flowers and use coordinate scaling and offsets to transform it to the Cartesian's workspace. Figure 5.7 is a picture of the different planes for the camera and the Cartesian robot. The green area is the image bay's FOV and the red is the workspace of the Cartesian robot.

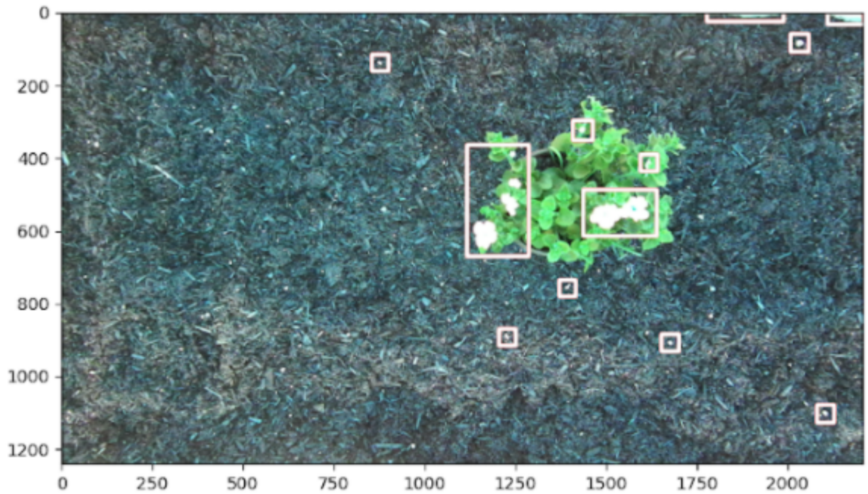


Figure 5.5: Flower identification pre filtering

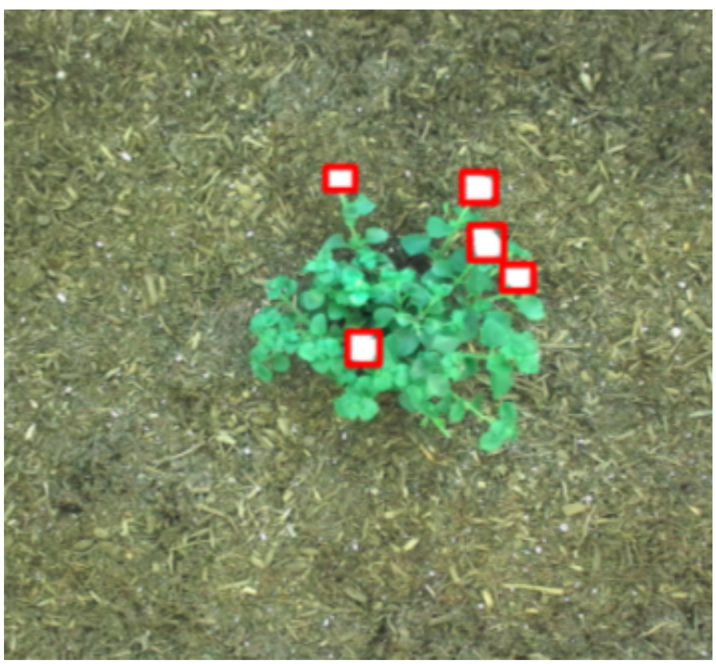


Figure 5.6: Flower identification post noise filtering

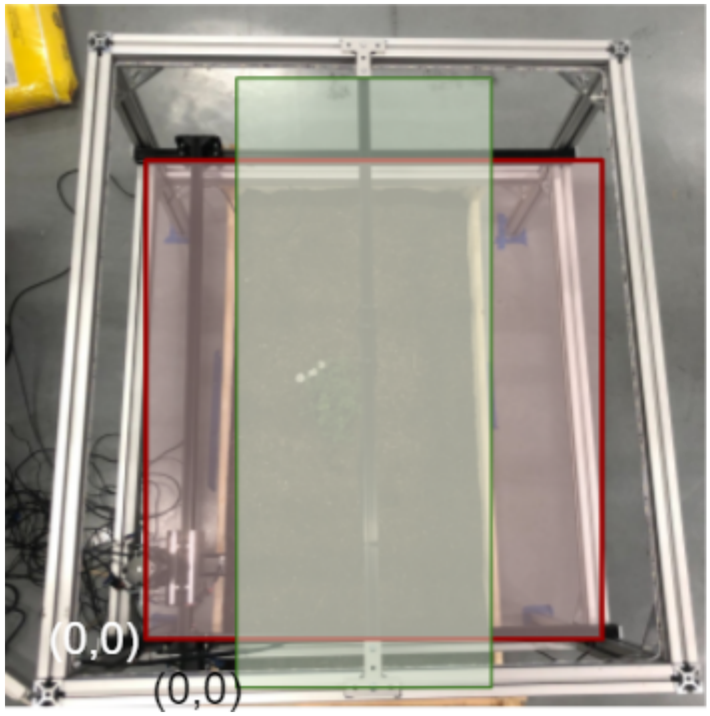


Figure 5.7: Camera and Cartesian coordinates

In order to find the correct scaling to convert the camera coordinates in pixel units to millimeter units, we did a scaling experiment with white squares. We placed a square roughly centered in the space and in real space measured approximately 100mm in the X and Y direction and placed another square there. From that point we could find the pixel delta between the squares and are able to divide that number by 100mm to get the pixels/mm scaling value. As a way to validate these scaling numbers we also positioned another set of three squares with different distances apart and location to confirm that we have the same scaling factor. Figure 5.8 shows the different squares and distances used between them to calculate and validate the scaling factor.

In order to get the offset of the different workspaces, we simply measured the difference between (0,0) on the camera's workspace and the Cartesian workspace. We subtracted the X offset since the camera was in the negative space of the Cartesian but added the Y offset because Y 0 was in the positive space of the Cartesian. The scalars and offsets were hardcoded into the code, below in Figure 5.9 is the basic code to get the scaled x and y coordinates.

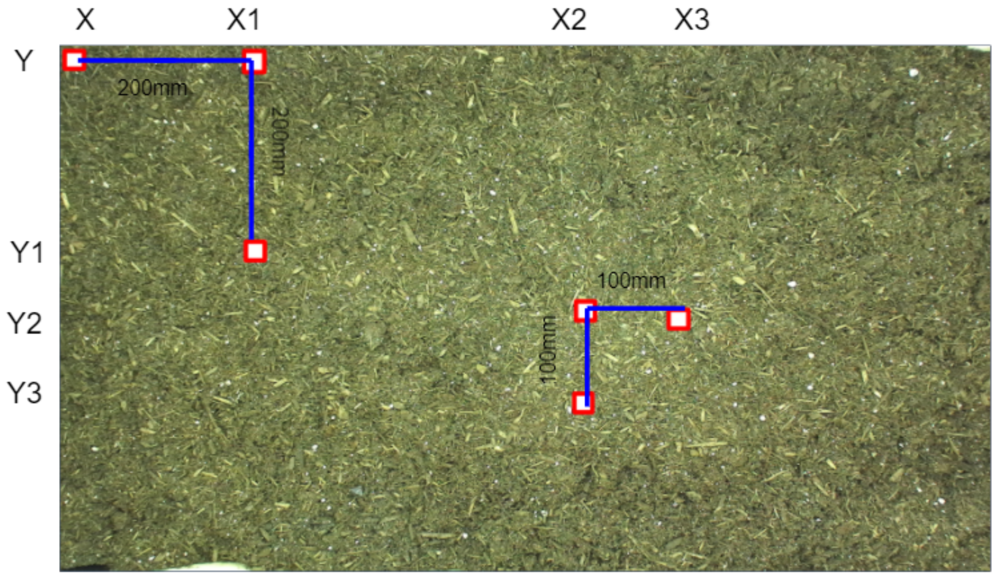


Figure 5.8: Calculating the scaling factor

```
scaled_x = (centroid[0] * X_SCALAR) - X_OFFSET
scaled_y = (centroid[1] * Y_SCALAR) + Y_OFFSET
```

Figure 5.9: Code for offsetting

The last position needed was the Z depth of the flowers in the image. We were able to get the depth of the flower from the ZED Stereo camera depth matix and were able to index the matrix with the pixel locations of the flowers previously identified. Since we have the range of pixels of the flowers, we could easily get the average depth of the flowers bounding box to get the millimeter depth of the flower. Due to time constraints we were unable to finish the exact offsetting of the Z stroke but given more time we would simply need to precisely measure the offset from the Z arm home to the camera's lens and subtract that from the returned depth from the ZED camera.

5.3 Expected System Requirements

In our initial design phase, we outlined a variety of requirements we wanted the image bay to contain which are outlined in Table 5.1.

Table 5.1: Image Bay System Requirements

Image System Requirements	Priority
Capture clear image	HIGH
Payload shell will have necessary number of cameras to be able to capture full work space area	HIGH
Accurately extract the flowers from the image with an accuracy >70% correct identification	HIGH
Be able to find the approximate the center of the flower and return a coordinate	HIGH
Be able to extract depth of the flower to the nearest mm	HIGH
Be able to convert pixel to mm distance in real space	HIGH
Create closed loop system of verifying the flower has been properly removed	LOW
Have serial communication with Cartesian robot control to transfer coordinates of flower	HIGH
Have open LAN port to communicate with the rest of the rover	MEDIUM
Have a live feed interface to view progress as needed	MEDIUM
Be powered by the existing rovers battery	MEDIUM

5.4 Alternatives and Tradeoffs

When considering possible methods on how to identify the flowers we considered using Machine Learning. We quickly moved away from this idea after considering the large size of a data set of strawberry flower images that we would need in order to create a model that would reach the kinds of accuracy we set in our requirements. Collecting the images ourselves would take very long and would have a very small window in January and February of 2021 to capture the images necessary. Due to the time constraints and lack of easy access to the farm due to COVID, we decided it would not be feasible to collect a data set in time to make Machine Learning possible. There were also no existing datasets online that we could find that would work well to train an ML model.

We also explored making our own image bay system with two cameras with overlapping fields of view. We quickly learned that this was going to be far too difficult to fit in the scope of the project so we decided to go with pre existing solutions in the form of the ZED Stereo Cameras.

5.5 Analysis and Design Considerations

5.5.1 Camera Analysis

The first analysis we did was the initial accuracy of the ZED camera. Specifically the accuracy of its depth analysis. We ran the camera algorithm a number of times to get an average accuracy of the depth of the camera versus the real depth. Table 5.2 shows the approximate differences between the camera values and the real Z depth, measured in millimeters.

Table 5.2: Camera depth testings

Camera Z	Approx Real Z	Delta
621.72	615	6.72
621.7	615	6.7
612	620	-8
625	616	9
605.922	611	-5.078
	Average Delta:	1.8684

5.5.2 Algorithm Analysis

The main analysis on the algorithm has to do with the accuracy of identification; can it successfully identify all the flowers that need to be removed. We were able to plant three different plants in our testing bed and run our algorithm and test if we identified all the unique flowers. There were 26 unique flowers across the three plants and our system was able to identify 19 of them. Figure 5.10 has the pre and post processed images and the identified flowers. This gave us an initial rate of 73% accurate. However if we account for the fact we can remove more than one flower at one point if the flowers are close together, then we have an accuracy rate of 91%. Both are within our initial set requirement.

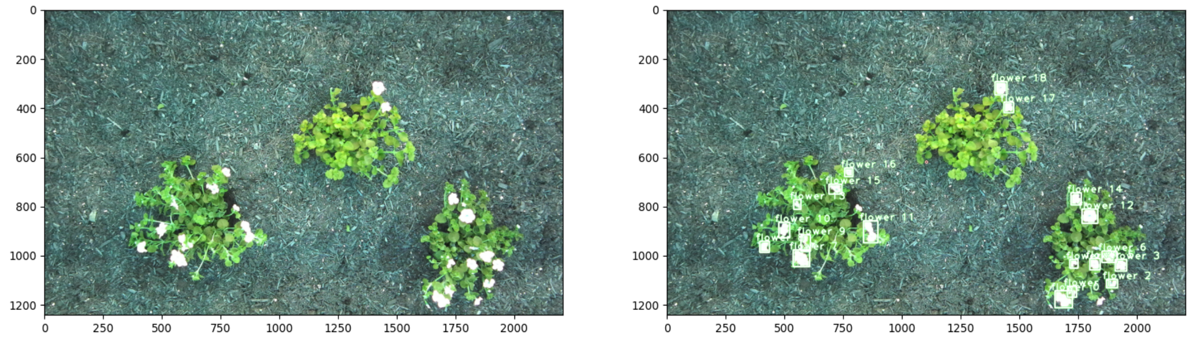


Figure 5.10: Identification of multiple plants

5.5.3 Scaling Analysis

In order to validate the scaling factors and the offsets calculated, we ran a variety of accuracy tests to make sure we could successfully move to the correct position. We used a single white square that we could identify 100% of the time and then moved the arm to the calculated position and measured the accuracy manually. The results and trial numbers of these tests are documented in Table 5.3. We adjusted the offsets slightly as the accuracy changed but typically it was very minute differences.

5.6 Final Design

Our final design consisted of a foam board enclosure with an LED lighting strip and the ZED Mini Stereo Camera mounted to the center of the top plane of the frame. We use an Nvidia Jetson to run the ZED Mini Stereo Camera. Figure 5.11 is an internal look at the enclosure, LED strip lighting and ZED stereo camera.

Figure 5.11: Image Bay Final Design

Table 5.3: Test runs for calculating the error of the positioning

	Estimated Error		**Camera Coords**		
Test Run	**X Error**	**Y Error**	**X**	**Y**	**Z**
1	-1	-5	217	271	
2	0	-3	219	271	613.87
3	-2	-5	220	271	614.8
4	-3	-10	219.12	272.12	614.74
5	-2	-12	219.73	268.32	614.96
6	-2	-5	220.19	271.77	615.26
7	-2	-3	217	273	615
8	-3	-4	217.73	273.32	615.45
9	-3	-5	217.73	273.77	614.82
10	-2	-5	217.73	273.32	614.82
11	-3	-7	217.74	273.77	614.88
12	-2	-6	217.74	273.32	614.84
13	-5	-4	214.73	275.22	614.73
14	-1	-4	219.74	274.78	614.95
15	0	-5	219.74	274.32	614.82
16	-1	-2	220.7	276.77	614.85
17	-1	-1	221.19	276.32	615.02
18	-1	0	221.19	276.33	615.03
19	-1	0	220.73	276.78	614.64
20	-1	0	220.74	276.78	614.74
		Standard Dev:	**1.710**	**2.316**	**0.305**
Average:	**-1.8**	**-4.3**	**0.573**	**0.249**	

6. Software Architecture Subsystem

6.1 Introduction

A key component of our overall system is the way each subsystem and module communicates with one another. In order to have Robocrop be used for multiple different applications and agriculture tasks, we designed each functional subsystem to have its own independent controller to give the farmer or user the ability to use each subsystem independently or in a different sequence. For this reason, the image bay, tooling head and cartesian robot have their own microcontroller that is exposed on an open LAN port to allow each to be called and interfaced with by any other system. It also abstracts many core functionalities of each system because instead of worrying about how the image bay gets the coordinate location of a flower and just getting the coordinate itself for example. We can call a function on it to return us the location without worrying about how it was done.

6.2 Design

The software architecture was built on top of ROS (Robot Operating System), specifically ROS 1 Melodic Morenia to be compatible with the ROS version running on the Ag Robot II Rover. We designed it using primarily ROS services in order to simply abstract the functions of each different subsystem. Services are ROS nodes that only execute when programmatically are called. This is different from the typical publish/subscribe model of topics or nodes in ROS that continually stream data and commands constantly. Each subsystem and their services that we were able to finish can be seen in Figure 6.1.

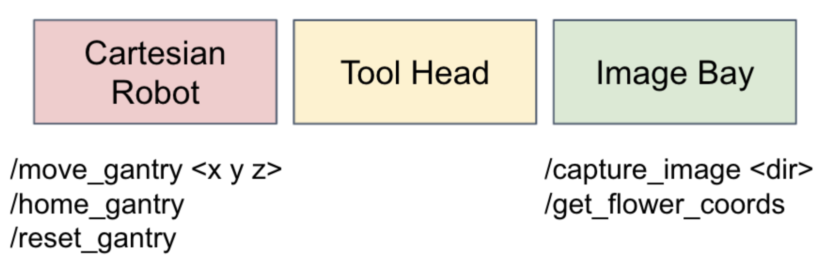


Figure 6.1: Subsystem and ROS Services running on each

For the computer system we used an Nvidia Jetson Nano to run the main software sequence and the ZED Mini Stereo Camera. The cartesian system ran off of a Arduino based CNC shield that was powered and controlled by a Raspberry Pi 3+ via serial communication. The shield contained replaceable motor drivers and separated power and electronic output for the NEMA 17 motors. The Arduino chip on the shield runs GRBL 1.1, an open source CNC machine firmware that can give the user an easy way to control stepper motors in a CNC scenario. GRBL 1.1 uses G-CODE, a CNC based set of commands that define movement, position and speed of the specific XYZ defined motors. Both the Raspberry Pi 3+ and the Nvidia Jetson Nano ran ROS on top of their Linux based operating systems. Figure 6.2 shows the Nvidia Jetson Nano in the top left, Raspberry Pi in the bottom left and the Arduino to the right of them all.

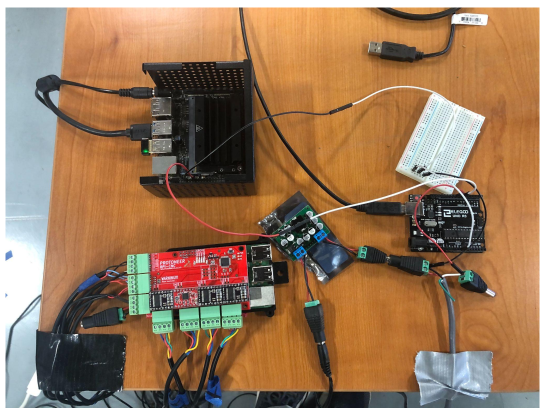


Figure 6.2: Computer Components

The exception to the ROS architecture can be seen in the control system for the tool head. We use an Arduino Uno for the control which cannot run ROS and thus receives a digital pin input from the Nvidia Jetson Nano as a supplemental way to control it. We ran a C++ script on the arduino to control the tool head. Given more time and resources we would dedicate a ROS capable microcontroller to the toolhead.

6.3 Services

These services are created within the *robocrop* ROS package under the scripts folder within the package. Every service returns multiple objects outlined in the detailed descriptions of each but all include a reason object that returns a string of the reason that the service might have failed. This is helpful for debugging and understanding what went wrong in an error scenario.

6.3.1 Cartesian Robot Services

/move_gantry <x> <y> <z> <f>

The /move_gantry service is an abstracted way to move the Cartesian controller to the desired <x>, <y> and <z> position at a feed speed of <f>. This service simply opened up a serial port connection to the CNC Shield running Arduino GRBL 1.1 on /dev/ttyAMA0. It clears the input buffer of commands because it typically has a lot of garbage characters when the serial port is first opened. We use pyserial as the main interface to open these serial ports.

The CNC Shield uses G-Code as the main form of commands to run. This service uses the most simple G-Code command G01 for linear movement. It sends G01 X<x> Y<y> Z<z> F<f> based on the passed <x> <y> <z> <f> parameters given when calling this service.

/home_gantry

This service uses the same serial communication as the /move_gantry service but is even simpler as it just sends the G-code command of $H which tells the CNC Shield to go into the homing sequence.

6.3.2 Image Bay Services

/get_flower_coordinates

This is the main service that returns a list of coordinate points of the identified flowers. It uses the image processing algorithm outlined in section 5.2.1. Takes the contours found, applies the scaling methods outlined in section 5.2.2 and then returns a list of coordinates in the format [(<x> <y> <z>), ...].

/capture_image <dir>

This service was made to help us interface with the ZED Mini Stereo Camera. It takes a directory <dir> path as the one and only parameter. This directory is used as the location of where to save the image captured when this function is called. This gave us an easy way to capture an image when doing camera calibration, testing and analysis.

6.3.3 Main sequence Service

/robocrop_main

This is the main sequence/service that we run when we want to carry out the entire task of identifying the flowers, moving to the location and then removing the flowers with the tool head. This service is really abstracted and easily readable because it follows the flowchart sequence in Figure 2.5. All it does is call the services necessary to make this work. It begins by homing the device by calling /home_gantry, then identifies the flowers through the /get_flower_coordinate service and then iterates through all the flowers found and moves to their location via the /move_gantry service. Once it moves we halay to make sure it has reached the position and then we turn a GPIO pin high to turn on the tool head clippers. Once it has iterated through each flower then it would be time to take another picture and be sure the /get_flower_coordinate service returns no flowers. Due to time constraints, we were unable to fully remove the flowers from the workspace and thus created an infinite loop of clipping the flowers but still being able to identify them because they are in the workspace frame. This will go into future work.

6.4 Expected System Requirements

The software architecture needed a set of requirements, which are documented in Table 6.1, in the beginning to make sure we could create something that is compatible with AgRover II and can be reliable and scalable.

Table 6.1: Software Architecture System Requirements

Software Requirements	Priority
System's subsystems will be able to work independently through modified user control	HIGH
All subsystems will be able to easily communicate between each other easily	HIGH
All subsystems will be able to communicate on the same communication bus as the rest of the Ag Robot II	HIGH

6.5 Alternatives and Tradeoffs Software System

Initially we believed that a single computer to control this entire system would be the easiest and most concise; however we quickly learned the benefits of designing in a modular way. This way we can have each subsystem be independently controlled if we wanted to convert our system to do various other tasks like weeding or crop data collection. It gives the users more flexibility on the way they use this robot. It also allows for higher reliability because we can confirm if any of the subsystems computers are down based on the status of the other working computers. As a result we decided to design our communication system to have multiple microcontrollers and computers to control each subsystem. This also allowed us to be able to use the same communication protocol and standard with the rest of the agriculture robot. This gives us the ability to control different parts of the rover outside our payload system.

We choose services over the typical publish/subscribe topics of ROS because services allow for more granular control and reduce the compute resources needed at any given time. We found that if we are continually streaming video from the ZED Camera and processing it in real time that it uses nearly all the compute power of the Nvidia Jetson driving it. This causes it to overheat and even crash the entire computer at one point. To reduce heat and improve reliability, we only use the camera and other processes when absolutely necessary thus optimizing our system as a whole.

6.6 Analysis and Design Considerations

Software processing speed was the first thing we analyzed about the system. Due to the way the software system communicates via a LAN, it ran slower than expected. Once we hardwire the system all together with an ethernet switch and router the speeds will significantly improve. During our testing we were having the Nvidia Jetson and Raspberry Pi communicate over a WiFi network which significantly slowed down the processing speed. The average speed of the main sequence was about 10 seconds long, which we believe to become shorter based on the improvements outlined above.

7. Manufacturing and Assembly

Our payload system was designed with careful consideration of its manufacturability. With the purpose of being an affordable option to supplement the agricultural workforce, our payload is easily attachable and detachable from the rover. Additionally, individual subsystems and components can be easily taken apart and swapped with little to no difficulty to allow for retrofits, small customizations, and opportunities for modular design. Our team selected Aluminum as our primary material for our frame and subsystems not only for its low cost, weight, and availability, but also for material continuity to provide ease of assembly and manufacturability which helps to make our design easily replicable. Some niche parts did need to be machined such as the end mounts, y-plates, and the tool head subsystem, but all of these parts were made using simple machining processes. These elements were custom made in the Santa Clara University machining lab and can be viewed in Figures 7.1 & 7.2.

Figure 7.1: Machined Aluminum Mounting Plates

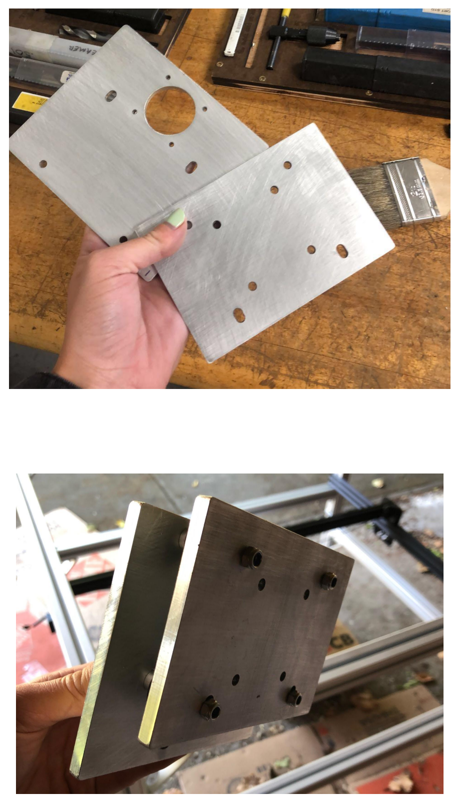


Figure 7.2: Machined Aluminum Y-Plates

All toolhead components were 3D-printed using PLA material, 20% infill. All screws used were standard M5 or M3 and attempted to keep as much of our design consistent as possible so that future assembly, replication, or modification can be standardized. For future work, machining of the toolhead component will require slight design modification to accommodate for proper machining of the selected metal used, desirably aluminum. This is due to the design detail being refined for the purpose of rapid prototyping,not machining, for the duration of this project. Rapid prototyping allowed the team to have the ability to produce and test several iterations of the tool head subsystem, and the design was able to be refined so that it easily interfaces with the Z-stroke.

The highest cost components in our design were the ZED mini camera, the electronic components such as the Jetson Nano. and the NEMA 17 stepper motors. With that in mind, the structure is quite cheap and easy to acquire the necessary parts for assembly which can allow for the system to be replicated within a reasonable time frame. Engineers with limited mechanical design experience would be able to assemble our system with ease if given a tutorial video or instructions.

Overall assembly of the entire RoboCrop payload device simply requires M4 & M5 screws, standard tools, and a computer to communicate. It is recommended to be assembled by engineers in the future due to the fact that this working prototype has yet to be refined for general customer use and assembly. Future work should consider user-friendly housing components for the electronics to safely operate within general agricultural conditions and commercial use of the payload device within Ag Robot II.

8. System Integration, Testing, and Results

8.1 Power Budget

We estimated the power budget using the max Amperage that each electronic device is specified at. This would give us the absolute minimum run time. This was determined to be around 2.9 hours for 1 50Ah battery.

Table 8.1: Power Budget

Item	Voltage	Recommended Amp	Watts	Notes
Raspberry Pi 3+	5	3.0	15	
Jetson Nano	5	4	20	
NEMA 17 Motors	24	10	240	
Arduino Uno	5	0.05	0.25	
	TOTAL AMP:	17.1	**Total Watts:**	
	Battery Size (Ah):	50	**275.25**	**W**
	Hours (rough):	**2.93**		

8.2 Speed Analysis

The speed and run time of our rover was calculated from knowing that at the Cal Giant farm there are roughly 16,000 strawberry plants per acre, and that there are 4 plants within RoboCrop's workspace at once. Through testing we found that for our rover the average time to complete one workspace was 90 sec, which can vary slightly depending on the number of flowers within the workspace. Also, knowing that the rover's charge time is 5 hours and that it can last 12 hours between charges, the maximum run time was determined to be 19 hours per day. However, assuming maintenance and some down time, we project our rover to operate in the field for 17 hours per day and would work at a pace of 5.8 days per acre. For reference, this is slightly faster than the speed of one human worker, who works at a pace of 6.6 days per acre.

The life between charges and the run time per day of RoboCrop is variable and dependent on the duration that all components operate throughout that day. The 17 hour per day runtime and the 5.8 days per acre was calculated assuming all components are running continuously when the rover is operating. In the field, however, not all components will be operating continuously and so the life between charges and runtime will likely be higher due to this difference. Tabulated data can be viewed in Table 8.2 regarding these specifications.

Table 8.2: Run Time and Speed Table

Category	Speed
XYZ speed	83 mm/sec
Workspace Speed	90 sec/workspace
Maximum Runtime	12 hours/charge 17 hours/day
Charge time	5 hours
Working Pace	5.8 acres/day

8.3 Weight Analysis

To best interface the RoboCrop payload item with Ag Robot II, it is essential that the weight constraints of the already existing chassis are not exceeded. The Ag Robot II required a maximum additional weight component of one that did not exceed 120 kg. Each item placed within the payload design was weighed and added up to analyze this constraint. After prototyping and machining of RoboCrop, the entire payload system was also weighed overall to ensure our calculations were sound. Itemized in Table 8.3, it is seen that the total mass of the payload device that RoboCrop entails is only 35.32 kg, a value much below the Ag Robot II's constraint. The team successfully fulfilled this requirement and accounted for future additions to be made in the future if needed.

Table 8.3: Mass Budget Breakdown

ARC Component Category	ARC Component	QTY	Mass (lb)	Mass (kg)
Preliminary ARC Chassis	Entire chassis + Electronics + Sprayer Device	1	453.00	205.48
Electronics	Nvidia Jetson Nano	1	0.53	0.24
	Raspberry Pi 4	2	0.11	0.05
	ZED Mini Camera	1	0.14	0.06
	Arduino and Shield	1	0.11	0.05
XYZ Extension	ACRO 1010 40x40"	1	7.17	3.25
Cutting Toolhead	Servos	2	0.27	0.12
	3D Printed Tray	1	0.50	0.23
Frame	Aluminum extruded frame + fastenings	1	69.03	31.31
	Total (Payload) =		77.86	35.32
	Total (Entire System) =		530.86	240.79

9. Project and Team Management

9.1 Project Challenges

In addition to the current state of the agriculture industry's struggles, the presence of COVID-19 presented even more challenges related to human interaction and contact in business. The use of automated robotic systems within a business ensures that high priority tasks may still be performed despite the limiting regulations around a world-wide pandemic. Autonomous systems provide employers with innovative solutions for labor shortages without compromising the health and safety of their current employees.

Not only did COVID-19 emphasize the problems faced in the field, it also presented problems in the prototyping process of this project. Due to state, county and school guidelines, the team was unable to meet in-person for a majority of the year. This resulted in team members taking the initiative to work independently and communicate teleconnectively to ensure that every subsystem was compatible in order to create a cohesive system.

When given the opportunity and clearance to meet in-person, the team worked swiftly to bring together individual parts and troubleshoot any integration problems. The need for rapidness during this time was due largely in part that it was unknown when another shut down or spike in COVID cases would occur and result in required isolating again. The uncertainty of potential shutdowns also discouraged the team from moving the chassis into Santa Clara University's designated lab space, in fear of placing the project there and then going through a shut down, consequently prohibiting the team from being able to be hands on with the project. Despite other struggles, like the machine shop being closed on occasion, the team was able to overcome the challenges presented by a global pandemic and produce a working prototype of a device that can successfully identify and prune strawberry flowers.

9.2 Budget Detail

The budget allocated for the academic year 2020-2021 is itemized in Appendix D.

9.3 Projected Project Timeline

The timeline of the project deliverable due dates and important milestones may be referred to in Appendix E.

9.4 Design Process

By building off a previous year's senior design project as well as working in conjunction with Dr. Manoj Sharma, the design process was jump-started knowing that the team would be working towards aiding in the farming process. From there it was decided to pick a one crop and have the goal to be to perform a single function on the crop, as a proof of concept. This allowed for future iterations on this initial design to be made. Then we started talking to stakeholders, such as JT, a strawberry farm manager and other farms. Based on what the stakeholders had to say, the team decided to pursue a pruning mechanism for strawberry flowers. Once it was decided that was the goal at hand, market research was conducted to see what other products were out there. In order to complete the task at hand, we divided the overall system into subsystems. By splitting it up we were able to also figure out what quantitative parameters our robot would have. This ultimately provided some insight into design generation. After multiple designs were produced for each subsection, some sort of decision method was used to decide which specific design would be the one pursued. From there some preliminary prototyping was conducted.

9.5 Safety Risks and Mitigations

For a detailed safety report, please refer to the Student Project Hazard Assessment in Appendix E.

9.6 Team Management

Team management was done well throughout the quarter. Having to adjust to an online setting, our team quickly realized that we needed to have 1-2 scheduled online zoom meetings each week to check in on progress and deliverables completed by each team member. Weekly meetings were also made with our faculty advisor and the post-doctoral student who are advising us. Each meeting was approached with quick presentations of previous week's work, speak upon analysis made and decisions for the upcoming week's work in consultation with our advisors input to better improve our design and modularity of the payload device. Constant communication, holding team members accountable for their action items, and effective individual progress between each team member resulted in an effective and successful project.

In order to maximize time and efficiency we decided to split up team members into different groups based on the subsystem they are primarily responsible for. This made it easier to schedule times to meet due to smaller groups. It also divided responsibilities better and made deliverable assignments much easier for each subsystem. The division of task items helped maximize efficiency and increase attention to detail for each component. During weekly meetings, each subsystem presented its findings and analysis from the previous week and opened the floor for discussion regarding their component. This allowed for the modularity of each component to interface seamlessly when it was time for final assembly. Because of the team's high autonomous efficiency and transparent communication, the final assembly of all components only required two attempts for final demonstration of proof of concept to be accomplished.

In addition, each member's list of tasks and assignments were combined onto a management tracking platform called JIRA to help with productivity and accountability. JIRA enforced accountability and was a user-friendly interface that made tracking our project status easier.

10. Costing Analysis

The Rough Budget Breakdown is listed in section Appendix D. The Santa Clara School of Engineering accepted our grant proposal request and granted us a budget of $2,500 for the production of our research. We also pursued and got an additional $1,000 funding from Santa Clara Universities Center for Food, Innovation and Entrepreneurship. This was however later in the project progress and due to some technical issues was never able to get the money transferred. Time restricted us from using the additional funding to deliver a more polished and finished design. A refined budget breakdown can be found in the Appendix D.

11. Engineering Standards and Realistic Constraints

11.1 Project Assumptions

The robot is assumed to operate autonomously alongside and in conjunction with labor workers. The typical labor worker will work 40 hour weeks, 8 hours per day, and one worker was calculated to work at a pace of roughly 6.7 days per acre. Our rover has a run time of 12 hours and a charge time of 5 hours, which leads to a maximum run time of 19 hours per day. However, assuming some maintenance and down time, we project our rover to operate in the field for 17 hours per day. Our rover was tested to complete one workspace (4 plants) in 1 minute and 30 seconds and would therefore work at a pace of roughly 5.8 days per acre.

The speed of both the labor worker and our rover was based on numbers received from Cal Giant Farms where they are estimated to have around 16,000 plants per acre, and that their workers have a typical workday of 8 hours. Our team also assumed that it takes a labor worker around 30 seconds to 45 seconds to complete one workspace, which is 4 plants. Our rover was also assumed to have a run time of 12 hours between charges, but this was calculated presuming all components are operating continuously which is not the case in application, and so the run time between charges may be longer. Furthermore, the time to complete one workspace for both the labor worker and our rover will slightly vary depending on the number of flowers on each plant. With all these assumptions taken into account it was shown that our rover works at a comparable speed, if not faster, than one labor worker, and so our rover can help meet the demand created by the labor shortage.

11.2 Economic Impact

Given that strawberries are a significant contributor to California's market, it's important to alleviate inefficient costs and streamline the growing and harvesting process to preserve their integrity. Our team specifically designed a robot that is cost effective, priced at $2,500. In comparison to competitors, our robot is a cost-effective solution to alleviate struggles created by labor shortages. To provide context, the cheapest robot on the market is priced at $2,995, whereas most field-servicing robots cost upwards of $500,000 due to the complex engineering and automated platforms provided[19]. Given that our robot, at a minimum, is roughly $500

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[19] Koerhuis , René. "World's First Robot Catalogue with 35 Propositions." *Future Farming*, Future Farming, 27 Nov. 2020, www.futurefarming.com/Machinery/Articles/2020/11/Worlds-first-robot-catalogue-with-35-propositions-677008E/#:~:text=The%20most%20affordable%20robot%20in,seeding%2C%20spreading%20and%20spraying%20crops.

cheaper than a working robot and, at the most, $497,500 cheaper, it is a sensible and economically viable option for farmers who are already tight when it comes to money. Additionally, agriculture workers in California are required to take one hour lunch breaks on top of 10 minute breaks every hour when the weather is 85 degrees Fahrenheit or higher. These breaks reduce what would be an 8 hour work day into roughly 5.5 hours of actual work. Coupled with the limited number of workers, farms have no choice but to either decrease their acreage or take their losses in a season because they simply don't have the manpower to maintain their fields. Our robot can work not only during the times where workers are on breaks, but also at night. Despite its slower speed, with our robot farmers can prune the white strawberry flowers 1.5x faster than with only man labor, and that's only with one robot. If a farmer used 2 robots, the flower pruning process would be 3x faster, therefore proving to save time and money.

11.3 Sustainability Impact

Before deciding on strawberry pruning, our team investigated a myriad of tasks including weed picking, monitoring soil absorption and pH levels, and targeted pesticide spraying. Our project, given its precise movements and interchangeable toolheads, has the potential to perform the previously stated tasks if slightly modified designs are created. Within the agriculture industry, the main sources of unsustainable farming include inefficient water use and pesticide runoff from plants which contaminates the soil and waterways. To combat these issues, our robot can be used as a data collector; the robot would traverse the fields as normal and insert a probe into each workspace to monitor the wetness of the soil and determine if the plants need more water. As a closed loop system, the thresholds would be 2.5 cm of water for winter and 6 cm of water for summer on a weekly basis[20]. This data would then be communicated to the field manager who can target specific areas to be watered. Considering that agriculture accounts for 80% of California's water use, small changes in water consumption can have a significant impact on the water supply[21]. Instead of watering 180 acres with the same amount each day and wasting

[20] Deyer, Mary H. "Please Enable Cookies." *StackPath*, Gardening Know How, 14 Mar. 2019, www.gardeningknowhow.com/edible/fruits/strawberry/strawberry-water-needs.htm#:~:text=Generally%2C%20there%20is%20no%20need,an%20inch%20(2.5%20cm.).

[21] California, State of. "Agricultural Water Use Efficiency." *Department of Water Resources*, California Department of Water Resources, 11 May 2021, water.ca.gov/Programs/Water-Use-And-Efficiency/Agricultural-Water-Use-Efficiency#:~:text=California's%20agricultural%20success%20would%20not,water%20is%20used%20very%20efficiently.

a minimum of 20% of that water, our robot can reduce that amount by 5% each year through the analysis of collected data and targeted application of water for undernourished crops. This number was calculated using 180 acres, with 15,000 strawberry plants per acre, and the comparison between the typical amount of water used (25 gallons per acre) versus the actual amount needed (20 gallons per acre).

Similarly, our robot can perform targeted pesticide spraying to minimize the amount of runoff that contaminates the soil and water. Performed by workers, pesticide is sprayed all over the plant, the plant bed, and the furrows. If we look at an entire bed, furrow included, the strawberry plants and their leaves only account for roughly 60% of that volume. To eliminate the excessive spraying, a different toolhead can be attached to our robot that has a bird's eye view of each strawberry plant and only disperses the correct amount of pesticide to match its diameter (about 12 inches). This has the opportunity to minimize the contamination of pesticides by 40% and will protect the integrity of the soil as well as the purity of the water runoff.

Through the implementation of both practices, our robot challenges the agriculture industry to actively participate in sustainable farming. Not only is our robot cost efficient, it also is customizable to fit a farmer's needs and works towards a more sustainable, environmentally-conscious future. In terms of the sustainability of the robot itself, its customizable features and ability for modification prove that it will be a versatile and useful product for a long amount of time. The parts and power components of the robot were selected for their robustness and weatherproofing qualities.

11.4 Ethical Implications

The main ethical concern of our project is that our rover can potentially be used to replace the human labor force currently used, and therefore put people out of work. While we cannot directly influence or dictate how a customer will use our system in the future, our team made sure to have careful considerations as to how our rover will affect the labor force. Firstly, there is a massive labor shortage within the strawberry industry, and in the farming industry as a whole. When talking with JT of Cal Giant Strawberries, he emphasized that he has not been able to find a sufficient number of workers to maintain and work the fields and was therefore losing a considerable amount of money because not all the plants could be reached and maintained. Our rover was designed for this reason to help supplement the current labor force, rather than be a replacement, and help bridge the gap created by the shortage of labor so that maximum profits could be achieved.

Second, there are many different tasks needed to be done in order to maintain a strawberry field and our payload system is specifically designed to focus on the pruning of flowers at the beginning of the season. This task is not only tedious and menial, but with the help of our rover, human labor can be effectively used elsewhere in the farming process to ensure maximum yield and profits.

Another reason is that while automation of the farming industry may cost some workers their jobs, in order to stay competitive as a farm, some form of automation is necessary or else you simply can't keep up with your competitors. It is for this reason that our rover can help automate and speed up the tasks such as pruning flowers, which can more easily be automated. However, even if the pruning of flowers is automated, not only will other tasks still need to be completed along the farming process, but jobs will be created to help maintain and deal with the agricultural robots being used.

11.5 Health & Safety

As mentioned previously, our robot has the ability to work during breaks which optimizes flower pruning efficiency. Ensuring that the work is finished, workers aren't required to work overtime, or take shorter breaks, in order to finish the amount of acreage on the farm. By eliminating the need for extra workers, or extra time invested by the limited amount of workers available, the robot puts the health and needs of workers first. To combat the argument of robots taking away valuable jobs, these robots actually ensure that workers are treated humanely and they allow for workers to be placed into more skilled, human-centered tasks. On another note, by pruning strawberry flowers the robot is essentially giving more energy back to the plant to produce more strawberries during the season. Because of this, our robot directly affects the food supply chain. By increasing the amount of strawberry flowers pruned by 30%, more strawberries are available for harvest and subsequently available to purchase by consumers.

Our robot has also been designed to work autonomously throughout the fields. Our team made sure to include safety features, such as limit switches on the XYZ movement, to prevent any erratic movement and our Cartesian robot physically cannot move outside of the designed workspace. This ensures user safety as well as workers who would be picking flowers alongside the robot. Most, if not all, of our manufacturing choices are performed with standard machines such as mills and lathes, which experienced machinists are able to operate with little to no issue. Our product was conceptualized and designed with safety as a main priority.

12. Summary and Conclusions

The ARC: RoboCrop project has experienced a multitude of design iterations. Originally intended to be a generic robot that could be used for a variety of crops and had multiple applications, our team refined our scope to service solely the strawberry industry with one specific application. By selecting a focus, our team has been able to develop a complex robot with three degrees of freedom that has the potential to transform the strawberry industry. Through in depth research and communication with local strawberry farmers, our team has been able to see firsthand the struggles caused by labor shortages and what can be done to lessen the burden on the agriculture industry.

RoboCrop has the potential to be a modular payload device that allows for flexibility with varying industry standards, such as bed widths, and allows a farmer to customize the robot to fit their needs when it comes to picking strawberry flower picking. To prove RoboCrop's reliability, the Image Bay not only accurately transmits the XYZ location of each flower to the Cartesian system, but it also verifies that no flowers were left behind. When performing such a critical task that can drastically affect the yield of crops for a season, this confirmation of success is vital for farmers. Meanwhile the Cartesian system, chosen for its simplicity and ability to be constructed before the end of the Academic year, performs the initial movement which positions the robot for pruning. Without the tool head, the removal of each white flower wouldn't be possible. By implementing a dual-function head attachment, RoboCrop will be able to efficiently prune the flowers with little margin for error. The vacuum/raking mechanism pulls the head taught, ensuring that the stem is exposed and in range of the cutter, and the cutter prunes the flower. Each individual subsystem is vital to the success of RoboCrop. Our team was able to create a robot that has proven functionality of the ability to snip white strawberry flowers within the defined workspace.

We are proud of the work that we've accomplished and recognize that there are opportunities for continued work. Project improvements have been identified and listed in Table 12.1 that future groups can undertake when continuing to develop this project.

Table 12.1: Opportunities for future project development

Cartesian Subsystem	• Weatherproof electronics, belts, and threaded rods to ensure reliability • Order sheet metal and design a more refined lighting enclosure • Redesign y-plates to limit amount of fasteners and material used
Tool Head	• Implement way to remove the flower from the bed better via vacuum • Improve way to separate flower from surrounding leaves/stems • Refine design for better manufacturability • Manufacture housing unit from aluminum or other metal to increase lifespan of toolhead component
Image Bay	• Create smarter motion paths to ensure no collisions • Finish closed loop system for verifying completed task
Entire System	• Power with rover batteries instead of an independent power source • Attach to existing rover and test compatibility in the fields

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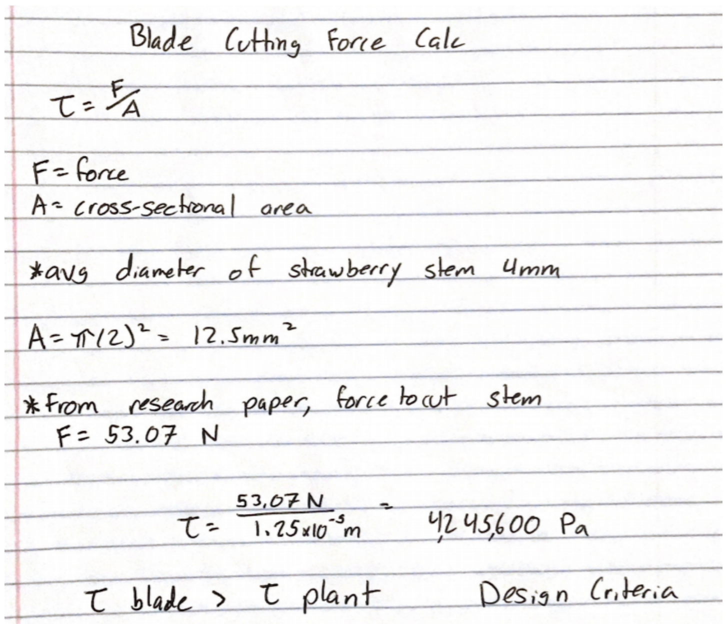
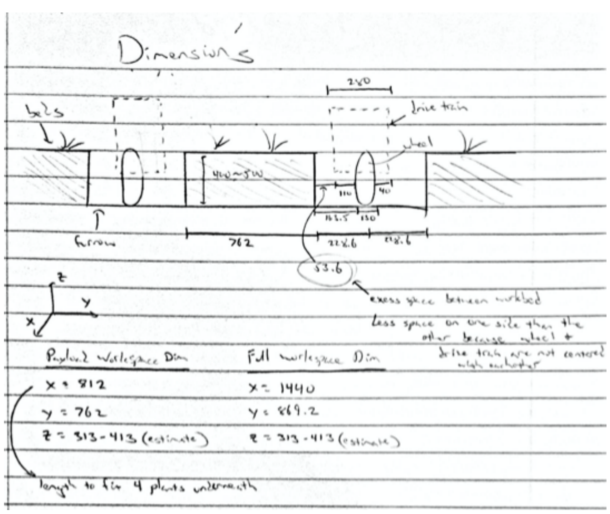
Appendices

Appendix A: Calculations

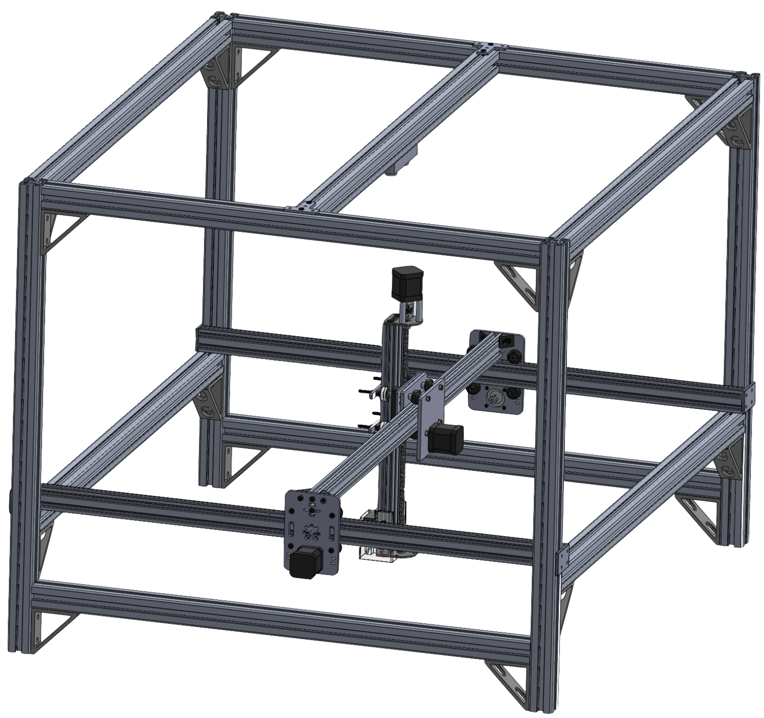
Blade Cutting Force Calculations

Flower Bed and Rover Calculated Dimensions





Appendix B: Assembly CAD Models



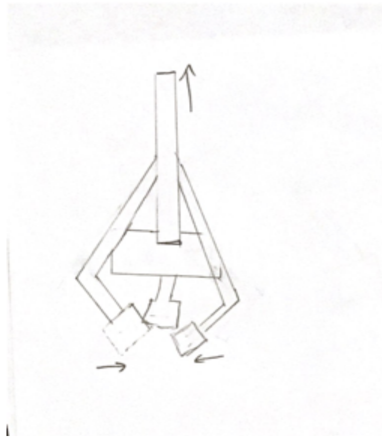
Appendix C: PDS

Project Design Specifications		
Design Project: Strawberry Pruning XYZ Cartesian Robot		
Team: ARC RoboCrop	Date: April 21, 2021	Revision: 1
Datum Description:		

	Units	Datum	Target-Range
Time to Snip One Flower	flower/sec	0.033	0.2
XY Speed	mm/sec	1100	2000
Z Speed	mm/sec	1100	1100
Rover Speed	m/sec	2	2.5
Toolhead Weight	kg	2	4
XYZ Repeatability	mm	1	0.5
Image Processing Accuracy	%	70%	90%
Run Time	hrs	6	6
Charge Time	hrs	6	3
Manufacturing Cost	dollars ($)	$5,500	$4,500
Service Cost to Customer	$/Month	$2,500	$1,500
Total Payload Weight	kg	120	25
Required Maintenance	months	6	12
Maintenance Time	hrs	5	3
Target Market	type	California Farmers	Strawberry Farmers

Appendix D: Toolhead Designs

<u>Design 1: 3-Pronged Claw</u>

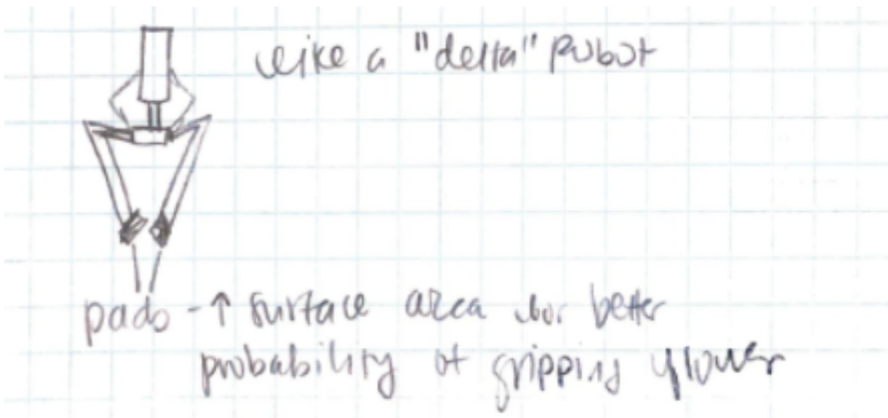


Description: 3-Pronged claw to grab and pull the flower
Pros: delicacy of picking the flower, ability to precise locate the flower at any point along its stem
Cons: Intricate controls, must have a light hand

<u>Design 2: Scissors</u>

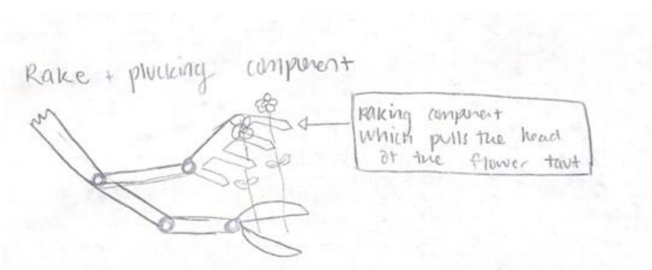
Description: Scissor mechanism that will come and snip the stem
Pros: Easy to prototype
Cons: May not be final product, uses scissors instead of a blade

Design 3: 2-Pronged Claw



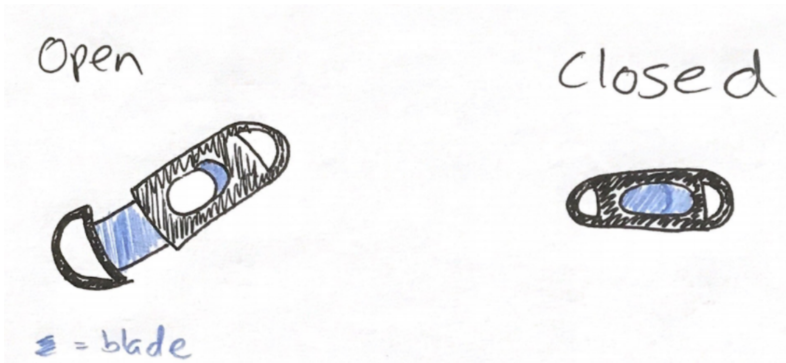
Description: 2-Pronged claw mechanism to pinch and pull the flowers
Pros: Simple Compared to design 1
Cons: Same concept as design #1

Design 4: Rake & Cut



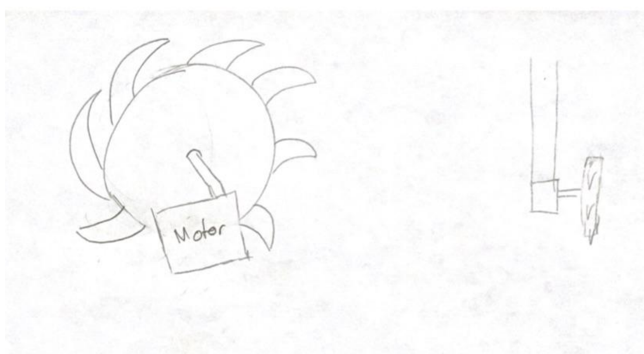
Description: Raking Mechanism that will pull the flowers taut and then snip them
Pros: allows for easy snipping of the stem
Cons: many moving joints

Design 5: Cigar Cutter



Description: Open/Closing mechanism that will surround the flower head and then close
Pros: Simple and sleek cutting mechanism
Cons: requires the cutter to be placed above the flower to coincide with the cutter. This may be very difficult to do if the flower is on the ground.

Design 6: Open Blade



Description: Open Saw Blade that will come down and saw off the stem
Pros: most similar to other gardening/trimming power tools
Cons: Could project the loose flower head forward while cutting, will only be utilized with a taut stem, messy?

Appendix E: Budget

Table 13.2: Initial Estimated Budget

Item	Quantity	Price	Total Cost
Nvidia Jetson TX2	1	$399.99	$399.99
Aluminum T-Slotted Framing 6 x 1.5 x1.5	10	$36.99	$369.90
ZED Mini Stero Camera	1	$399.99	$399.99
Rail Bearing	4	$64.79	$259.16
Brushless 24V Motor X axis	4	$134.30	$537.20
Brushless 24V Motor Y/Z Axis	2	$69.00	$138.00
Motor Controller	4	$119.00	$476.00
Battery	4	$99.00	$396.00
Misc. Wires	1	$40.00	$40.00
Servos	3	$13.00	$39.00
Shears	1	$14.50	$14.50
Arduinos	4	$22.00	$88.00
Computer Interface	1	$122.00	$122.00
Rapid Prototyping	1	$500.00	$500.00
Total			**$3,779.74**

Table 13.3: Final Budget Breakdown

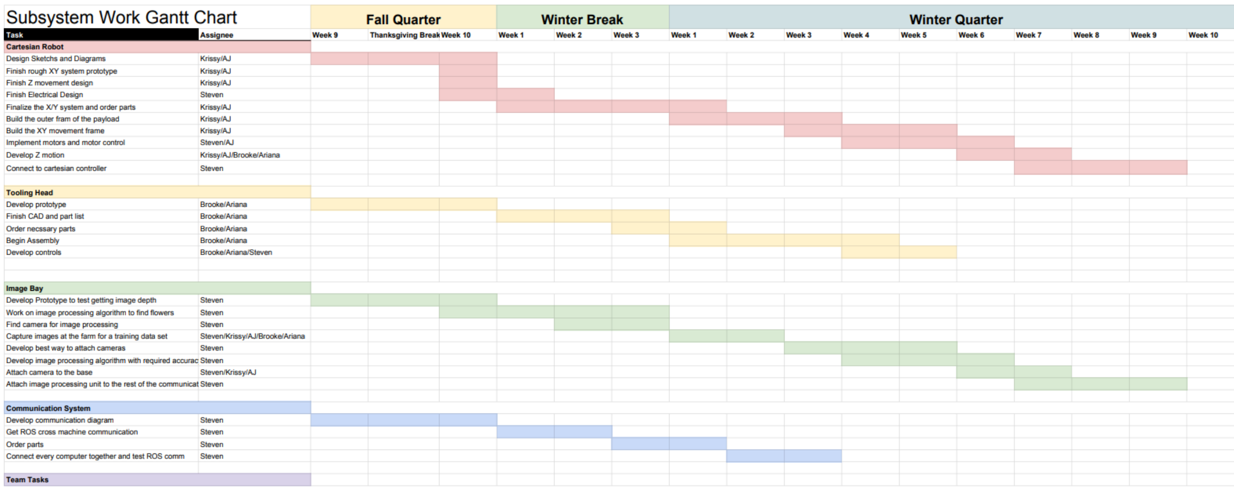
	Part	Quantity	Price	Cost	Extra	Total
Image Bay	ZED Mini SteroCamera	1	$399.00	$399.00	$50.38	$449.38
	Nvidia Jetson Nano	1	$99.00	$99.00	$0.00	$99.00
Cartesian Subsystem	ACRO 1010 40"x40"	1	$411.99	$411.99	$19.11	$431.10
	Tight-Tolerance Multipurpose 6061 Aluminum with Certificate	1	$76.14	$76.14	$15.46	$91.60
	Multipurpose 6061 Aluminum, 5 mm x 15 mm, 1 Foot Long	3	$2.15	$6.45	$1.95	$8.40
	Multipurpose 6061 Aluminum, 5 mm x 40 mm, 1 Foot Long	3	$5.06	$15.18	$8.95	$24.13
	Xtension Wire Set - 2 Conductor	2	$4.59	$9.18	$9.14	$18.32
	Xtension Limit Switch Kit	4	$6.29	$25.16		$25.16
	SMAKN DC 5V/4A 20W Switching Power Supply Adapter 100-240 Ac(US)	1	$9.99	$9.99	$0.00	$9.99
	McMaster nut return	1	-$112.31	-$112.31	$0.00	-$112.31
	Shipping of returned nuts	1	$10.75	$10.75	$0.00	$10.75
	316 Stainless Steel Nylon-Insert Locknut, M5 x 0.8 mm Thread, DIN 985, Packs of 50	1	$6.09	$6.09	$12.44	$18.53
	Super-Corrosion-Resistant 316 Stainless Steel Socket Head Screw, M5 x 0.8 mm Thread, 25 mm Long, Packs of 25	1	$11.49	$11.49		$11.49
	Thread-Forming Screws for Soft Metal, Zinc-Plated Steel, Torx-Plus Drive, M4 Thread, 12 mm Long, Packs of 25	1	$8.47	$8.47		$8.47
	T-Slotted Framing, Drop-in Spring Loaded Ball Nut, M5 Thread Size	10	$1.44	$14.40		$14.40
	T-Slotted Framing, Drop-in Hammer Nut with Button Head, M6 Thread Size	10	$0.63	$6.30		$6.30

	T Slot Gussets	16	11.52	184.32	$36.16	$220.48
	T Slot Gusset Screws	64	$1.61	$103.04		$103.04
	XLarge C-Beam Gantry Plate	1	14.99	$14.99	$12.15	$27.14
	V-Slot® NEMA 17 Linear Actuator Bundle (Lead Screw)	1	$144.99	$144.99		$144.99
Tool Head	VIVOSUN Garden Hand Pruner Shear with Curved Blade and 8 Inch Bypass Pruning Shear, Orange	1	$14.50	$14.50	$0.00	$14.50
	Servo Tester	1	$13.99	$13.99	$0.00	$13.99
	Savox SA-1230SG Monster Torque Coreless 6.0V Digital Servo .16/500	1	$71.99	$71.99	$5.14	$77.13
	Pololu 6V, 15A Step-Down Voltage Regulator D24V150F6	1	$39.95	$39.95	$0.00	$39.95
	Clippers	1	$4.99	$4.99	$0.00	$4.99
	[4-Pack] MG996R 55g Metal Gear Torque Digital Servo Motor for Futaba JR RC Helicopter Car Boat RobotUrgent	1	$18.99	$18.99	$0.00	$18.99
	FEETECH Continuous Rotation Servo FS5106R	1	$13.95	$13.95	$5.56	$19.51
Software/ Motor Controller	Arduino UNO	1	$13.98	$13.98	$0.00	$13.98
	Raspberry Pi 3 - Model B Plus (B+)	1	$62.85	$62.85	$10.00	$72.85
	DRV8825 Stepper Motor Driver Carrier, High Current	4	$7.95	$31.80	$12.43	$44.23
	Raspberry Pi CNC Board V2.60	1	$34.95	$34.95	$10.00	$44.95
	64GB MicroSD Card	1	$12.49	$12.49	$0.00	$12.49
	TP-Link USB WiFi Adapter	1	$7.99	$7.99	$0.00	$7.99
	Geekworm N100 Metal Case/Enclosure with Power & Reset Control Switch & Camera Holder for Jetson Nano A02/B01/2GB/ Jetson Xavier NX	1	$23.99	$23.99	$2.15	$26.14
Power	Barrel Power Jack connectors	1	$6.85	$6.85	$0.00	$6.85
	LED Power Supply Adapter 24V 10A - 240W	1	$45.99	$45.99	$5.26	$51.25

	AC/DC Power Adapter Transformer					
	Terminal Block Set	1	$11.29	$11.29	$3.80	$15.09
	DIY USB Terminal Set	1	$7.99	$7.99	$0.00	$7.99
	Pololu 5V, 15A Step-Down Voltage Regulator D24V150F5	1	$39.95	$39.95	$9.34	$49.29
Enclosure and Testing Bed	Foam Core Board	1	131.01	$131.01	$0.00	$131.01
	2 ft. x 4 ft. x 10.5 in. Original Pine Raised Garden Bed	1	$57.99	$57.99	$5.22	$63.21
	6 ft. x 8 ft. Silver Black Heavy Duty Tarp	1	$11.17	$11.17	$1.01	$12.18
	3/4 in. x 2 ft. x 4 ft. PureBond Red Oak Plywood Project Panel	1	$27.34	$27.34	$2.46	$29.80
	Plant soil etc	1	$51.79	$51.79	$0.00	$51.79
	LED Light Strip	1	$15.98	$15.98	$0.00	$15.98
			CFIE Funding*	Starting Funding	Remaining Budget	Total Spent
			$1,000.00	$2,500.00	$59.49	$2,440.51

Appendix F: Projected Timeline

The image displays a Gantt Chart of the projected timeline of the project.



Appendix G: Copies of Important Patents

US 20060213167A1

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2006/0213167 A1**

Koselka et al. (43) **Pub. Date: Sep. 28, 2006**

(54) **AGRICULTURAL ROBOT SYSTEM AND METHOD**

(76) Inventors: **Harvey Koselka**, Trabuco Canyon, CA (US); **Bret Wallach**, San Diego, CA (US)

Correspondence Address:
DALINA LAW GROUP, P.C.
7910 IVANHOE AVE. #325
LA JOLLA, CA 92037 (US)

(21) Appl. No.: **11/354,548**

(22) Filed: **Feb. 15, 2006**

Related U.S. Application Data

(63) Continuation-in-part of application No. 11/009,909, filed on Dec. 9, 2004.

(60) Provisional application No. 60/481,781, filed on Dec. 12, 2003.

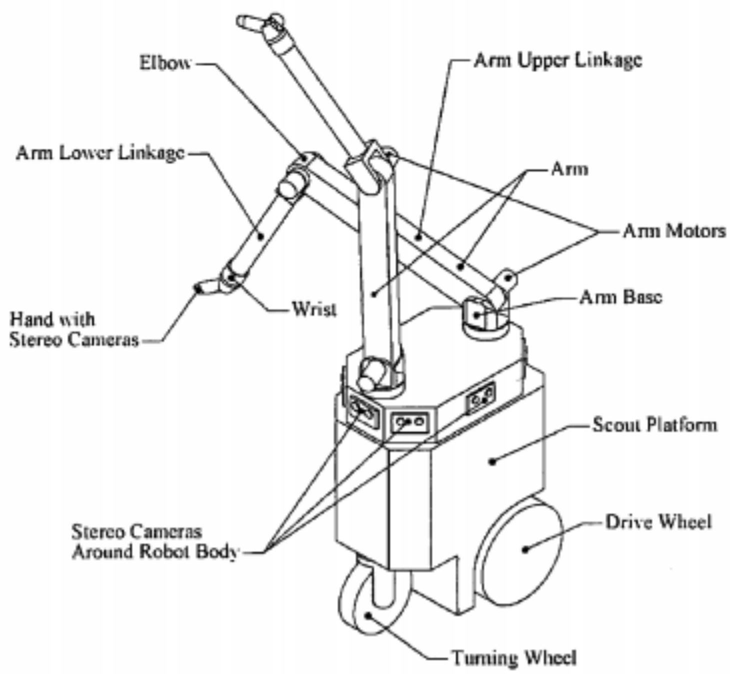
Publication Classification

(51) **Int. Cl.**
A01D 34/00 (2006.01)

(52) **U.S. Cl.** .... **56/10.2 A**

(57) **ABSTRACT**

An agricultural robot system and method of harvesting, pruning, culling, weeding, measuring and managing of agricultural crops. Uses autonomous and semi-autonomous robot(s) comprising machine-vision using cameras that identify and locate the fruit on each tree, points on a vine to prune, etc., or may be utilized in measuring agricultural parameters or aid in managing agricultural resources. The cameras may be coupled with an arm or other implement to allow views from inside the plant when performing the desired agricultural function. A robot moves through a field first to "map" the plant locations, number and size of fruit and approximate positions of fruit or map the cordons and canes of grape vines. Once the map is complete, a robot or server can create an action plan that a robot may implement. An action plan may comprise operations and data specifying the agricultural function to perform.



US 20170105346A1

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2017/0105346 A1**

Davidson et al. (43) **Pub. Date: Apr. 20, 2017**

(54) **ROBOTIC SYSTEMS, METHODS, AND END-EFFECTORS FOR HARVESTING PRODUCE**

(71) Applicant: **Washington State University**, Pullman, WA (US)

(72) Inventors: **Joseph Ryan Davidson**, Somerville, MA (US); **Changki Mo**, Richland, WA (US); **Qin Zhang**, Richland, WA (US); **Abhisesh Silwal**, Prosser, WA (US); **Manoj Karkee**, Richland, WA (US)

(21) Appl. No.: **15/383,000**

(22) Filed: **Dec. 19, 2016**

Related U.S. Application Data

(63) Continuation of application No. 14/849,729, filed on Sep. 10, 2015, now Pat. No. 9,554,512.

(60) Provisional application No. 62/050,048, filed on Sep. 12, 2014.

Publication Classification

(51) **Int. Cl.**

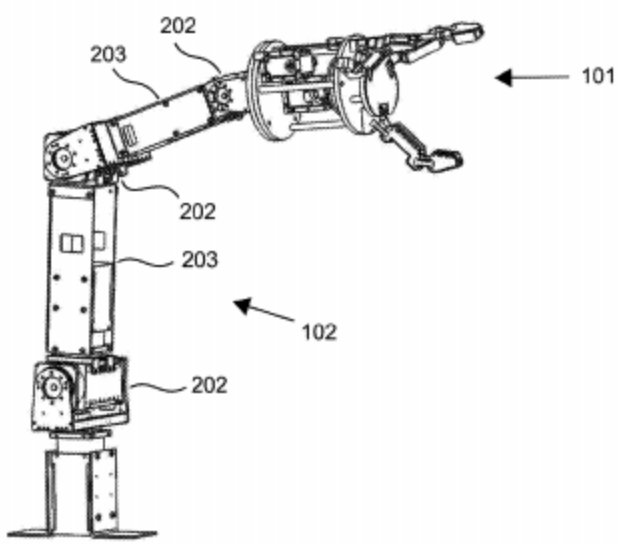
A01D 46/30 (2006.01)
B25J 15/10 (2006.01)
B25J 9/16 (2006.01)
B25J 13/08 (2006.01)
B25J 9/10 (2006.01)
B25J 15/00 (2006.01)

(52) **U.S. Cl.**

CPC ***A01D 46/30*** (2013.01); ***B25J 9/1075*** (2013.01); ***B25J 15/0009*** (2013.01); ***B25J 9/1697*** (2013.01); ***B25J 9/1664*** (2013.01); ***B25J 13/084*** (2013.01); ***B25J 9/1612*** (2013.01); ***B25J 15/10*** (2013.01); *G05B 2219/45003* (2013.01)

(57) **ABSTRACT**

Robotic systems and specialized end-effectors provide for automated harvesting of produce such as fresh market apples. An underactuated design using tendons and flexure joints with passive compliance increases robustness to position error, overcoming a significant limitation of previous fruit harvesting end-effectors. Some devices use open-loop control, provide a shape-adaptive grasp, and produce contact forces similar to those used during optimal hand picking patterns. Other benefits include relatively low weight, low cost, and simplicity.



Appendix H: Safety and Hazard Report

EHS
ENVIRONMENT HEALTH & SAFETY
SANTA CLARA UNIVERSITY

Student Project Hazard Assessment

A Hazard Assessment is designed to help students and project advisors recognize hazards associated with student projects at the early planning stages to find ways to minimize the chance of injury, loss, or harm while you are working on the project. This form is intended to be used for projects where the primary hazards are associated with engineering work (physical, mechanical, electrical, etc.). Chemical and biological focused projects require a separate project assessment form.

Each student project must complete a Hazard Assessment and must obtain the required approvals before proceeding with the project. It is important that all team members participate in the process, with close supervision of your advisor. To help ensure that hazards and risks associated with your project are not overlooked or underestimated, you are encouraged to contact any university staff (Lab Directors/Managers, EHS, etc.) with relevant knowledge or experience for guidance. However, your advisor and the department chair must approve this form prior to obtaining *formal* approvals from other relevant university staff.

The Hazard Assessment process usually involves these five steps below, with an example:

Step:	Example:
1. **Identify the specific tasks** that must be completed to reach your project goals	One of your project tasks involves testing a live electrical circuit
2. **Determine if there are hazards** associated with completing the tasks	On the form, you select the "Electrical parts and assemblies > 50V or high current", under the Hazardous Conditions/Processes/Activities, Electrical Hazard section
3. **Identify the risks** connected with the hazards of each task. Ask yourself, what could go wrong? If you are not already familiar with the risks, do a quick internet search	After some research, you learn that there is potential of electrical shock from accidental contact with exposed live components
4. **Develop a list of controls** (things you can do) to eliminate the hazard or reduce the risks. Refer to *Hierarchy of Controls* on the next page	To minimize the risk identified above, you could: o De-energize and isolate the system or o Guard live components to prevent accidental contact
5. **Create a safe working procedure**. Describe how you will safely complete each task	You write a detailed procedure for testing a live electrical wire, that includes all the information from your hazard/ risk assessment and which controls you will use to reduce the risks

Definitions:

A **Hazard** is something that has the potential to cause harm (injuries, accidents or other undesirable effects). Hazards can be eliminated but not reduced. A hazard can be in the form of an Agent, Condition, Process or Activity.

Risk is the likelihood (probability) of a hazard causing harm to people, property or the environment. Risks associated with a hazard can be reduced. Put another way, *Risk = Hazard x Exposure*

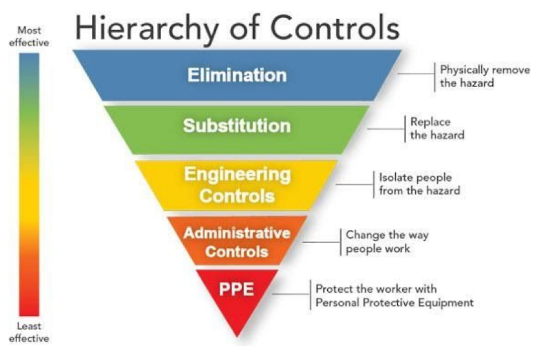
A **Hazard Assessment** is the process of identifying anything that can cause harm (hazardous agents, conditions, processes or activities).

A **Risk Assessment** is the process of determining how great the chance is of harm occurring from a given hazard.

Hierarchy of Controls

Unless the hazardous agent, condition or activity is removed, hazards cannot be eliminated. However, risks from the hazard can be minimized by employing the proper control measures and safe work practices that will have been identified from completing a hazard assessment.

Some controls are more effective than others at eliminating hazards or reducing risk. Use the hierarchy of controls chart below to evaluate the controls measures you plan to use. Priority should be given to the most effective controls at the top of the hierarchy (elimination and substitution) and moving down, rather than start with the easiest one. While personal protective equipment (PPE) should always be used, it should be considered the last line of defense from potential hazards.



Hierarchy of Controls		Description and Examples
Most Effective	Eliminate the Hazard	Use alternative work procedures
	Substitution	Use less hazardous material or process
	Engineering Controls	Isolate people from hazard using ventilation, barriers, lock-out, safer equipment and tools, etc.
	Administrative Controls	Change the way people work: rules, warning signs, training, alarms, safe working procedures, etc.
Least Effective	Personal Protective Equipment (PPE)	Appropriate clothing and footwear, safety glasses/goggles, lab coat, welding mask, face shield, ear plugs, etc. Best if used in combination with engineering controls

Student Project Hazard Assessment Form

This form is to be used for student projects where the primary hazards are associated with engineering work (physical, mechanical, electrical, etc.). Chemical and biological focused projects require a separate form.

Complete this form and obtain all the required approvals (Faculty Advisor, Department Chair, Laboratory Manager, EH&S, etc.) before proceeding with the project. Please refer to the hazard assessment guide for assistance in filling this form.

Project Title: RoboCrop - A Smart Agricultural Robot Toolset			
Project Team Members: Steven Bucher, Ariana Low, Brooke Brozsus, Krissy Ikeda, Alejandro Gutierrez			
Project Advisor			
Name:	Department:	Phone:	Email:
Christopher Kitts	MECH		ckitts@scu.edu
Proposed Project Location(s) (Department, building, room#): Robotic Systems Lab			
Anticipated Dates of Project Duration: 11/15/2020 - 6/12/2021			
Summary of Project Objectives: Create a payload device that can perform general agricultural tasks to help alleviate labor strains in the agriculture industry. We will be focusing on pruning strawberry plants as our main agricultural task but will design in a modular way to allow for additional agriculture tasks to be carried out by it in the future. Our project is made up of three subsystems, an image capturing bay, a cartesian robot, and a tooling head. The image bay aims to accurately identify strawberry flowers or other distinguishable features in a grouping of strawberry crops through cameras and an onboard image processing unit. The cartesian robot will use linear rails and motors to be able to navigate to the identified flower and the toolhead will safely remove the flower. This system will be able to interface with and be implemented on the Ag Robot II project in the Robotic Systems Lab.			

Hazard Checklist (check all that apply)

Identify all the tasks that must be completed for your project. Carefully evaluate each task to determine if there are any associated hazards. After identifying the hazards of your project, you will be asked to assess the risk connected to each hazard and to identify control measures that will either eliminate the hazard or reduce the risk to an acceptable level. Safe work procedures for each step involving a known hazard will need to be developed.

HAZARDOUS CONDITIONS/PROCESSES/ACTIVITIES		
Electrical Hazards ☐Electrical parts and assemblies > 50V or high current ☐Batteries ☐Control Panels	**Mechanical Hazards** ☐Power tools and equipment ☐ Machine guarding/power transmission – gears, rotors, wheels, shafts, belt/chain drives, rotating parts, pinch points ☐Robotics ☐Sharp Objects ☐ Stored Energy (springs, gravity, pneumatic, hydraulic, pressure)	**Physical Hazards** ☐ Extreme temps (high temp fluids: water > 160 °F, steam, hot surfaces > 140 °F, cryogenic fluids ☐ Material handling of heavy objects ☐ Elevated heights (scaffolding, ladders, roofs, lifts, etc.) ☐ Overhead falling objects (cranes, hoists, drones, projectiles, etc.) ☐ Confined Spaces ☐Airborne Dusts ☐Bonding / Grounding ☐Electrostatic Discharge
Reaction Hazards ☐Explosive ☐Exothermic, with potential for fire, excessive heat, or runaway reaction ☐Endothermic, with potential for freezing solvents decreased solubility or heterogeneous mixtures ☐Gases Produced ☐Hazardous reaction intermediates/products ☐Hazardous side reactions	**Hazardous Processes** ☐Generation of air contaminants (gases, aerosols, or particulates) ☐Heating Chemicals ☐Large mass or volume ☐Pressure > Atmospheric ☐Pressure < Atmospheric ☐Scale-up of Reaction ☐Metal Fabrication (welding, cutting, drilling, etc.), Soldering, ☐Construction/Assembly, etc.	**Other Hazards** ☐Noise > 80 dBA ☐Vehicle traffic ☐Hazardous waste generation ☐Other (list):

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Hazard Checklist (continued)

HAZARDOUS AGENTS			
Physical Hazards Of Chemicals	**Health Hazards of Chemicals**	**Non-Ionizing Radiation**	**Biohazards**
☐Compressed Gases ☐Cryogens ☐Explosives ☐Flammables ☐Oxidizers ☐Peroxides or Peroxides Formers ☐Pyrophorics ☐Water Reactives	☐Acute Toxicity ☐Carcinogens ☐Nanomaterials ☐Reproductive Toxins ☐Respiratory or Skin Sensitization ☐Simple Asphyxiant ☐Skin Corrosion/ Irritation ☐Hazards Not Otherwise Classified	☐Lasers ☐Magnetic Fields (e.g. NMR) ☐RF/Microwaves ☐UV Lamps	☐Bsl-2 Biological Agents ☐rDNA ☐Human Cells, Blood, BBP ☐Animal Work ☐Other (List):

Description of Potential Hazards

Provide a summary of the procedure and describe the risks associated with the each hazard that you have identified above or on the previous page. Use one box below per hazard. You may add supplemental pages if needed. Define the hazard control measures that will be employed to minimize the risks based on the hierarchy of controls (elimination, substitution, engineering controls, administrative controls, PPE), and then describe specific control measures you will use (e.g. Work on system de-energized, receive hazard specific training, shield hot surfaces, guard pinch points, relieve stored energy, wear protective equipment, use less hazardous chemical, etc.). Refer to "Hierarchy of Controls" in the instructions sheet for more information to decide which hazard controls measures are most appropriate

Hazardous Activity, Process, Condition, or Agent (identified from previous page): Electrical parts and assemblies > 50V or high current -
Summary of Procedure or Tasks: Electrical wiring between the motors, motor drivers/controllers, and the microcontroller units. These will also all be connected to a battery that will be able to support their use for hours on end. We are not certain the level of Voltage and current we will be working with but want to be prepared in case we need it.
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): This is a risk because high current can be harmful to humans if handled improperly. Also if handled improperly without proper insulation and wire management it could result in possible fires.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):

In order to eliminate this risk we will be using insulated gloves when working with exposed wires and electrical connections. We will also be sure to isolate electrical wires with proper insulation in the form of electrical tape and electrical rubber insulation

Hazardous Activity, Process, Condition, or Agent (identified from previous page):Batteries
Summary of Procedure or Tasks: Since our system will be independently powered we will need to incorporate batteries into our design.
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): Batteries pose a risk because, depending on type, they are prone to combustion and hazardous waste output if punctured or damaged in any way. The high electricity output is something that is also a risk to humans who do not handle them properly.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): Be sure the battery is secured and protected on our system. Handle batteries with proper electricity safety procedures that are laid out in the previous hazard.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): Power tools and equipment
Summary of Procedure or Tasks: We will need to use power tools in order to assemble the frame of our system and certain attachments to the frame.
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): Power tools can have hazards of burns, shocks, and other harm to limbs if improperly used.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): We will follow OSHA recommendations for handling power tools, go through any necessary RSL training and machine shop safety training.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): Machine guarding/power transmission – gears, rotors, wheels, shafts, belt/chain drives, rotating parts, pinch points
Summary of Procedure or Tasks: Since we will be using motors to drive some kind of linear movement, we will likely have pinch points, wheels, shafts, gears and or belt/chain drives.
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk):

Main risk is one of these mechanisms gripping hair, clothing and hands if they are brought to close during function.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): Whenever working with these mechanisms we will be sure to wear hair up, no loose clothing, and vocally express to the entire team that it is on. When possible, include guards in the design to avoid exposing these mechanism.
Hazardous Activity, Process, Condition, or Agent (identified from previous page): Robotics
Summary of Procedure or Tasks: Our robotic system will have many moving parts and we need to be sure that these moving parts will be able to detect force
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): If the cartesian robot does not detect collision and hurts someone. If the robot itself does not respond to emergency stop commands
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): Be sure there are safeguards mechanically and programmatically that prevent any rogue movement that could be threatening to us the operators. Have necessary kill switches to be able to seize movement immediately.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): Sharp Objects
Summary of Procedure or Tasks: The tooling head of our device will include some kind of cutting or sharp mechanism to remove the flowers from the rest of the crop. This involves testing and working with a variety of sharp objects
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): If improperly handled one could risk a cut injury from these sharp objects.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): We will use thick gloves, close toed shoes, and goggles for eye safety.

Hazardous Activity, Process, Condition, or Agent (identified from previous page):Material handling of heavy objects
Summary of Procedure or Tasks: Making the frame of our system might include working with heavy or large materials.

Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk):
Large materials can be difficult to use and have a risk of falling on someone and injuring them.

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):
Be sure that multiple people are around to adequately stabilize the large material when transporting and working on it.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): Elevated heights (scaffolding, ladders, roofs, lifts, etc.)

Summary of Procedure or Tasks:
Our payload's main work area is below it since it is elevated on the Ag Robot II that it will be attached onto. We will also need to use elevated heights to be able to reach certain areas of the payload when we elevate it.

Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk):
There is risk of it falling on any of us if we are beneath it and it is not properly secured. We also risk falling off other elevated heights like ladders that we use to work on the system.

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):
Be sure there are secure braces and blocks to stop the system from falling on us. Be sure elevated heights are secured and when needed have an additional person secure it in case of instability.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): Metal Fabrication (welding, cutting, drilling, etc.), Soldering, Construction/Assembly, etc.

Summary of Procedure or Tasks:
For construction of the frame of our system and various parts might need metal fabrication to get the exact kind of part. We expect to use metal fabrication to cut aluminum T-slot and possibly smaller guards for the system and certain mechanisms on it. We will also likely need soldering to make many electrical connections. We also plan to use 3D printing from the maker lab for small fabrication

Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk):
Working with machining tools can have a lot of risk of injury to the user. Fumes, sparks and heat from soldering and machining can result in respiratory issues and other burn injuries if not properly handled.

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):
Go through all proper machining tool safety training and comply with all machine shop rules and safety measures. Get guidance from a shop professional when doing new and unfamiliar tasks.

SAFETY EQUIPMENT and PPE
Select the appropriate PPE and safety supplies you will need for the project (Check all that apply)
☐ Appropriate street clothing (long pants, closed-toed shoes)
☐ Gloves; indicate type: Thick electrical gloves
☐ Safety glasses/ goggles
☐ Face shield and goggles
☐ Lab coat
☐ Hearing protection
☐ Fire extinguisher
☐ Eyewash/safety shower
☐ Spill kit
☐ Other (list):

TRAINING REQUIREMENTS
Identify the appropriate training (check all that apply)
☐ Biology & Bioengineering Lab Safety Camino Course – contact Lab Manager or EHS to enroll
☐ Chemistry & Biochemistry Lab Safety Camino Course – contact Lab Manager or EHS to enroll
☐ Electrical Safety for Engineering Camino Course – contact EHS to enroll
☐ LiPo Battery Safety Training – contact MAKER Lab to enroll
☐ Review of SDS for chemicals involved in project – access SDS library at: rms.unlv.edu/msds/
☐ Laboratory Specific Training – contact Lab/Shop Owner
☐ Project Specific Training – contact Project Advisor
☐ Other (describe below):

ACKNOWLEDGEMENT
By signing, I verify that: 1) I am aware of the hazards and risks of all the tasks associated with the project 2) I have received, or will receive all the necessary safety training and/or have read the safety manual and safety data sheets (SDSs) relevant to the project before performing any hazardous tasks 3) I will follow all required safety precautions while working on this project, including but not limited to use of engineering controls, following safe work practices, and wearing appropriate personal protective equipment 4) I will follow in accordance with all university COVID-19 protocols both on and off campus

Name of Project Team Member	Signature	Date
Steven Bucher	Steven Bucher	11/5/20
Ariana Low	Ariana Low	11/11/20
Brooke Broszus	[illegible]	11/11/20
Krissy Ikeda	Krissy Ikeda	11/12/20
Alejandro Gutierrez	Alejandro Gutierrez	11/11/20

APPROVALS		
This document must be reviewed and approved by the people below before any project work can begin. A copy of the approved document must be kept where the work is being conducted		
Faculty Advisor		
Name:		
Department:	Signature	Date
Department Chair		
Name	Signature	Date
Laboratory Director/Manager		
Name	Signature	Date
EH&S		
Name	Signature	Date
Other		

Name	Signature	Date

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