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Automatic Romaine Heart Harvester

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AUTOMATIC ROMAINE HEART HARVESTER

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

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Abstract

The Romaine Robotics Senior Design Team developed a romaine lettuce heart trimming system in partnership with a Salinas farm to address a growing labor shortage in the agricultural industry that is resulting in crops rotting in the field before they could be harvested. An automated trimmer can alleviate the most time consuming step in the cut-trim-bag harvesting process, increasing the yields of robotic cutters or the speed of existing laborer teams. Leveraging the Partner Farm's existing trimmer architecture, which consists of a laborer loading lettuce into sprung-loaded grippers that are rotated through vision and cutting systems by an indexer, the team redesigned geometry to improve the loading, gripping, and ejection stages of the system. Physical testing, hand calculations, and FEA were performed to understand acceptable grip strengths and cup design, and several wooden mockups were built to explore a new actuating linkage design for the indexer. The team manufactured, assembled, and performed verification testing on a full-size metal motorized prototype that can be incorporated with the Partner Farm's existing cutting and vision systems. The prototype met all of the established requirements, and the farm has implemented the redesign onto their trimmer. Future work would include designing and implementing vision and cutting systems for the team's metal prototype.

Table of Contents

List of Figures

List of Tables

Acknowledgements

1. Introduction

1.1 Background

1.1.1 Agricultural Labor Shortage

Agriculture is one of the oldest and most important economic activities, providing food and fuel necessary for our survival. However, with the "global population expected to reach 9 billion by 2050... agricultural production must double if it is to meet the increasing demands for food and bioenergy" [1]. Figure 1.1 illustrates the rising demand and production of romaine lettuce, increasing about four times in a 20 year span.
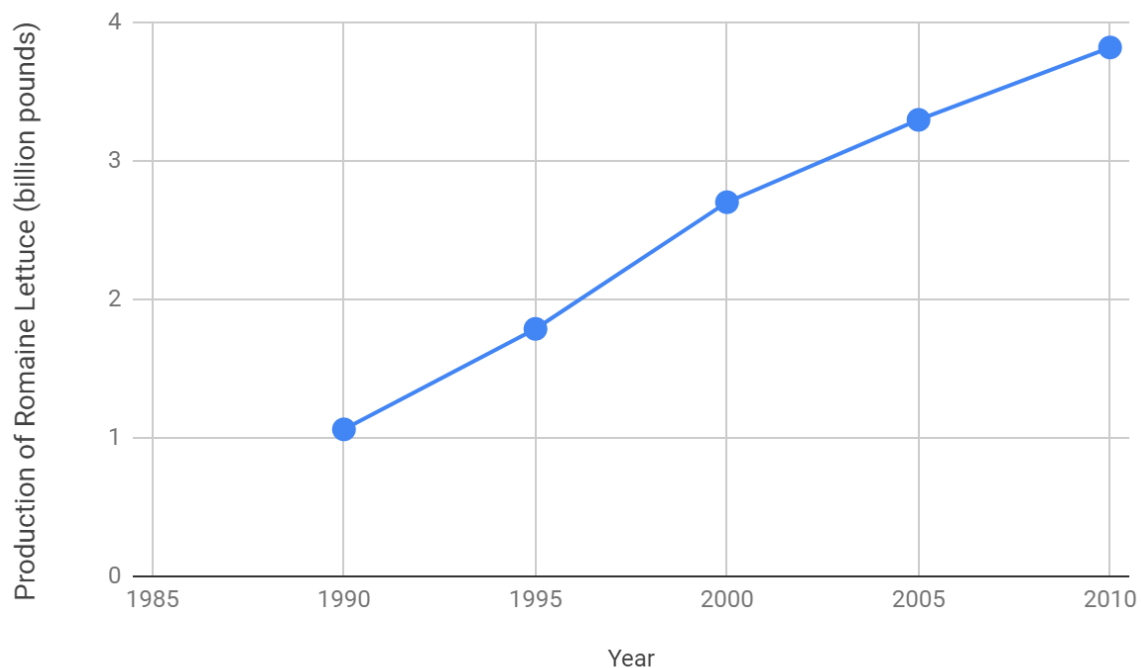
Figure 1.1: Increasing Romaine Lettuce Production in US [1]

Due to many factors, including rising standards of living, the difficulty of the work, and a changing immigration landscape, agricultural employment is decreasing and resulting in a labor shortage in the market [2].

As shown in Figure 1.2, the availability of agricultural labor went down by roughly 20% between 1985 and 2010.
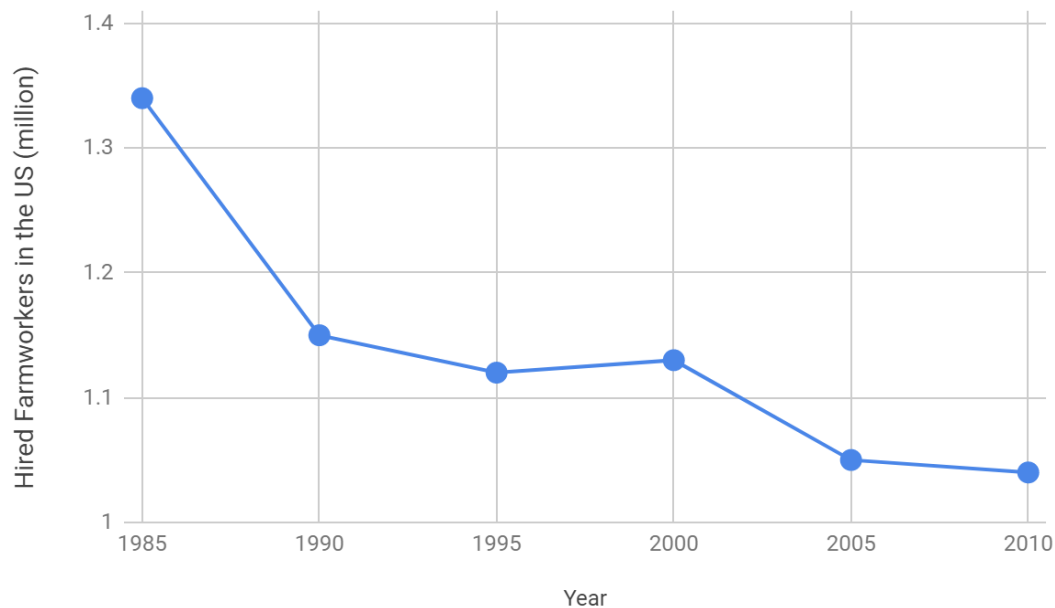
Figure 1.2: Decreasing Agricultural Labor Availability in US [2]

Given limited land and dwindling labor resources, modern farms must sustainably produce high quality yields at lower expenses despite a dwindling labor force. Thus, to address these challenges, farming enterprises will require innovative technologies, particularly automation.

1.1.2 Need for Agricultural Automation

Since the invention of combine harvesters and the cotton gin, agricultural automation has evolved and become highly mechanized, with innovations such as tractors, planters, dynamic drainage, irrigation machines, and motor vehicles. For agricultural automation to be successful, however, it must be cheaper than relying on manual labor. As a result, difficult-to-mechanize crops such as cherries, peppers, apples, and lettuce have continued to use human laborer to this day.

As the human labor force dwindles, automation is becoming increasingly important. To match the growing food demand, farms are planting as many crops as possible. Crops that grow in specific seasons, such a romaine lettuce, must be planted in a short time frame to grow correctly. However, these crops must also be harvested in a very short time window. After this time window, the crops rot and are wasted.

This Senior Design Team has established a relationship with a romaine lettuce hearts "Partner Farm" (name under NDA) in Salinas, CA. They must harvest more than 2 million romaine hearts per day if they are to fully reclaim planted lettuce [Appendix A2]. In interviews with the farm, they emphasized that due to the labor shortage, it was becoming increasingly difficult to harvest romaine hearts at a fast enough rate. They explained that although they offered competitive salaries and benefits to their worker, less and less people were interested in the grueling labor.

Another challenge the farm discussed was that human labor can be unreliable. Laborers can miss work days due to sickness or injury, when this happens, the farms production decreases. As a result of labor challenges and not being able to harvest fast enough, the farm described that they frequently had lettuce rot in the field, wasting time, money, and water. If this process was automated, wasted food could be reclaimed. Also, if harvesting speeds increased their economic returns would increase since they have expressed their ability to grow, pack, and sell more if harvesting capabilities increased. Thus, as the demand for food increases and the amount of people willing to do labor decreases, even crops that are more fragile and difficult-to-mechanize must be automated.

1.2 Review of Field

1.2.1 Romaine Lettuce Harvesting Process

The need for automation is particularly present in the harvesting of romaine lettuce hearts. This delicate crop must be either cut perfectly, or cut and then trimmed, so as to remove the outer,

thicker, leaves and ship only the crunchy, inner "heart." This delicate crop cannot be harvested by a large combine or other purely mechanical harvester, and currently the only automation employed is a tractor which human laborers can follow behind and toss their crops onto. This process is shown below in Figure 1.3.
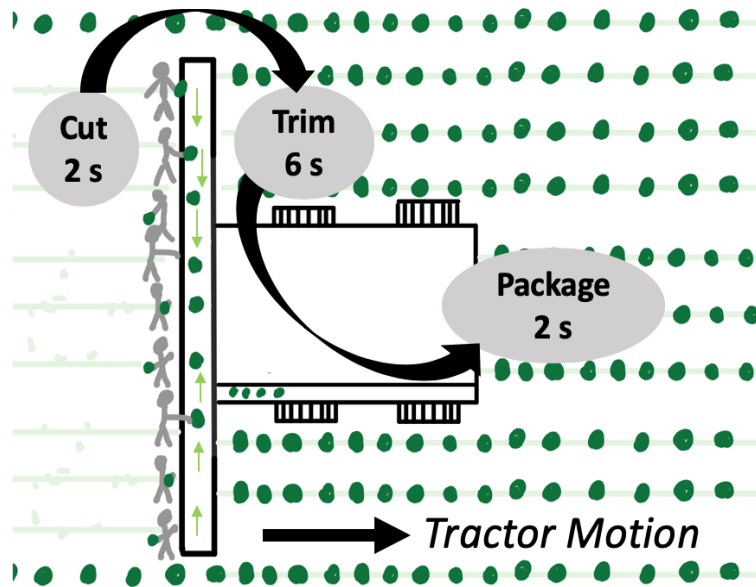
Figure 1.3: Laborers Follow Tractor Placing Trimmed Hearts onto Conveyor Belt

With this current method of harvesting, human laborers cut, trim, and bag lettuce by hand. The trimming process, shown in Figure 1.4, is the most time-consuming part of harvesting.
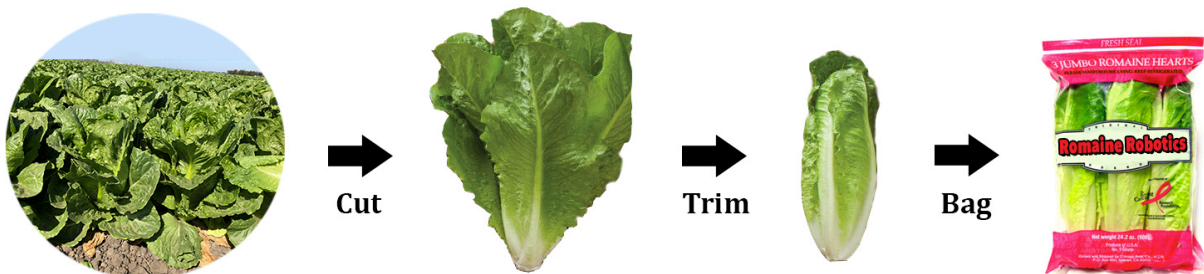
Figure 1.4: Untrimmed vs. Trimmed Romaine Hearts

1.2.2 Automatic Romaine Trimming

The team initially considered designing a fully robotic harvester to cut the romaine heads to the perfect height on the first cut, completely removing the need for additional trimming [4]. However, the Partner Farm described that they had already tried this single-cut approach, and had many difficulties. The farm's system shown in Figure 1.5 uses an expensive overhead LIDAR to direct a robot arm with a pneumatically actuated soft robotics gripper and cutting blade.
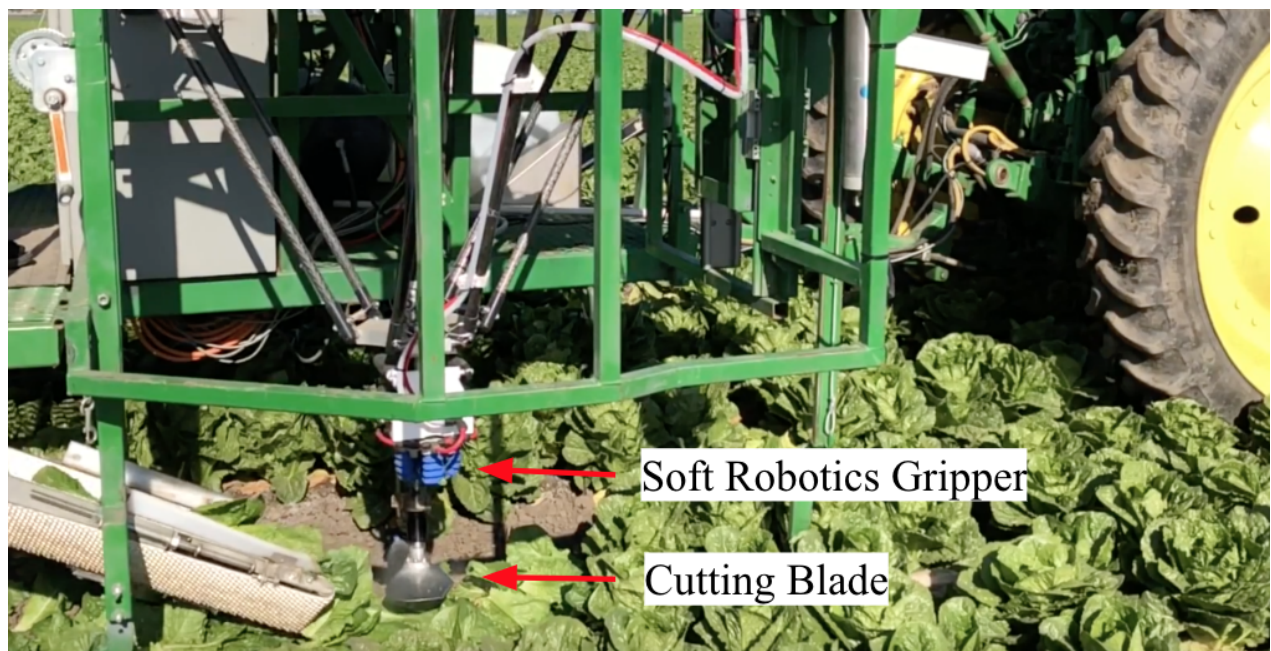
Figure 1.5: Fully Automatic Harvester Experiences Lost Yields of as High as 20%

The robot attempts to extrapolate the ideal cut height using an overhead imaging system. However, because the lettuce has so many outer leaves and each lettuce varies so much in shape, size, and color, the system cannot accurately interpolate the height to cut each stem. Despite iterating on their robotic system for 3 years, the robotic harvester still only yields 80% quality product due to occasionally cutting too high or crushing the plants. Thus, further development of the automatic trimming process is needed to match the laborers' output, who can achieve 95% quality product.

However, instead of continuing to iterate the design of an expensive, complicated, robotic harvester, the team proposed building an automatic trimmer for use after the lettuce was already cut off of the ground. This system allows the harvester to deliberately cut low and capture close to 100% of the lettuce with the trimmer assuming all responsibility for achieving the proper final cut location. The system can also use a human harvesting team, reducing the labor time from 6 to 2 seconds per heart by removing the need for the human to perform the iterative trimming step. With the trimmer, laborers simply make the initial cut and put the lettuce on a conveyor belt that routes the lettuce to the automatic trimmer.

An automatic trimmer allows the same number of crops to be harvested in the same amount of time with half the number of workers. This alleviates the labor shortage problem, reduces labor costs to the farm, and maintains the 95% yield achieved by human laborers. As shown in Figure 1.6, the team's trimmer replaces the manual trimming step of the harvesting process.
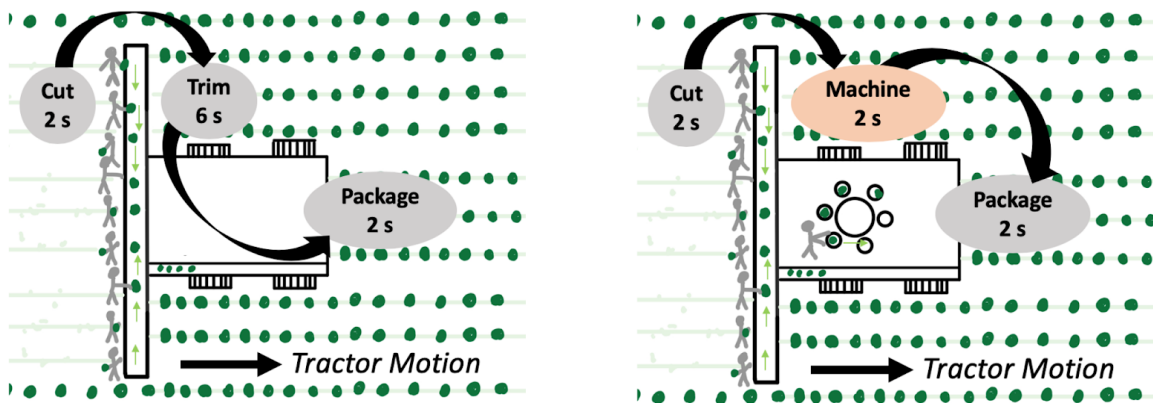
Figure 1.6: Comparison Between Current Romaine Harvesting Process [left]
and Proposed Harvesting Process [right]

This trimming system can be developed and manufactured quickly and cheaply, and ultimately allow the farm to increase their efficiency and reduce food waste.

1.3 Project Objectives: Romaine Heart Trimmer

1.3.1 Issue and Impact

This project creates an automatic romaine lettuce heart trimming system that addresses a growing labor shortage in the agriculture industry by eliminating or significantly reducing reliance on manual labor. Despite an increasing demand for romaine lettuce, the labor shortage in agriculture is preventing lettuce farms from harvesting their fields before the grown lettuce begins to spoil, wasting invested resources and preventing food from getting to those in need.

1.3.2 Solution and Project Objective

Romaine Robotics was contracted by a Partner Farm to redesign their romaine heart trimmer to improve its ability to handle and control the lettuce in order for it to be consistently sensed and cut. The Partner Farm already had a working camera for sensing and cutting system, so the team was not tasked with redesigning those systems.

To accomplish this goal, customer needs were determined and quantitative requirements were established. System design included several iterative prototypes in order to proof concepts and obtain quality feedback from the customer. System level testing verified that all requirements were met by the final design. The system allows for proper loading, gripping, and ejection of the lettuce while maintaining a constant rotational speed. The system has been accepted by the Partner Farm and integrated with their existing trimmer with hopes of field evaluation during the next growing season. Fully implemented, the system has the potential to greatly increase the efficiency of the romaine heart harvesting process, enabling full harvests in the face of labor shortages and growing demand.

2. Systems and Project Overview

2.1 Introduction

As described in Chapter 1, the team's goal is to address a growing labor shortage in the agriculture industry and its impacts on a Partner Farm's ability to harvest romaine lettuce before it rots in the fields. The team will achieve this by redesigning the farm's existing trimmer's handling and control of lettuce by improving the loading, gripping, and ejection stages. This chapter will refine the overarching goal by detailing the farms previous lettuce trimming machine and its issues, and describing the results of customer and user interviews to find underlying needs.

After confirming the project goal and scope, a list of needs are identified, prioritized, and then quantified into requirements. Some requirements were ambiguous and undefined, so the team conducted testing and analysis to determine them. These system-level requirements serve as the final metrics upon which verification testing was conducted to confirm the team built a system that would work and address the needs.

Finally, the team presents its plan for team and project management: what steps and methods the team took to ensure it could accomplish these goals given their limited timeline and budget.

2.2 Existing System Overview

2.2.1 User Scenario and Explanation

The romaine heart trimmer would be placed on one of two trailers pulled by a tractor as it moves down the field. The first trailer will have four of the existing robotic harvesting systems that are able to make the initial cut on the romaine heads, dropping them onto a conveyor belt that leads

to the second trailer. This second trailer would have laborers standing on it, grabbing heads of lettuce from the conveyor belt and putting them into the automatic trimmer.

To use the system, the laborers will place the head of lettuce into one of the rotating cups of the trimmer. As the indexer rotates, the cups will open to accept the lettuce from the laborer. The lettuce will be placed into the open cup, with a platform zeroing the height of the stem. As the cup continues to rotate, it will close onto the outside of the lettuce, holding it firmly as the machine calculates the correct cut height and cuts the stem. After cutting, the trimmed heart and excess leaves will be ejected from the trimmer, falling down onto the same conveyor belt so another laborer can bag them for shipping.

2.2.2 Device Sketch and Subsystem Description

To accomplish the trimming, the team proposed building a system similar to the existing prototype made by the partner farm. This existing system is sketched below in Figure 2.1.
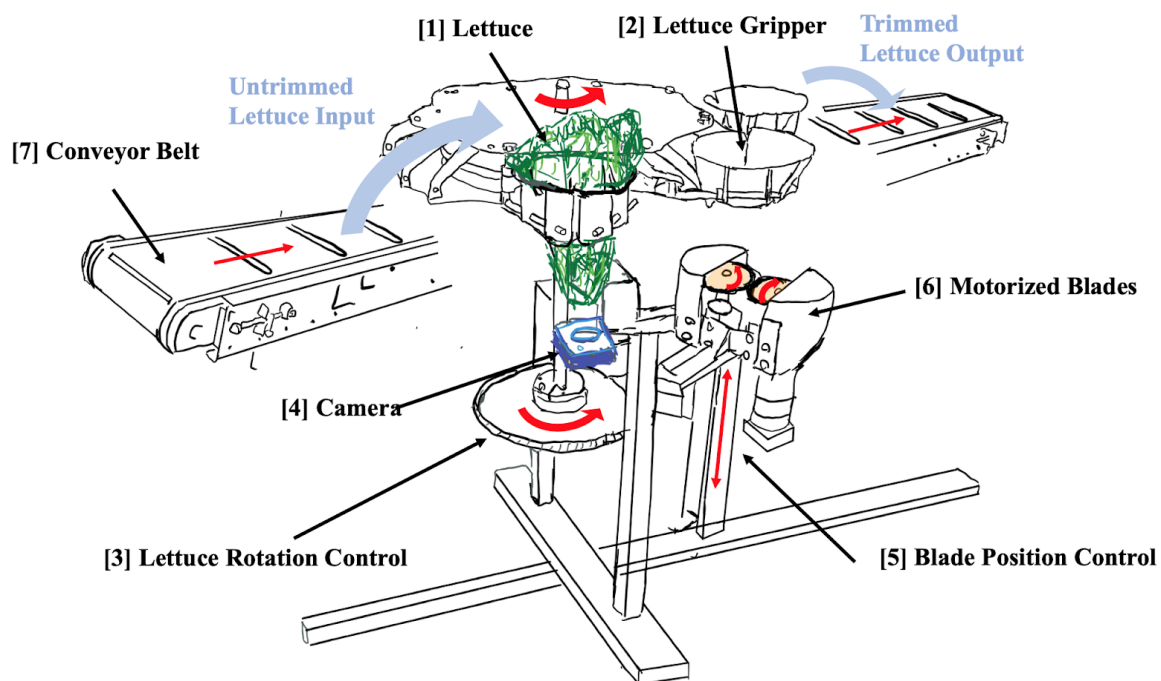
Figure 2.1: System Level Sketch of Existing Farm Prototype with Overall Subsystems

Lettuce [1] is input as full romaine heads dropping them into cup-shaped Lettuce Grippers [2]. The Lettuce Rotation Control [3] then moves the lettuce to expose its stalk to the Camera [4] below. The Camera uses machine vision to determine the diameter of the stalk and thus how high the lettuce needs to be cut to achieve the desired diameter for proper trimming. The Blade Position Control [5] then lifts the counter-rotating cutting Blades to the calculated height before the lettuce stem is fed into the Motor [6] blades. Finally, the trimmed romaine heart is dropped back onto the Conveyor Belt [7] so a human can package it.

2.2.3 Existing Subsystems and Issues

The overall lettuce trimmer is composed of 5 main subsystems: the Gripper, Indexer, Cutter, Superstructure, and Mechatronics. These subsystems will be detailed in the following sections.

Existing Gripper Subsystem

The Gripper, shown in Figure 2.2, opens to accept lettuce from users, holds the lettuce during the trimming process, and then ejecting the lettuce once it is trimmed to the proper size. The current solution uses three conical hard plastic cups. The cup on the bottom right, closest to the wheel, is stationary, while the other two are connected to the arms of the actuating linkage. The linkage uses a follower wheel to ride along a cam in the Indexer, opening and closing the cups
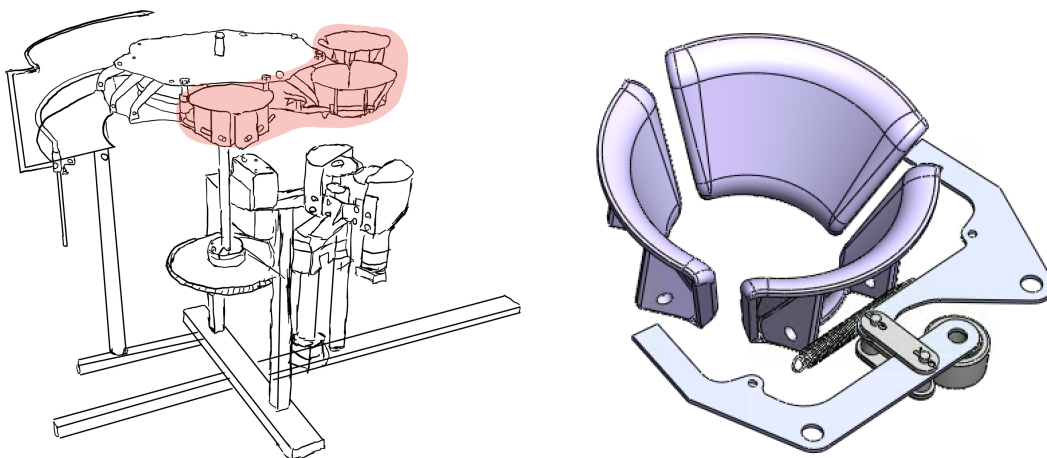
Figure 2.2: Existing Gripper System Features 3 Cups and Sprung Linkage

The biggest problem with the existing gripper subsystem was that it did not fully open to drop the lettuce for ejection causing the system to jam. The cups would not squeeze tight enough to hold the lettuce upright during trimming. The third, back cup was redundant and did not provide extra support, needlessly increasing the complexity of the linkage. Finally, there was little compliance in the cups making it difficult for a laborer to load when closed and potentially allowing damage to the sensitive lettuce leaves.

Existing Indexer Subsystem

The Indexer, shown in Figure 2.3, is made up of a cam and two plates that hold the grippers at their linkage pivots. As the system rotates, these pivots allow the linkage to open and close as the follower wheel rides along the indexer cam profile. As a whole, the indexer subsystem queues the lettuce, opening and closing the gripper cups for processing steps.
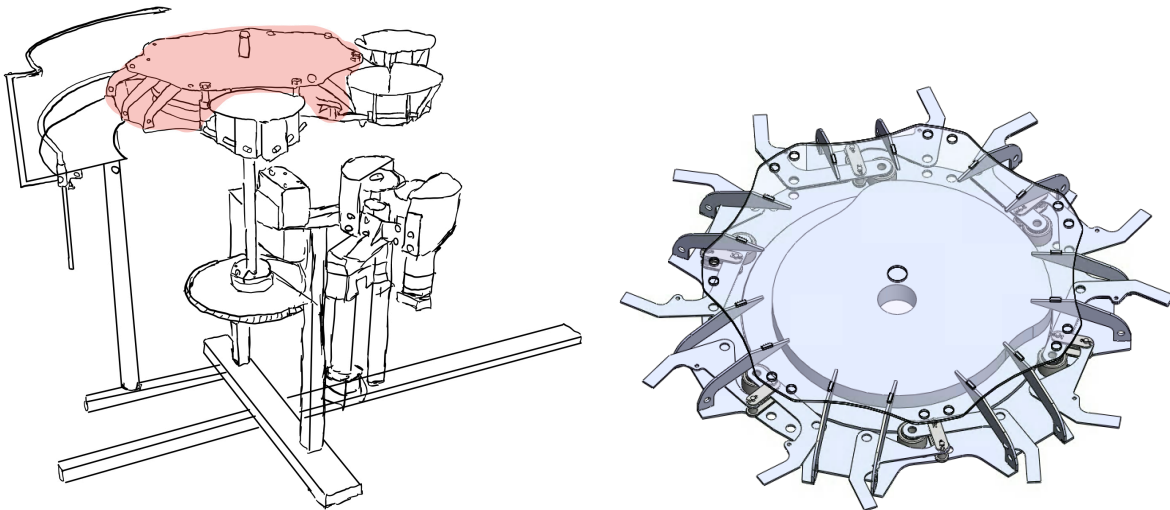
Figure 2.3: Existing Indexer has Cam and Holds 7 Grippers

While the two plate indexer design worked well, the indexer cam needed the most improvement. The subsystem only accommodated two different processing stages, gripping and ejection. It did not have any loading position to facilitate a laborer inserting lettuce into the grippers. The existing indexer used welding and a large, cumbersome superstructure to support the live axle.

Existing Cutting Subsystem

The cutting mechanism, shown in Figure 2.4, is made up of two counter-rotating blades that perform the trimming operation on the lettuce stem.
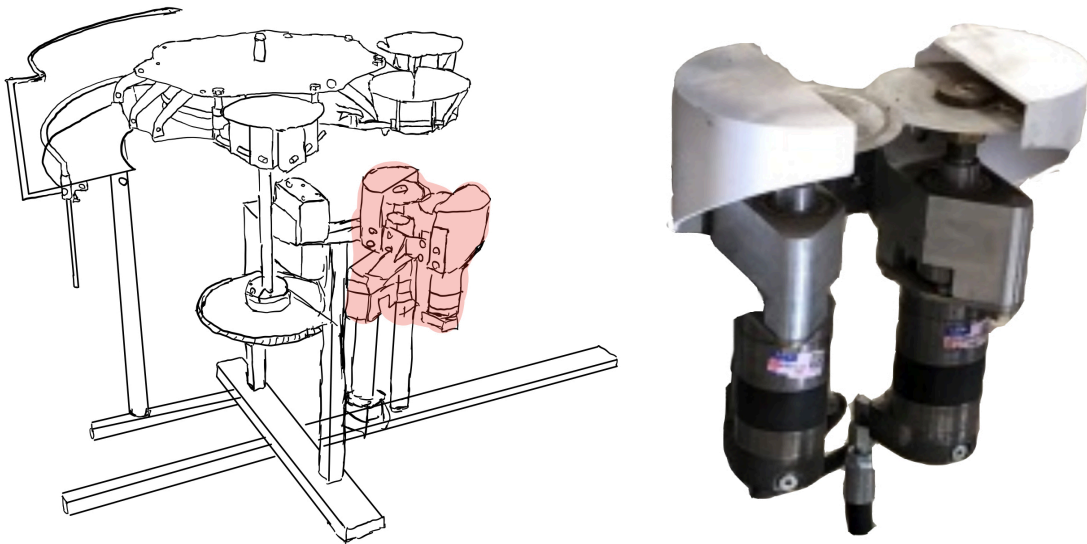
Figure 2.4: Existing Cutting Blades feature counter-rotating blades spun by hydraulic motors

As the indexer rotates the lettuce heads towards the blades, the system adjusts the height of the rotating blades. By the time that the lettuce reaches the blades, an vision system will have sensed the stalk diameter and determined the optimal cut location. The blades are then able to move along its linear actuator via a closed loop control system to the correct position, allowing the lettuce to be properly trimmed.

The cutting subsystem was considered to be the least critical due to the partner farm already having a viable solution. Thus, the cutting mechanism was not redesigned or addressed in the scope of the team's Senior Design project. However, it could be a project for a future team.

The superstructure, shown in Figure 2.5, holds the indexer, allowing the motor of the mechatronics system to rotate it. It raises the indexer to a suitable working height, so user does not have to bend down to load lettuce into the machine. The superstructure also features a large base to stabilize the system from tipping against its own vibrations and indexer motion. In addition to stabilization, the system has mounting positions for the cutter, camera, and electrical equipment. Finally, the superstructure holds a horizontal leveling platform intended to zero the vertical position of the lettuce so a machine vision camera can use a known reference for it's diameter determination.
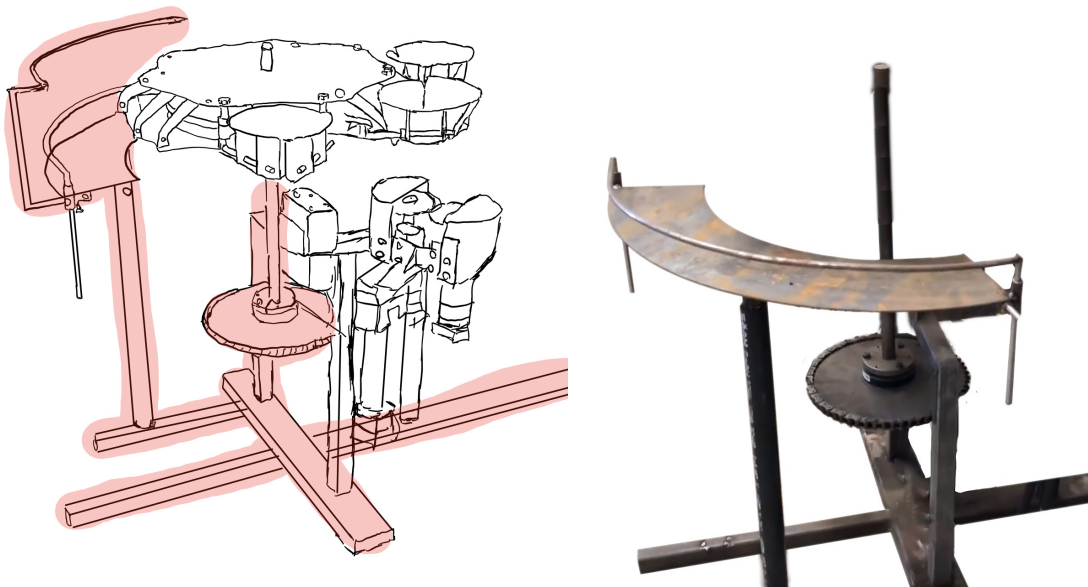
Figure 2.5: Existing Superstructure with Horizontal Leveling Platform

The overall superstructure is very large and cumbersome to support the indexer's live axle. The team plans to simplify the superstructure, making it more compact so the system can be more easily mounted on the Partner Farm's tractor and incorporated into a conveyor belt system.

The mechatronics subsystem consists of the electronics (actuator, sensors, and controllers) and corresponding software to make the trimmer run automatically and with consistent performance. The existing mechatronics use hydraulic motors running in open loop control via a variable flow valve to control the indexer rpm and cutting blades' height. For the purposes of this Senior Design Project, the team did not have access to such a hydraulic system, so they adapted the system to use a DC motor, battery system, shaft encoder, and off-the-shelf controller to provide closed loop control. The following section outlines the functional analysis and how these different subsystems interface together.

2.2.4 Functional Analysis

The main function of the system is to take untrimmed romaine lettuce heads and trim them at the correct height, eliminating the outer leaves and leaving just the romaine lettuce heart as shown in Figure 1.4. The most important functions required are achieved by the Gripper, Indexer, and the Cutter. Figure 2.6 below outlines these systems and their respective functions and sub-functions.
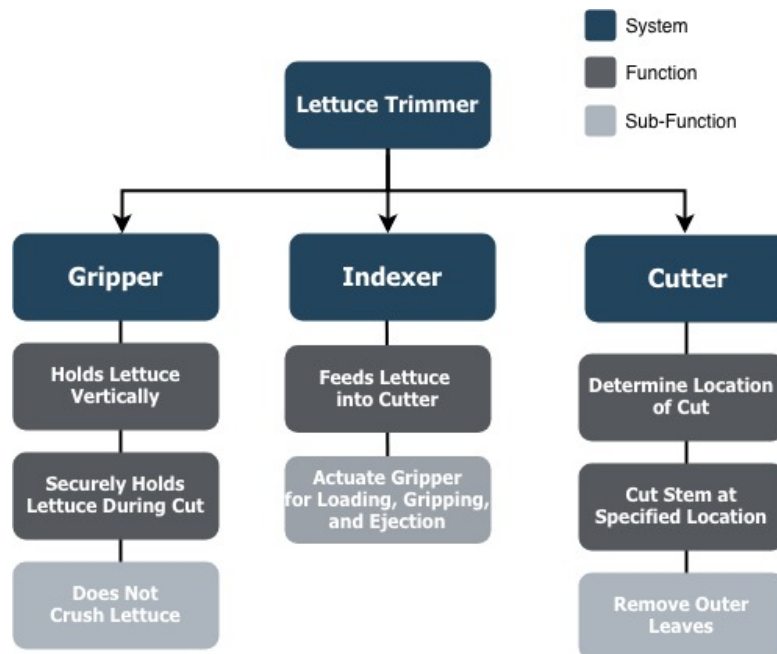
Figure 2.6: Functional Decomposition Diagram

Since the farm already has a working cutter subsystem the team did not need to design a cutter. Also since *Romaine Robotics* is designing a stand alone system it is necessary to also design a superstructure, for attaching all the other subsystems to a sturdy base, and a mechatronics subsystem to rotate the indexer and grippers.

2.2.5 Benchmarking Competitors

The number of agricultural robots in development has grown rapidly, with a few of those in development shown in Appendix A6. However, among those that are targeting the Partner Farm's specific crop, romaine lettuce hearts, only a few systems for harvesting have been publicized. These systems, including the predicate team of human laborers, are compared below in Table 2.1 alongside the estimated specifications for the trimmer this senior design team hopes to develop.

Table 2.1: Benchmarking and Comparison among Romaine Lettuce Harvesting Systems

	Romaine Robotics Trimmer	**Current Laborer Team**	**Partner Farm Robot Harvester**	**Taylor Farms Water Jet/Bandsaw**
Output Product	Trimmed Romaine Hearts	Trimmed Romaine Hearts	Cut Romaine Heads	Cut romaine leaves (not hearts)
Cutting Method	Spinning blades trim bottom of heads. Height determined by machine vision.	Knife held by laborers. ~3 seconds spent trimming per head	Chopping blade on robot arm directed by overhead LIDAR	Water Jet or bandsaw 0.5" off ground slices 5 heads at once.
Output [product/minute]	30	30	30	100
Complexity (max 5)	2	1	5	4
Operators Needed [#]	1	0	3	4
Packers Needed [#]	2	2	2	6
Harvesters Needed [#]	6	12	0	0
Operating Cost (labor+utilities) [$/hr]	210	350	100	550
Cost to manufacture [$]	3,000	100	50,000	30,000

It can be seen from Table 2.1 that among the systems that are capable of harvesting romaine lettuce hearts, *Romaine Robotics* strikes an optimal compromise between the easy to establish but operationally expensive current human team and the cheap to operate, but expensive to manufacture, partner farm robot arm harvester. The *Romaine Robotics* Trimmer can be manufactured at a lower cost and needs half as many laborers because it takes care of the trimming process, which is time consuming when done iteratively by humans. Together, these lower costs mean it can be more affordable for expansion or parallelization compared to other romaine heart harvesting systems.

2.3 Customer Interviews and Needfinding

2.3.1 Introduction and Mission Statement

As presented in Section 1.1, market analysis and conceptual design of the lettuce harvesting robot reiterated the Partner Farms need for further development of harvesting/trimming robots. However, the team needed to interview first-hand customers to confirm the usefulness and acceptability of an automatic romaine heart trimmer. The mission statement summary presented in Table 2.2 outlines not only the project goal but also the relevant markets and stakeholders.

Table 2.2: *Romaine Robotics* Mission Statement Summary

Product Description	● System for Romaine lettuce heart trimming
Benefit Proposition	● Faster, more efficient, money saving
Key Business Goal	● Address labor shortage ● Double speed of manual labor
Primary Market	● Large Romaine lettuce heart harvesting farms
Secondary Markets	● Small romaine lettuce heart harvesting farms ● Cauliflower, broccoli, cabbage harvesting farms
Stakeholders	● Consumers ● Laborers ● Farmers ● Partner companies for technologies and distribution

The following sections provide a detailed summary of identifying customers, collecting data, and interpreting and prioritizing needs.

2.3.2 Data Collection

To gather high-quality information directly from consumers, the team conducted interviews and observed existing products in use. Needs were identified by interviewing both lead users (directly involved with the purchase and use of an automatic trimmer) and regular users. A customer selection matrix, presented below in Table 2.3, helped plan exploration of both market and customer variety.

Table 2.3: Customer Selection Matrix

Market Segments	Lead users	Users
Large Farm Vice-President	1	0
Garden Hobbyist	0	1
Laborers	1	1
Consumers of lettuce	0	3
Experienced Roboticists	1	2

Lead and regular users were identified through Santa Clara University and the partnership with the Salinas farm. Consumers were found by leveraging friends and family. When collecting data, the goal was to elicit an honest expression of needs.

2.3.3 Interviews

To have effective communication, the team watched for nonverbal information and was alert for expressions of latent needs. To conduct interviews with consumers and lead users, prepared interview guides were created. After the interviews, notes were organized into a customer need table as shown in Appendix A2.

2.3.4 Observations

The team visited the Partner Farm in Salinas in the Fall to observe the existing process and the Partner Farm's existing trimmer. Throughout the entirety of the visit, observations were made to determine underlying customer needs that often do not come out in interviews. Notes were taken throughout the tour and during demonstrations of current technologies. Photos from the visit are shown in Appendix A3. Observations encouraged follow up questions and clarifications throughout the interview process. The farm visit proved extremely valuable, and more visits and Skype phone calls were taken to further clarify needs and refine requirements throughout the year-long design process.

2.3.5 Interpretation of Needs

After collecting interview and observation data, notes were organized in data collection tables with customer statements paired up with an interpreted need. To do this, members of the team interpreted needs independently before coming together as a group and discussing results. The final results are shown in the customer data collection tables. Examples are shown for the consumer and lead farm users in Tables 2.4 and 2.5, respectively. All data collected for users are in Appendices A1 and A2.

Table 2.4: Data collection for user: Consumer Rose

Prompt	Customer Statement	Interpreted Need
Consumption of lettuce habits	Used to buy 3 a week but now buys pre-washed mixes	Buying lettuce must be convenient
Knowledge of lettuce brands	Brand not important	Lettuce must be inexpensively harvested
How to identify quality	Look for "organic" and freshness	Lettuce must be free from dirt and dust
Value added to product with robot harvesting	Does not affect decision	Lettuce must be inexpensively harvested
Labor shortage or replacing labor	Not bothered, farm labor is hard	Lettuce is harvested easily
Food Safety	Robot harvest may be more sterile	Lettuce must be safe to eat
Conservation of Resources	Would feel better about brand	Lettuce must not waste resources

Table 2.5: Data collection for Lead User: Farm Executive VP Stephen

Prompt	Customer Statement	Interpreted Need
Production yield	Partner farm harvests 2 million hearts a day, with about 1.5 passing quality and being shipped	System should operate at least as fast a human crew
		System should produce as high yields as a human crew
Company operations in Winter	Company moves to Yuma (500+ miles south) from November to February	System must be transportable to Yuma for winter harvesting
Thoughts on robotic automation?	Even if robot produces the same yield as current humans, the easier work would convince more laborers to come to partner farm (instead of competition) and thus still be extremely valuable	System could operate similar to human crew if labor is easier on workers
	Automated equipment (easier work) would allow for 2 shift days	System should be able to operate for 2 shifts per day
Labor shortage	25% of laborers are H2A temporary agricultural workers	System should be usable by any skill or language-level worker
Overall scalability	If harvesting increased, they could easily grow, cool, package, and ship more	Harvesting is the limiting factor in the overall production

2.3.6 Organizing and Prioritizing Needs

After compiling over 30 customer needs, the need statements were categorized based on topic. Redundant statements were eliminated and the remaining were organized into a hierarchical list consisting of primary and secondary needs. Next, the needs were given a rating from 1 (minimal) to 5 (essential) based on their importance to the overall project goal, shown in Appendix A5.

2.3.7 Customer Needs Summary

Overall, the team conducted extensive customer identification and need finding through literature review, information gathering, and interviews with both consumers (users) and farm managers (lead users). These needs were used to determine the team's requirements, discussed in Section 2.4. The following key needs are outlined below.

Upright Lettuce

One important need is for lettuce to be cut perpendicular to the stem. The current system is able to accept lettuce from users, but struggles to maintain the romaine hearts' vertical alignment through the cutting process. Because of great variation in size and shape between lettuce heads, the cups often hold the lettuce at an angle; lettuce is tilted by the time it reaches the blades, causing an undesirable cut. The team has identified this as the largest problem with the design and seeks to iterate on the gripper so that the lettuce is more consistently held vertical.

Rapid Loading

The partner farm made clear that if a lettuce trimming system was to be successful, it would need to be rapidly loaded by a laborer. The existing trimmer system currently has two stages, gripping, and ejection. Their system requires laborers to load the lettuce onto a platform with the grippers wide open in the ejection stage. However, this means that the lettuce will tilt if not held by the laborer. Thus, a new, third, loading stage is required to allow the labor to quickly insert the lettuce into a semi-opened gripper that can allow for easy insertion and holding the lettuce upright. The geometry of the loading, gripping, and ejections stages need to be determined through lettuce measurements.

Lettuce Ejection

The system should run continuously without needing to pause or delay. While the existing trimmer system has an ejection stage to drop the lettuce, the lettuce often gets stuck because the gripper does not open wide enough, causing the whole system to become jammed. Jamming temporarily halts the entire harvesting process, wasting time and money, so it was critical that this does not occur. *Romaine Robotics* decided that a new gripper linkage that opens the cups wider, ejecting them safely without slowing down the trimmer was needed. Further measurements of lettuce needed to be taken to determine the optimum ejecting width.

Consistent Stalk Height

For the imaging system to determine the proper diameter of the lettuce stalk and thus the optimum cut height, it is important that the sensed stem is at a known height. The current system has a leveling platform that laborers can push the lettuce down onto, providing the desired reference height. However, because of misalignments during the loading stage, lettuce stem heights often came off of the platform during the gripping stage causing an inconsistent height.

Constant Speed System

For laborer safety and ease of use, the system should not speed up or slow down. The current trimmer uses open loop speed control powered by a hydraulic system. Since many parts on the tractor use the same hydraulic system, it is possible that the hydraulic pressure could vary, slowing or speeding up the trimmer. Additionally, varying resistance or friction within the trimmer's rotation could vary the torque on the motor, also causing speed variance.

Pressure Distribution

The farms current lettuce trimmer has hard, 3D printed plastic cups that hold the lettuce. As the system grips the lettuce, there is concern that the cups could damage the produce. Even if it is not initially visible, cell damage can occur that causes browning after several days, making the lettuce more difficult to sell. One way to solve this issue could have utilized compliance in the material of the gripper cup. However, as discussed in Section 3.3.2, a tradeoff analysis showed it was more effective and robust to use hard plastic cups but achieve compliance with a dual-pivoting gripper linkage system.

Although the team's proposed solutions could improve system level issues, they required tradeoffs. For example, redesigning the cup could help vertically align the lettuce to improve cutting angle, but it could also slow down the overall system. Changing the material of the cup could better distribute pressure, but could be more expensive or require more maintenance. An improved linkage for gripper actuation could require a more complex design. To help find alternative solutions to remedy the current gripper issue, a system level concept generation was performed, shown in Appendix B1. Furthermore, to make sense of various system tradeoffs, a concept generation was performed for the individual subsystems in Appendices B2 and B3. The following section provides an overview of these designs and tradeoffs for each subsystem.

2.4 Quantifying Product Requirements

2.4.1 Introduction

After interviewing the partner farm and interpreting the needs of the lettuce trimming system, the team needed to further distill the large list of needs and quantify them into requirements to serve as metrics for verification of the final system design. Some needs, such as the geometry of the gripper or the harvesting rate, were easily translated into requirements. Other needs were more abstract, such as the rotational speed or ensuring no damage to the lettuce, and required testing to establish. The following sections detail how these requirements were determined.

2.4.2 Easily Defined Product Requirements

The first quantitative requirements established were based on the needs that the system hold the lettuce upright, be rapidly loaded and fully drop the lettuce after trimming. To achieve this, the team decided that three gripper states were required. A loading state would roughly match the diameter of lettuce so that a laborer could push it in without much force, the gripping state would

apply force, using a spring, and close to a smaller diameter, and finally the grippers would open wide enough to drop even the largest lettuce. To determine the geometry of each state, the team measured several untrimmed lettuce heads as shown in Figure 2.7.

Figure 2.7: Measuring the Dimensions of Untrimmed Lettuce Heads

After measuring the smallest and largest lettuce available, the team determined that the loading and gripping state should be 4.25in and 3in respectively. These diameters would allow small lettuce to be loaded and held straight while still accommodating large heads of lettuce. The ejection size was found to be approximately 8in after measuring the largest heads.

Other needs such as having a consistent stalk height were driven by the farms desire to use an imaging camera, which should image the lettuce at a consistent distance. The need of matching a human harvesting rate was also determined through interviews to be 2 seconds per head of lettuce. A summary of these simple-to-establish requirements are shown in Table 2.6.

Table 2.6: Initial System Requirements

Need	Requirements	Value	Tolerance	Units
Holds Lettuce Upright	Gripper Gripping Size	3	± 0.5	in
Rapid Loading	Gripper Loading Size	4.25	± 0.5	in
Full Ejection	Gripper Ejection Size	8	± 0.5	in
Consistent Stalk Height	Height Variation of Lettuce Stem	0	+ 0.00 - 0.25	in
Does not damage lettuce	Grip Strength	TBD	TBD	lbf
Constant Speed	Rotational Speed	TBD	TBD	RPM
Match Harvesting Rate	Lettuce Head Throughput	2	± 0.1	secs/head

Some needs (shown as TBD in Table 2.6) were more abstract, such as the rotational speed or not damaging the lettuce, and thus required further testing to establish.

2.4.3 Defining Grip Strength with Lettuce Load Testing

The farm emphasized that a great need for the system was that it did not damage the lettuce, otherwise the lettuce would not be able to be sold. Not damaging the lettuce is an abstract need that can not be easily established, so a test was required to determine the maximum forces that the lettuce can withstand. To find the maximum force before damage occurs to the lettuce, and thus the maximum force requirement, the team conducted a crush test.

To conduct the experiment, the team 3D printed the cups with tapped threads in the back to securely connect the base and load cells. This experimental setup is shown in Figure 2.8.
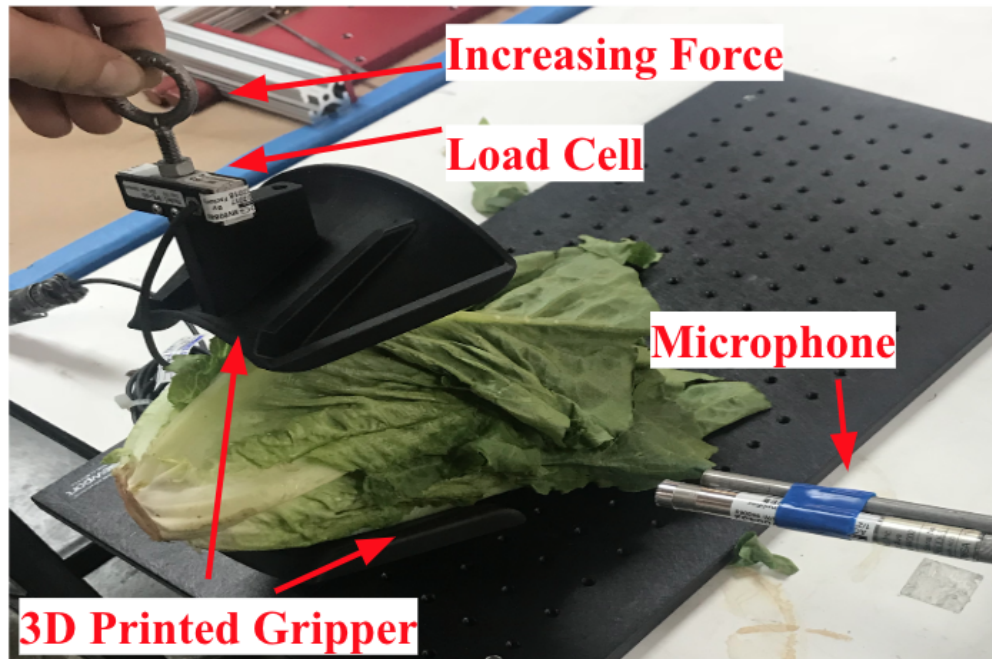
Figure 2.8: Experimental Setup for Lettuce Squeeze Tests

An increasing load was then applied to the lettuce until the lettuce failed under compression. The farm indicated that audible cracking to the lettuce would indicate internal damage, so failure was identified with a microphone. Noise greater than 0.2 dB was considered significant cracking.
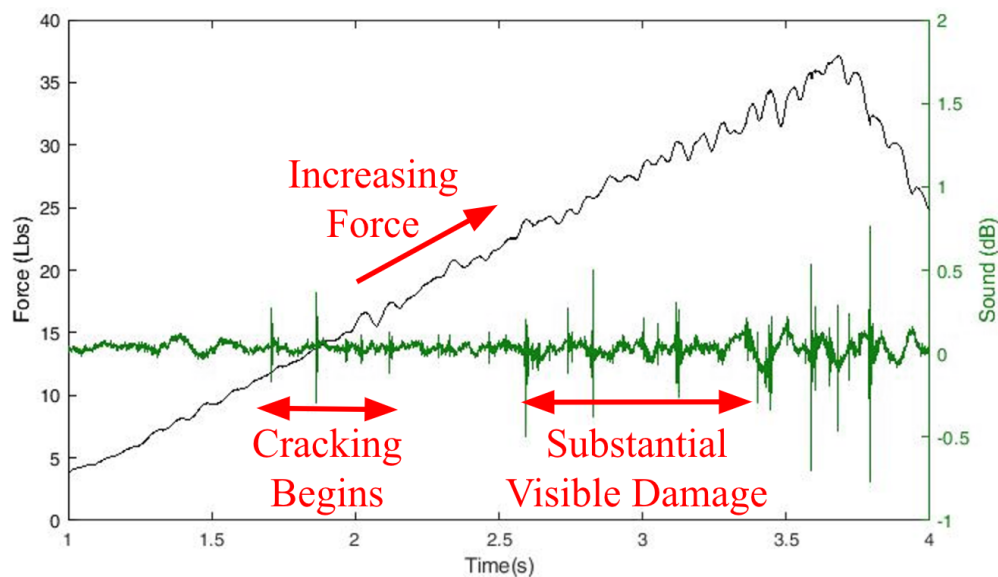
Figure 2.9: Lettuce Force (black) Vs. Lettuce Cracking (green).

The results of the experiment are presented in Figure 2.9, which shows that significant lettuce cracking begins to occur at about 12 lbf, so with a factor of safety of 2, the team determined that the maximum force the grippers should apply is 6 lbf.

2.4.4 Defining Rotational Speed with Throughput and Workspace Study

The rotational speed of the system to achieve a throughput requirement of 2 seconds per head is highly dependent on the size of the system and number of cups. The team conducted a workspace study to find the optimum balance between the overall size of the system and number of grippers to maintain the desired throughput. To do this, an estimate of a "human workspace" overlapping with a "lettuce path" was used to create a "loading workspace", shown in Figure 2.10.
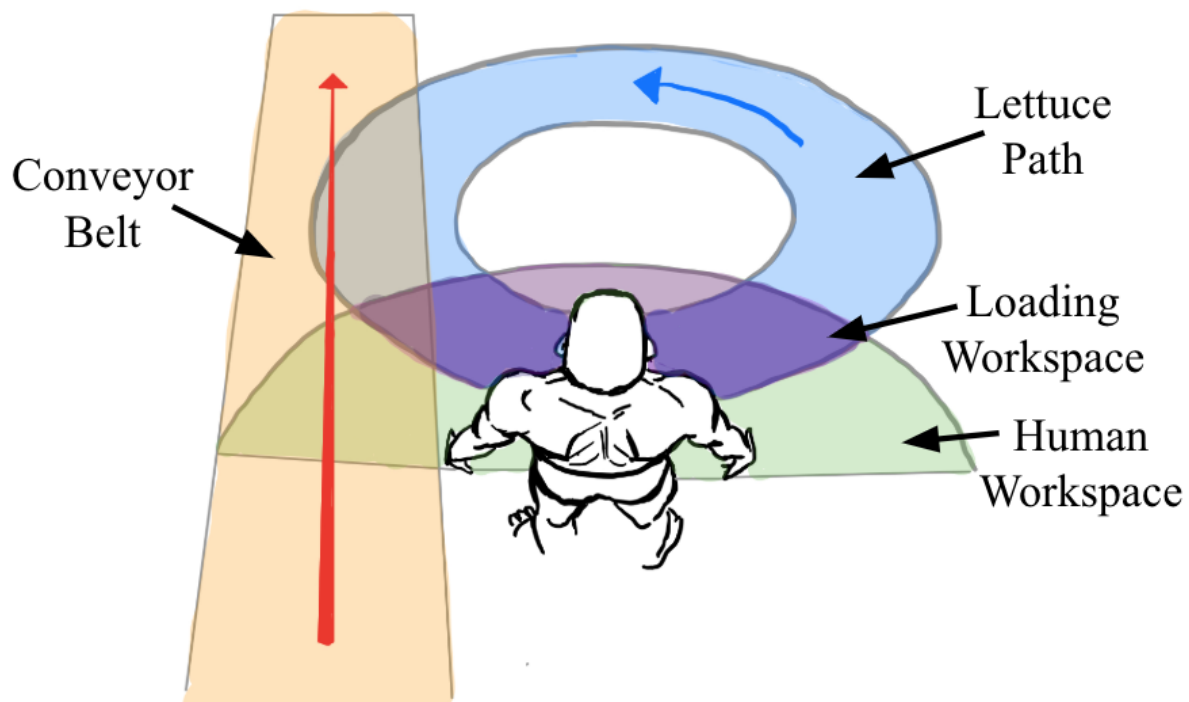
Figure 2.10: Interface Between Lettuce Path and Human Workspace

Using this simulated workspace, the team created a spreadsheet so that an input radius of the lettuce path (directly related to overall system size) and known cup size constraints could be used to calculate the rotational velocity and number of cups required to match the 2 second per lettuce head throughput requirement. The results are shown below in Table 2.7.

Table 2.7: Workspace Calculations

Inputs				Outputs						
Lettuce Diameter (in)	Radius of Lettuce Path (in)	Throughout (#Lettuce/min)	Workspace Angle (Deg)	Workspace Arc Length (in)	Theta (deg)	# Cups	RPM	Tangential Velocity (in/s)	Worktime (s)
13	8.5	30	120	17.80	99.76	3	10.00	8.90	2.00
	9			18.85	92.48	3	10.00	9.42	2.00
	10			20.94	81.08	4	7.50	7.85	2.67
	11			23.04	72.44	4	7.50	8.64	2.67
	12			25.13	65.59	5	6.00	7.54	3.33
	13			27.23	60.00	6	5.00	6.81	4.00
	14			29.32	55.33	6	5.00	7.33	4.00
	15			31.42	51.36	7	4.29	6.73	4.67
	16			33.51	47.94	7	4.29	7.18	4.67
	17			35.60	44.96	8	3.75	6.68	5.33
	18			37.70	42.34	8	3.75	7.07	5.33
	19			39.79	40.01	8	3.75	7.46	5.33
	20			41.89	37.93	9	3.33	6.98	6.00

The number of cups are determined by taking into account the maximum size of a lettuce head, 13 inches, ensuring that there would not be interference during ejection. With the number of cups, the required rotational speed and thus tangential velocity to match the throughput can then be calculated. Finally, the tangential velocity along and an assumption of a 120 degree human workspace, the loading time can be found. Each row of the spreadsheet varies the radius of path, ultimately calculating the tangential velocity and loading time for a laborer. Looking at the permutations of the spreadsheet, a lettuce radius of 13 inches along with 6 cups was chosen. This system size and number of cups provides a loading time of 4 seconds, giving a human a time factor of safety of 2 to catch up loading the cups if there is a delay, while maintaining a compact system size and reasonable tangential velocity.

In addition to averaging 5 rpm to achieve the desired throughput, the system also has to be easily loadable, having a relatively constant speed. If the speed varies too excessively throughout the cycles it could result in the operator mistiming a load and missing the cup, resulting in them

falling behind. Also by maintaining a constant speed this allows for the operator to fall into a rhythm, improving their overall workflow and efficiency. Through discussions with the partner farm, it was decided that a tolerance of $\pm 10 \%$ would be adequate for achieving easy loading. This results in the final derived speed requirement of 5 ± 0.5 rpm.

2.4.5 Conclusion: Derived Requirements from Needs

With the additional testing and analysis the team arrived at a final summarized list of quantified requirements, presented below in Table 2.8, that would serve as metrics upon which the product could be verified through testing (discussed in Chapter 8).

Table 2.8: Complete Quantified Product Requirements

Need	Requirements	Value	Tolerance	Units
Holds Lettuce Upright	Gripper Gripping Size	3	± 0.5	in
Rapid Loading	Gripper Loading Size	4.25	± 0.5	in
Full Ejection	Gripper Ejection Size	8	± 0.5	in
Consistent Stalk Height	Height Variation of Lettuce Stem	0	$+ 0.00$ $- 0.25$	in
Does not damage lettuce	Grip Strength	6	± 1	lbf
Constant Speed	Rotational Speed	5	± 0.5	RPM
Match Harvesting Rate	Lettuce Head Throughput	2	± 0.1	secs/head

With these established system-level requirements, the team then sought to break them up by subsystem so they could serve as design metrics for each component. The following section presents an overview of the team and project managements steps taken to ensure the team's ability to meet these requirements.

2.5 Team and Project Management

2.5.1 Project Challenges and Constraints

The primary project challenge was the available time the team members had to do design, analysis, and manufacturing for the system. The Partner Farm was expecting results quickly, at the rate of a contractual engineering firm, but the 3 team members were also full-time students and taking other courses. To overcome this, the team was taking what would be a 5-month full-time development project and turning it into a 9-month Senior year capstone project.

Another constraint was the ability of the team to test the prototype on real full heads of romaine lettuce for verification and iteration. The lettuce was only ready for harvesting in the Fall and Spring, so when the team was doing much of the design and analysis in the Winter they had to rely on previously taken measurements. Not having physical lettuce to test with also increased the importance of designing a highly compliant and adjustable prototype that can be dialed-in once lettuce was harvested again in the Spring.

2.5.2 Available Budget

Table 2.9, below, highlights some of the received income from sources such as the SCU School of Engineering. As-needed, flexible funding was also available from the Partner Farm Contract Grant with Dr. Kitts. Much of the prototyping costs were covered by the SOE, but the final manufacturing and assembly costs would be taken over by the Partner Farm and their team as they are the final recipients of the system.

Table 2.9: Income Amounts from Various Sources

Description	Source	Amount ($)	Notes
SOE Funding	SOE	1500	$500 per team member
Farm Contract	Dr. Kitts	~2500	Flexible as needed from contract with Partner Farm in Salinas
		4000	TOTAL INCOME ($)

With this established budget, the team felt confident they could build a prototype that would address the needs and meet the requirements of the Partner Farm. The results of the cost of the prototypes and ability to meet the budget are presented in Chapter 9.

2.5.3 Timeline

The team strove to build a function metal prototype system with working gripper, indexer, superstructure, and mechatronics subsystems in time for demoing at the Senior Design Conference in early May of Spring Quarter. All other timeline requirements, such as conceptual design, CAD, analysis, drawings, ordering, and manufacturing were derived backwards from this deadline.

A Gantt chart, Appendix C2, created via the team's internal action item and milestone tracking software, Trello, showcases the previously mentioned deadlines. It shows the dependencies, tasks that must be complete before beginning subsequent tasks, and opportunities for parallelization.

2.5.4 Design Process Approach

The team followed a traditional engineering design process, moving from conceptual designs and proof-of-concept prototypes to initial analysis and eventually final design, drawings, and manufacturing. The team aimed to use design thinking and human-centered-design principles for brainstorming and concept generation.

Prototypes were made to be highly adjustable so that exact features such as size, compliance, and linkage geometry could be quickly adjusted on-site when romaine lettuce was available. Prototypes were also fully realized with CAD software, SolidWorks, before hands-on building began. The team heavily used laser cutters and 3D printers to make prototypes so that they did not need to rely on the SCU Machine Shop's availability.

Where possible, the team used simulations and analysis techniques to verify designs before manufacturing was done or components ordered. Finite Element Analysis (FEA) with SolidWorks and Kinematic/Dynamic Modeling with MATLAB allowed the team to ensure the system would be strong enough to withstand abuse and spin continuously.

2.5.5 Risks and Mitigations

As discussed in section 2.5.1, the primary risks to the completion of the project was the timeline and ability of the team to meet the aggressive deadlines. To mitigate this, parts of the project had to be scaled back since the team was unable to complete everything. For example, the team initially conceptualized a trimmer that automatically bagged the romaine hearts upon ejection, but this would require a new bag design that could accommodate automated loading, and so was too difficult for the team to accomplish in this year-long project.

Another risk was the team's ability to collaborate on designing multiple subsystems without losing data or communication. This was mitigated through the use of cloud-based software for project management (Slack, Google Drive, Trello) and CAD files (GrabCAD Workbench for SolidWorks). The team also met at least three times a week to collaborate and stay in constant communication. Potential risks to the project's success and their corresponding consequences and mitigation strategies are outlined below in Appendix C5.

2.6 Conclusion: Proposed System

As a result of customer interviews and benchmarking, the team came to the conclusion that the best solution would consist of 4 main subsystems: gripper, indexer, mechatronics, and superstructure. The grippers are the interface between the lettuce and the system, holding the lettuce firm but not crushing it, and fully ejecting the lettuce after it is trimmed. The indexer holds 6 grippers and rotates them through the different stages. The mechatronics drive the indexer and grippers around the central pivot at a constant speed. Lastly, the superstructure is

responsible for the zeroing of the lettuce stalk height and for attaching all of the other subsystems to a sturdy base. The complete assembly of these subsystems is shown in Figure 2.11.
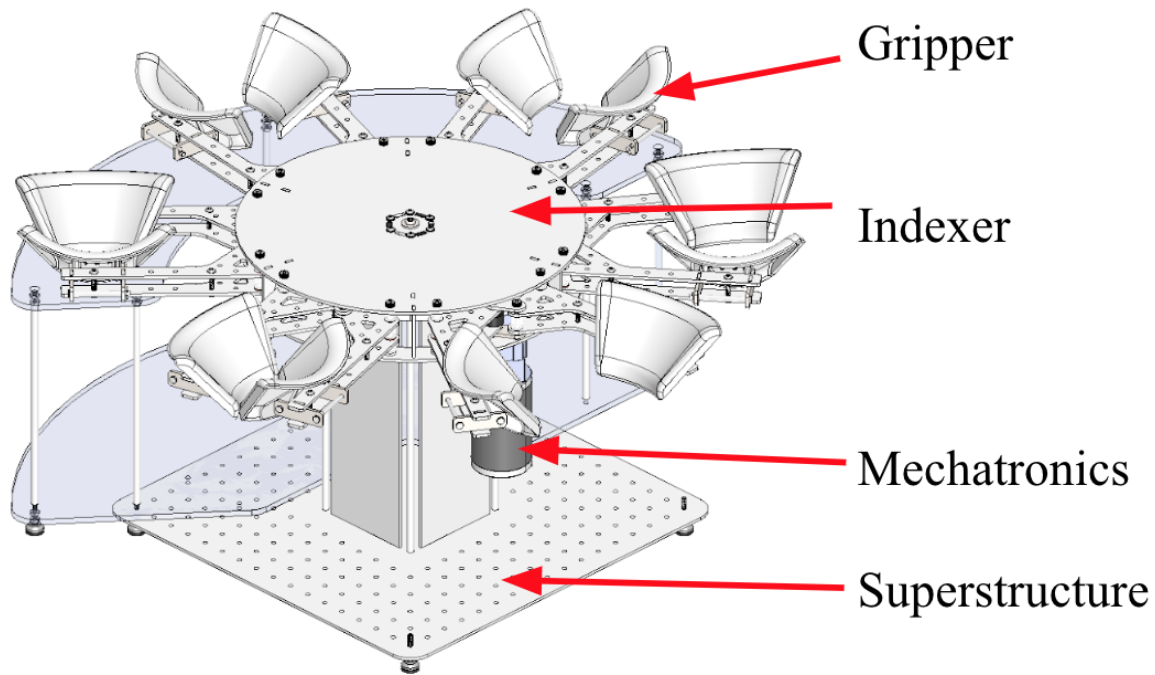
Figure 2.11: System Level Sketch of Romaine Robotics Trimmer Prototype

All of these subsystems were designed to meet the requirements determined in Section 2.4, and utilize the design process described in Section 2.5.4. In the following chapters, the detailed design and analysis of each subsystem will be discussed and then the verification of the system requirements are presented in Chapter 8.

3. Gripper Subsystem

3.1 Introduction

The farm emphasised to the team that improving the gripper subsystem, shown in Figure 3.1, was a high priority. The gripper subsystem's job is to physically interface with the romaine hearts, accepting the lettuce from a human laborer during a loading stage, holding the lettuce tightly during a gripping stage, and finally fully releasing the lettuce in the ejection stage.
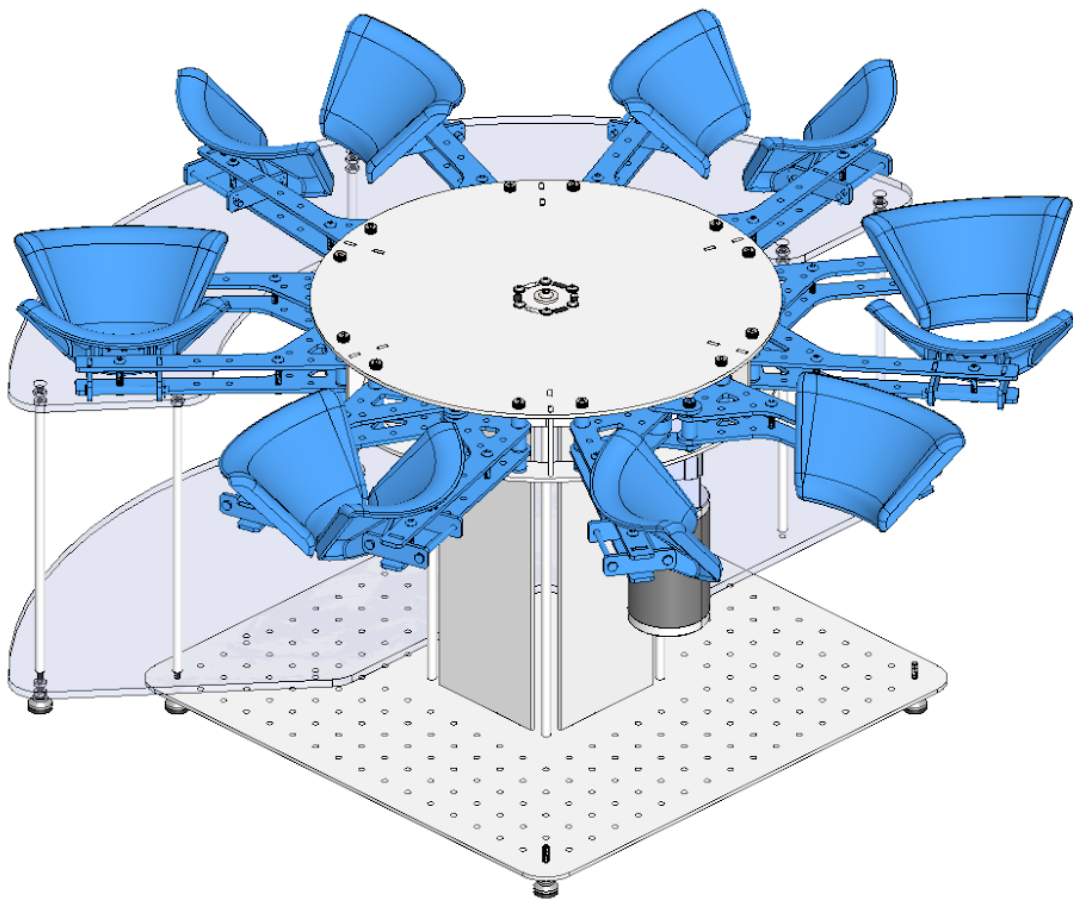
Figure 3.1 CAD Design highlighting Gripper Subsystem

3.2 Desired Characteristics and Requirements

3.2.1 Loading

The heads needed to be easily loaded by a human operator standing between the conveyor and rotating indexer of the trimmer. From rapid prototyping and customer empathy gathering, the team determined that as opposed to the farms original system, which had grippers open for ejection and then later closing around the lettuce, the best method for loading is to put the heads in while the cups are lightly sprung-loaded closed with a new loading stage.

3.2.2 Ejection

After trimming the head, still surrounded by loose leaves in the grasp of the gripper, it must be ejected and dropped back onto the same conveyor. Another laborer standing downstream can then pick out the quality heads allowing waste leaves to drop back onto the field.

The farm's original trimmer design had grippers that did not open wide enough, often resulting in large heads of lettuce getting stuck in the gripper, jamming the machine. In these cases, laborers would have to manually perform ejection, wasting valuable time and creating a safety hazard reaching over the machine. Thus, improving the ejection process became a focus of our design effort.

3.2.3 Pressure Distribution

The romaine hearts, and to an extent the outer head leaves, feature brittle veins that should not be cracked or bruised by the gripper in order to guarantee high quality product. The farms original design has simple conical hard plastic gripper cups that by themselves did not offer compliance or distribute pressure. Determining the optimal pressure, cup geometry, and compliance to avoid crushing also became a design emphasis.

3.3 Summarized Options and Tradeoffs

3.3.1 Gripper Concept Generation

The team chose to break apart the overall gripper into two primary functions: geometry and material. The gripper geometry (Appendix Table B.2) determines the way in which the gripper moves when actuated by the cam to squeeze the plant and largely affects the gripper's loading, ejection, and grip strength. The gripper material (Appendix Table B.3) is the texture, shape, and compliance of the parts that touch the romaine head and largely impacts the grip strength, pressure distribution, cost, and durability.

3.3.2 Gripper Concept Refinement: Weighted Scoring Matrix

To quantify the quality of each of the gripper cup designs a scoring matrix was generated. The designs were scored based on 7 criteria, each of which were assigned a weight based on how crucial it was to the overall design. The weighting of the criteria is shown in Table 3.1.

Table 3.1: Criteria Weighting for Gripper Cup Desired Characteristics

Criteria	Loading	Ejection	Grip Strength	Pressure Distribution	Low Cost	Durability	Manufacturability
Weight	25	25	10	10	5	15	10

Based on the criteria weighting, all of the concepts were scored as shown in Table 3.2, where each concept consisted of a gripper cup geometry and material. The team members brainstormed each concept and then individually scored each component before coming together to discuss their rankings and normalize their scoring schemes to come up with a final score for each concept. The full Scoring Matrix with individually assigned scores for each concept can be found in Appendix Table B.6.

Table 3.2: Results of Scoring Gripper Cup Concepts

Gripper Geometry	Gripper Material	SUM
Conical (Reference)	Hard Plastic (Reference)	430
Conical	Compliant Silicone	400
Conical	Compliant Foam	365
Conical	Air Bag	215
Two Level	Hard Plastic	415
Two Level	Compliant Silicone	395
Two Level	Compliant Foam	360
Many Fingers	Hard Plastic	235
Many Fingers	Compliant Foam	160
Ribbed	Hard Plastic	415
Ribbed	Compliant Silicone	385
Ribbed	Compliant Foam	350

The results of the scoring matrix, indicated by the scores in the SUM column, point to the Hard Plastic Conical cups, being the best gripper concept to pursue due to its high durability and manufacturability. As a result of the decision to use hard plastic for the cups, the compliance required for not damaging the lettuce will be achieved with sprung-loaded pivot points in the gripper linkage.

3.4 Gripper Analysis

3.4.1 Gripper Cup FEA and Hand Calculations

The team then performed a finite element analysis simulation of the cup using Solidworks to analyze the stresses that develop within a cup. The cup was fixed at the two mounting holes with a surface load applied to the center of the cup shown in Figure 3.2.
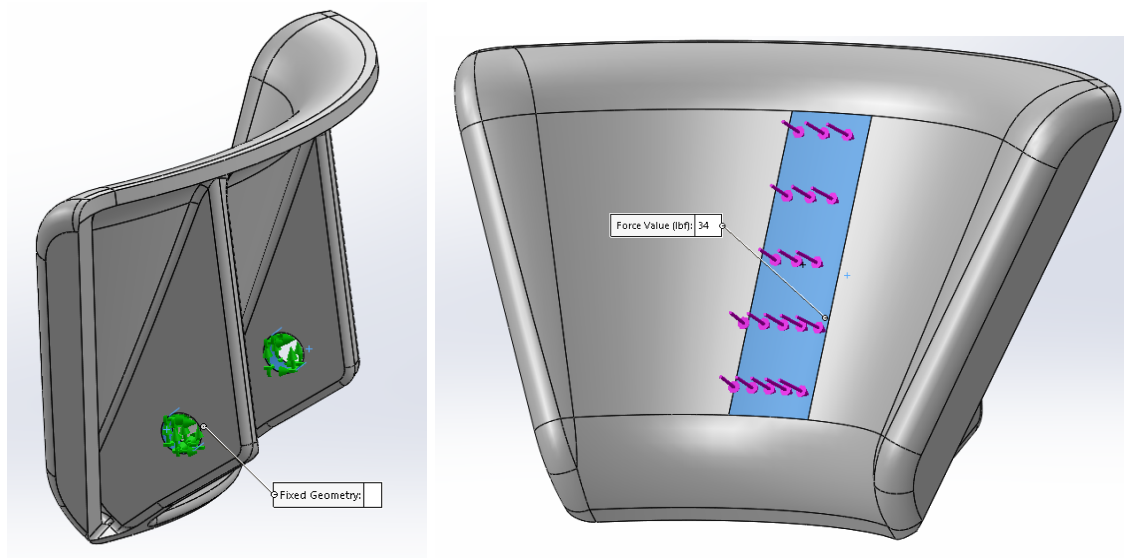
Figure 3.2: Cup FEA Fixturing and Loading Locations

The load applied was 34 lbs as this was found to be the point at which the most severe damage to lettuce occurs (see Section 2.4.3). This load was distributed over a surface area of 1.725 in^2, the approximate area of a lettuce vein pressing the cup shown in Figure 3.3.
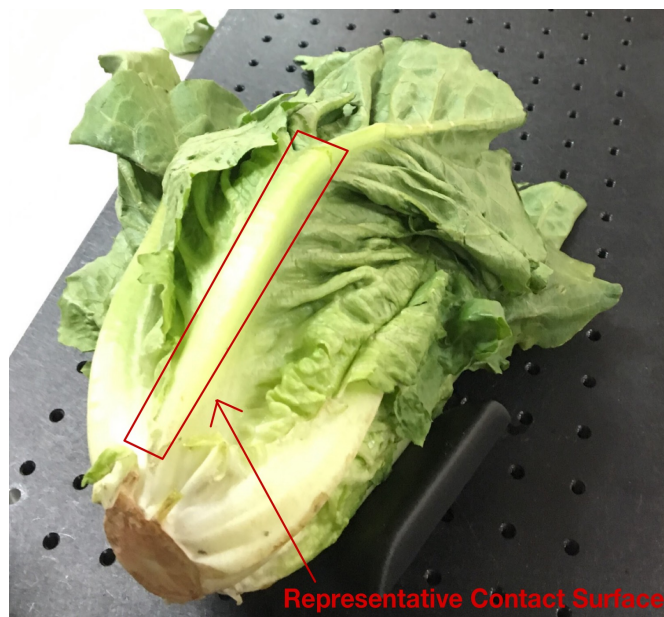
Figure 3.3: Lettuce Contact Area

The results of the FEA simulation are presented below in Figure 3.4.
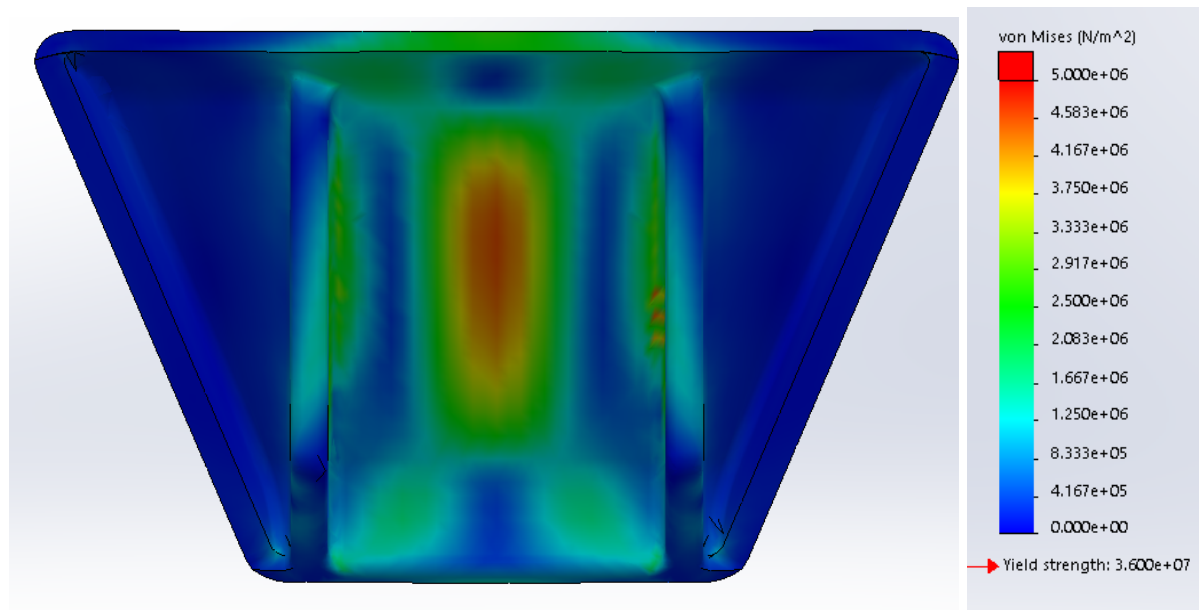
Figure 3.4: FEA Stress Contour Plot of Loaded Cup shows Factor of Safety of ~7

To verify the results of the FEA, hand calculations were also conducted shown in Figure 3.5.
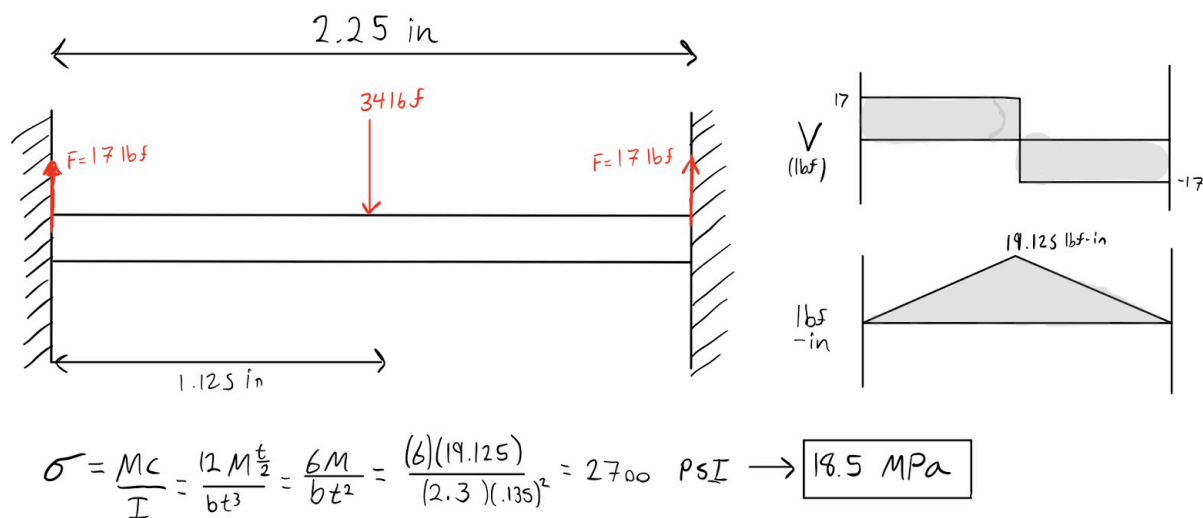
Figure 3.5: Hand Calculation using Simply Supported Beam Assumption

The system was modeled as a beam fixed on both sides with a point load applied to the center, shown in Figure 3.6.
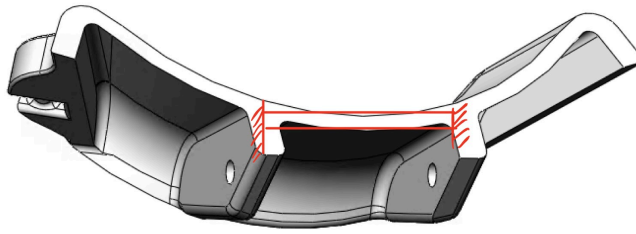
Figure 3.6: Cross Section of Hand Calculation Location

From this calculation the maximum load was found to be 18.5 MPa. This was roughly 4.5 times larger than the maximum load found in the simulation. This difference can be attributed to the fact that the hand calculation assumes the cup to be a flat beam with a constant thickness of 0.135 in. The stress is also reduced by the support material, shown in Figure 3.7.
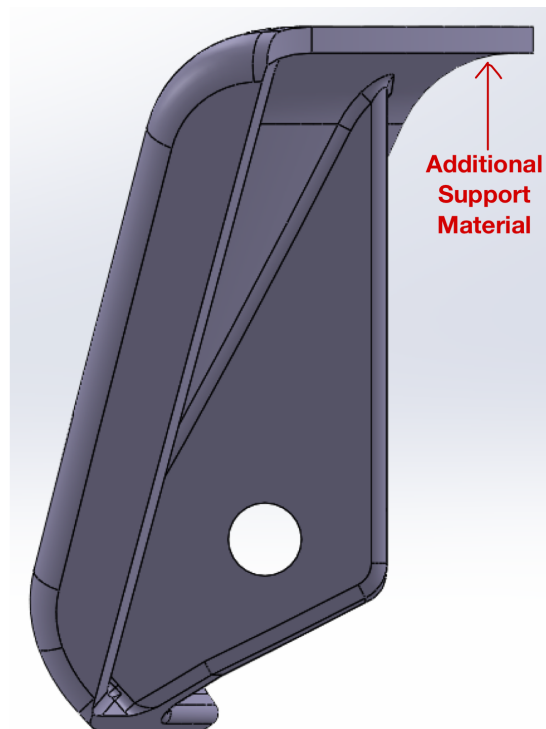
Figure 3.7: Cross Section of Hand Calculation Location

The goal of analyzing the gripper cups was to verify that the cup would not reach the yielding point under the expected loading conditions found from physical testing. The simulation showed that the maximum stress that the cup is likely to encounter is around 4 MPa, about 7 times lower than the yielding point for the material. In addition, the hand calculation confirmed that for even a worst case simplified beam, the safety factor is around 2. Finally, to avoid crushing the lettuce, the actual applied load these cups would be subjected will be no more than 6 lbf, meaning these safety factors would actually be about 5x as large as this worst-case analysis predicted. Therefore the analysis of the cup has proved that given the current geometry of the cups, they will not fail under the worst case loads.

The team determined that the 3D printed plastic cups are sufficient for both not crushing the lettuce as long as the grip strength is kept below the measured 6 lbf and also strong enough to not yield or deform at this grip strength.

3.4.2 Gripper Linkage Abuse Case: Loading and Fixturing

Another important analysis the team performed was a confirmation that the design and material selection of the gripper and indexer result in a system strong enough to withstand abuse cases. After discussions with the partner farm, the team concluded that the most likely worst case loading that the system should be expected to withstand was a laborer leaning on the system, applying a downward force to the ends of the grippers that translates to a moment experienced by the gripper about its pivot points and by the indexer about its dead axle shaft (described in Section 4.7). Separating the cases allowed for individual analysis of failure modes. The team analyzed each of these cases using both hand calculations and FEA to determine if the system would fail if a laborer were to apply a downward force of 100 lbs on the outer tips of the gripper shown in Figure 3.8.
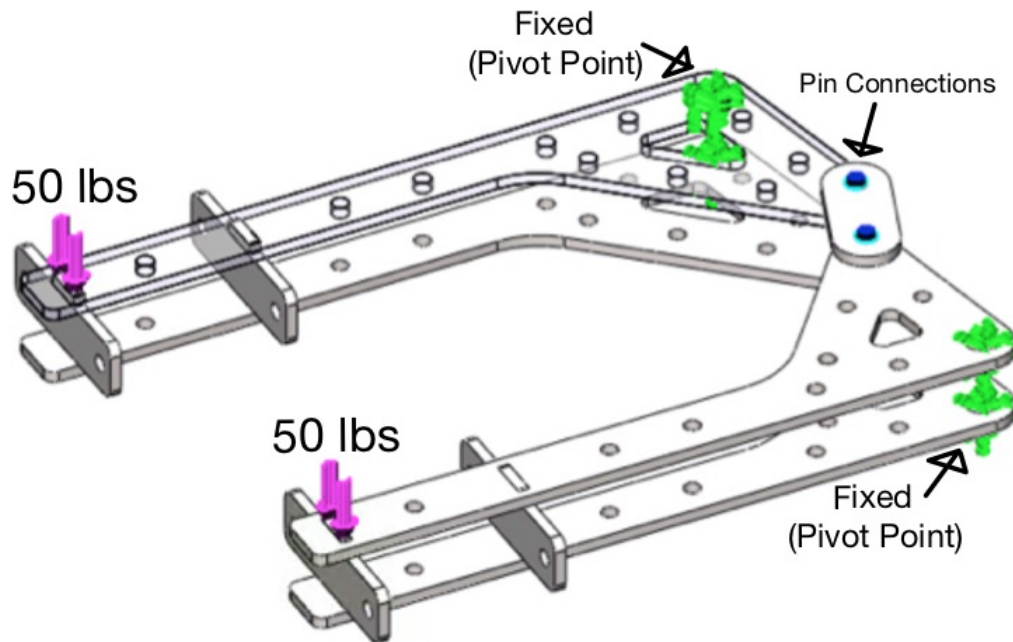
Figure 3.8: Gripper Loading (50 lbs at each tip) and Fixturing (fixed at pivot points)

The team conducted an FEA on the entire gripper, so that the two sides could work together to resist the downward force of 100 lbs (split evenly on each side). The gripper is assumed to be fixed at each of the pivot points, which is a fair assumption since the pivot consists of oil-embedded bronze bushings on a stainless-steel shoulder bolt, resulting in a tight fit that should be fixed relative to the bending axis. Standard SolidWorks mesh quality and default tetrahedral pattern worked well, showing no singularities or meshing issues.

3.4.3 Gripper Linkage Abuse Case: Hand Calculations

The team expected the gripper to failure mode to be bending in the span of unsupported material between the applied load and the fixed pivot point. The two parallel plates offer high resistance to bending, but still are relatively thin and thus there is potential for failure due to bending and the lack of a shear wall connecting them.

As shown in Figure 3.9, the team performed a hand calculation by simplifying the complex geometry of the parallel plates with numerous holes into a simple beam of the gripper arm's length fixed at one end and subjected to the downward load of 50 lbs at the tip. The moment of inertia of the two parallel plates was converted to an equivalent moment of inertia about the bending axis using a moment of inertia for rectangular beam and the parallel axis theorem.

$$I = 2[I_0 + Ay^2] = 2\left[\frac{bh^3}{12} + bh\left(\frac{.822}{2}\right)^2\right]$$

$$I = 2\left[\frac{(.722)(.1345)^3}{12} + (.722)(.1345)\left(\frac{.822}{2}\right)\right] = 0.0331 \ in^4$$

$$F = 50 \ lb \qquad L = 8.35 \ in$$

$$M_{max} = FL = 417.5 \ in\text{-}lb$$

$$\sigma_{max} = \frac{Mc}{I} = \frac{(417.5)(.478)}{.801} = \boxed{\begin{array}{c}6000 \ PSI \\ \sim 4.2e7 \ \frac{N}{m^2}\end{array}}$$
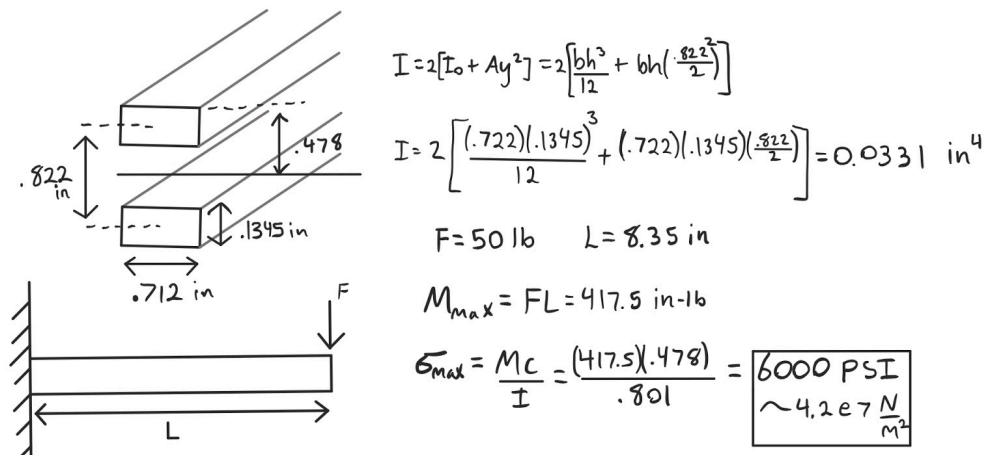
Figure 3.9: Gripper Hand Calculation Analysis using Simplified Fixed Beam in Bending

This calculation results in a maximum tensile stress due to bending at the pivot point (where the moment is maximum) of about $4.2*10^7$ Pa. This is a safety factor of over 8 from the tensile yield stress of the 1020 HR Plain Carbon Steel ($3.52*10^8$ Pa) and thus the team does not expect the gripper to fail due to this loading.

3.4.4 Gripper Linkage Abuse Case: FEA Results

The gripper FEA results, shown below in Figure 3.10, revealed that, as expected from the hand calculations, the gripper would not fail under such loading. However, the stress ($2.5*10^8$ Pa) is quite a bit higher than the hand calculations ($4.2*10^7$ Pa). This may be due to stress concentrations arising at the holes of the pivot points that were not factored into the hand calculations. Despite this, the stress is still well enough below the tensile yield stress of the steel plate (Safety Factor of 1.4 is sufficient) and so the team moved forward with this design.
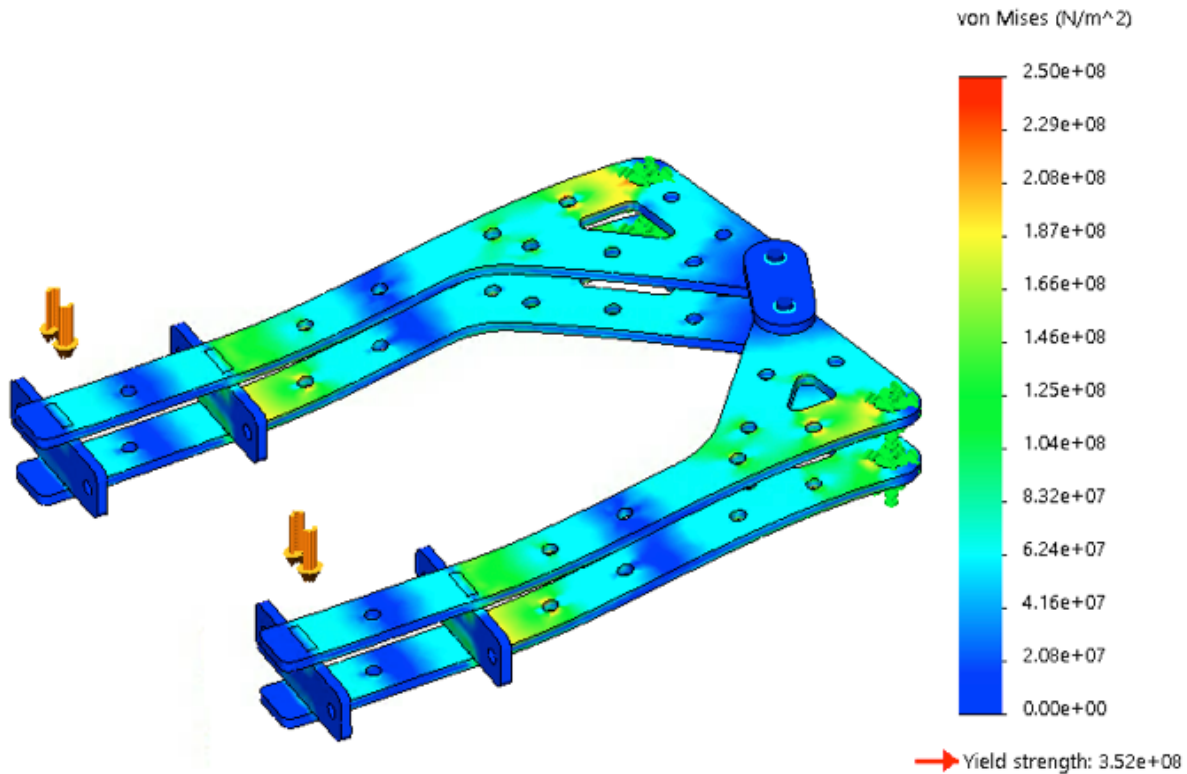
Figure 3.10: Gripper FEA shows max stress of $2.5*10^8$ Pa, a 1.4 Safety Factor

3.5 Gripper Subsystem Conclusion

It was determined through the physical testing of the acceptable applied loads on the lettuce heads that crushing the lettuce is not a very large concern if the force is kept at a reasonable 6 lbs. Similarly, the Gripper Linkage FEA and Hand Calculations showed the structure would survive the abuse case, and so the parallel steel plate design with a 3D printed conical cup continued to be the primary design and was manufactured. Discussed in Chapter 8, the assembled gripper worked well in testing, and successfully gripped the lettuce without crushing it. Overall, the gripper subsystem is a success and the team has improved the gripper compared to the partner farm's existing version.

4. Indexer Subsystem

4.1 Introduction

The team was also tasked with improving the indexer subsystem, shown in Figure 4.1, which is responsible for actuating the gripper so it is in a compliant state for loading by a human, a tight gripping state for feeding through the blades, and an open state to eject the trimmed heart and excess leaves so they can fall back onto the conveyor belt to be carried to the packaging stage.
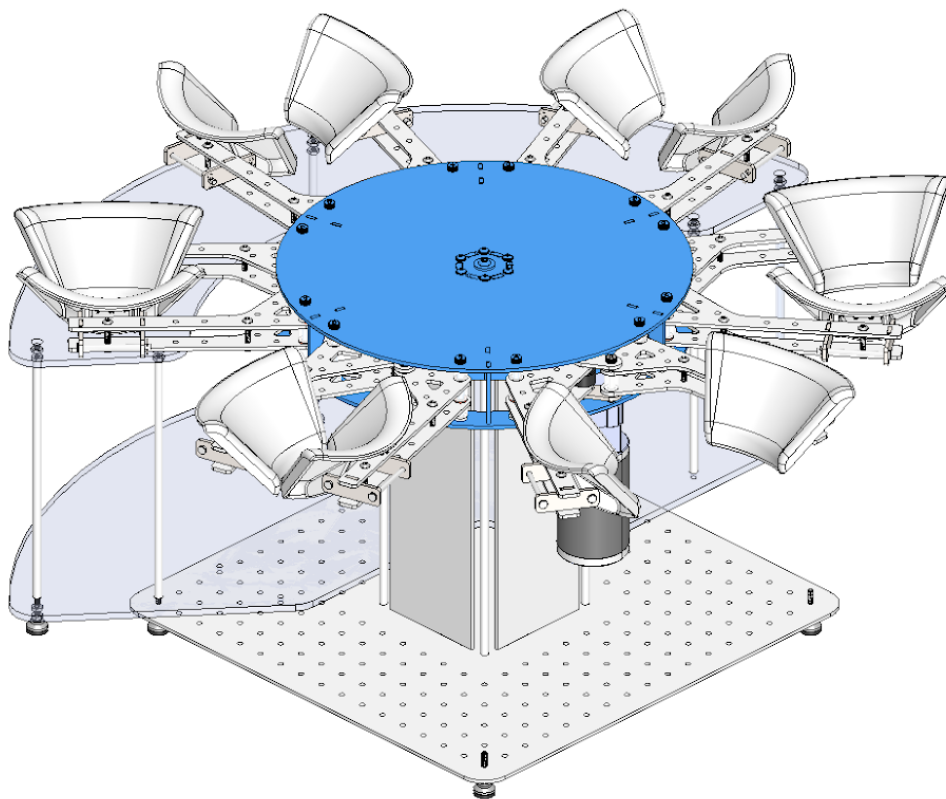
Figure 4.1 : CAD Design highlighting Indexer Subsystem

The Partner Farm's current system struggles to hold the lettuce vertically, due to a weak gripping stage, and also fails to fully eject the lettuce, resulting in frequent jams.

4.2 Desired Characteristics and Requirements

The following sections outline the primary characteristics to improve in the indexer redesign.

4.2.1 Loading

For loading, it is desired that the lettuce can be easily loaded by an operator while at the same time ensuring the vertical alignment of the heart. The operator picks up the untrimmed head off the conveyor belt and needs to quickly (~2 seconds) place it into the gripper, pushing it down so that the cut stalk rests against a horizontal surface. This serves two purposes. It "zeroes" the height of the stalk so that a single camera can be used for a machine vision estimation of the stalk diameter (and thus a determination of the ideal trim height and where to raise the cutter). Also, pushing the stalk down makes it rest "normal" to the horizontal surface, thus guaranteeing the head is sitting upright in the gripper and the trim will be perpendicular to the stalk axis. Thus, the loading stage of the indexer should have a compliant, but mostly closed gripper through which the operator pushes the head until its stalk zeroes off a horizontal surface.

4.2.2 Grip Strength

Once the lettuce is loaded to the zeroed location and upright, the indexer must increase its grip strength so as to tightly hold the head and prevent it from falling down or tilting over. If either of the characteristics change, during the machine vision or cutting processes, then it cannot be guaranteed that the trim will be correct and accurate.

Therefore, the gripping stage of the indexer must allow the gripper to close fully, and the closing force must be between 5 and 7 lbs, as measured at the center of the gripper, so that the strength is large enough to hold the lettuce but not so strong that it would crush it (see Section 2.4.3 *Defining Grip Strength with Lettuce Load Testing*).

4.2.3 Ejection

Once trimmed, the heart and excess leaves must be fully ejected from the gripper so it is empty and ready to receive the next head. This ejection must work reliably, without jamming, and require no assistance from the operator. The current trimmer in use by the Partner Farm is unable to successfully eject bushy heads and their large leaves 50% of the time, so this was an incredibly important element to improve upon in the team's functional prototype. Based off measurements of typical lettuce heads, the gripper should open to a diameter of at least 8" to reliably eject the heart and excess leaves.

4.3 Summarized Options and Tradeoffs

4.3.1 Indexer Concept Refinement

The partner farm's current indexer design works reasonably well and offers the correct features necessary for basic functionality, thus the team redesigned the geometry, while using the same overall architecture. The existing indexer, pictured below in Figure 4.2, consists of a indexer spun by a large shaft driven by the Lettuce Rotation Control subsystem.

Figure 4.2: Photo of Existing Trimmer Indexer Subsystem

The Indexer has multiple grippers mounted at fixed pivot points. At the base of each linkage, a follower wheel rolls along the edge of a large cam. As the cam radius increases, the wheel moves outward, pushing the linkage components and opening up the jaws of the gripper. The gripper cups are attached on pivots at the tip of linkage, allowing the conical cup to vertically adjust to accommodate different lettuce shapes.

The new indexer designed for the team's motorized prototype features largely the same architecture as the existing system described above, except the cam will have 3, as opposed to just 2 radii, allowing for unique loading, gripping, and ejection stages. Further, the linkage geometry was improved to open wider to improve ejection.

4.3.2 Indexer CAM and Linkage Design

To design the new indexer for the scale mockup, a large self-referencing sketch, shown in Figure 4.3, was created in SolidWorks to relate the loading, gripping, and ejection states to each other and the cam dimensions.
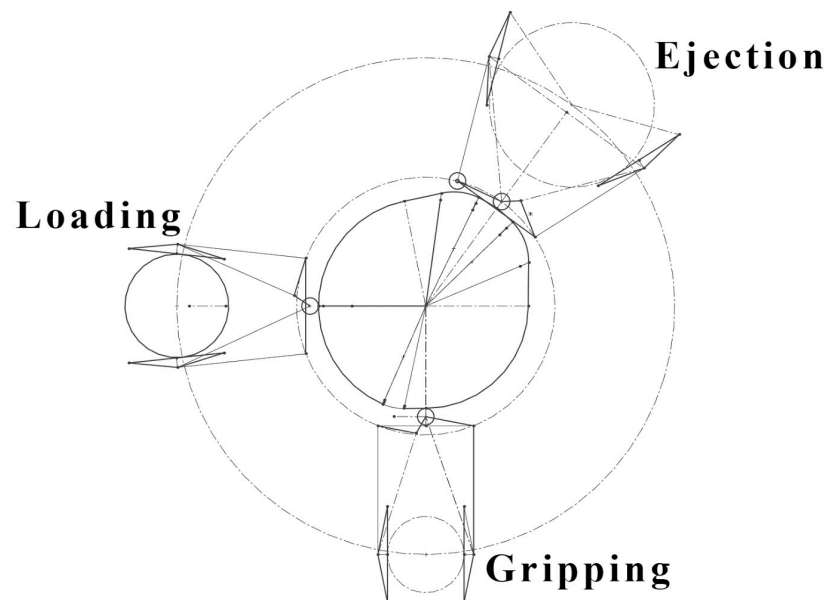
Figure 4.3: CAD Sketch of Cam and Linkage States to define geometry

This allowed for a very parametric and easily adjustable model. The only dimensions input were the diameter of the lettuce, the size of the scale model, and some of the cam and cup dimensions; the relations defined the linkage and everything else.

4.4 Indexer Scale Mockup

From the sketch defining all the geometry, a 3D model was made of a scale mockup version of the indexer (smaller to only hold 4 grippers), including the cam, linkage, and other structural elements (top/bottom indexer plates, central shaft, and base plate). Most of the plates were laser cut ¼" or ½" thick plywood. Pivot points and connections were made using #10-32 Button Head Cap Screws. The following figures illustrate some CAD renders alongside photos of the as-built physical mockup.
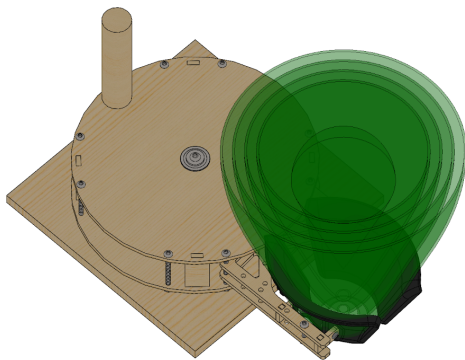
Figure 4.4: Mockup Render "Gripping"

Figure 4.5: Mockup Photo "Gripping"
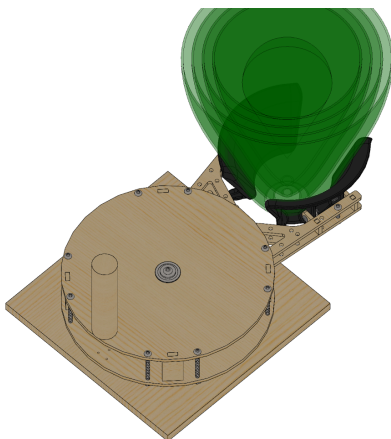
Figure 4.6: Indexer "Loading"
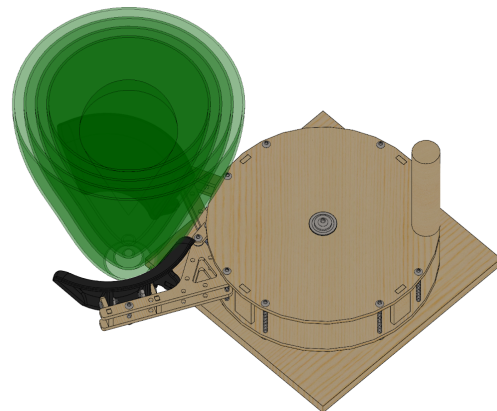
Figure 4.7: Indexer "Ejection"
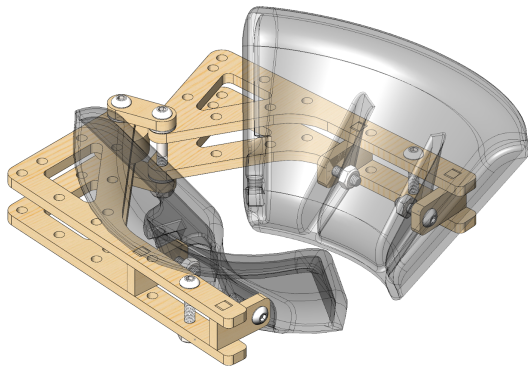
Figure 4.8: Linkage "Gripping"   **Figure 4.9:** Linkage "Ejection"
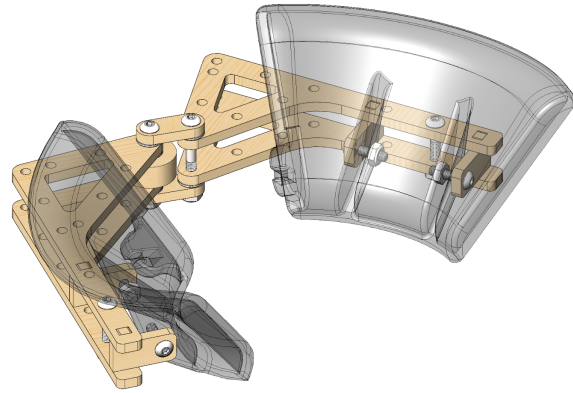
From the scale mockup, the team learned that their initial ejection state was not sufficient, and the cam would have to be redesigned to cause the grippers to open more during ejection. However, for the most part, the other states worked as designed (albeit the team did not have real lettuce from the field to test with in December).

4.5 Indexer Full Scale Mockup

Following the scaled mockup, the team built a full-size mockup in February, shown in Figure 4.10, that had the ability to hold the full 6 cups.
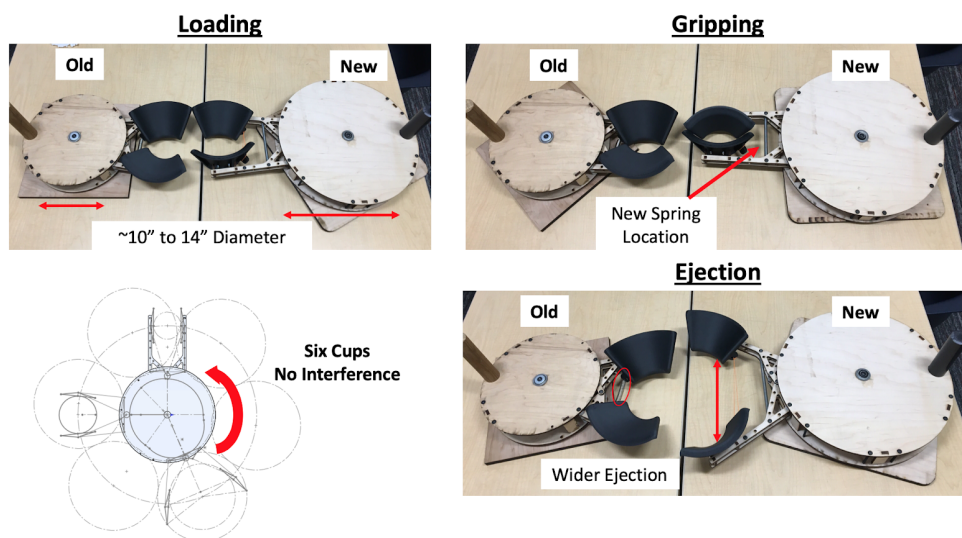
Figure 4.10: Full Scale Mockup Compared to Scale Mockup

This full size mockup would ensure that the next prototype, motorized and made of metal, could be accurately represented with a cheaper wooden mockup. As opposed to the former mockup that had the spring spanning the distance between the 3D Printed Cups, the new location moves the spring closer to the linkage pivots so the relative increase in spring length (and thus force) from gripping to ejection would not be as great, so the spring would have a more normalized grip strength through all stages. Additional springs were added between the linkage arms and the cups to pull the cups back and upright.

Overall, construction methods featuring laser cut plywood and screws remained the same. The full scale mockup also featured a new location for the linkage spring. Figure 4.10 shows the improved ejection, larger size, and new spring location of the full scale mockup compared to the original scale mockup.

4.6 Indexer Motorized Prototype

Building on the improvements found from the wooden mockups a metal prototype was designed. The design consisted of the same architecture as the wooden mockups, a top plate and bottom plate secured together with a combination of shoulder bolts and standoffs, with the fixed cam positioned between the two as shown in Figure 4.11.
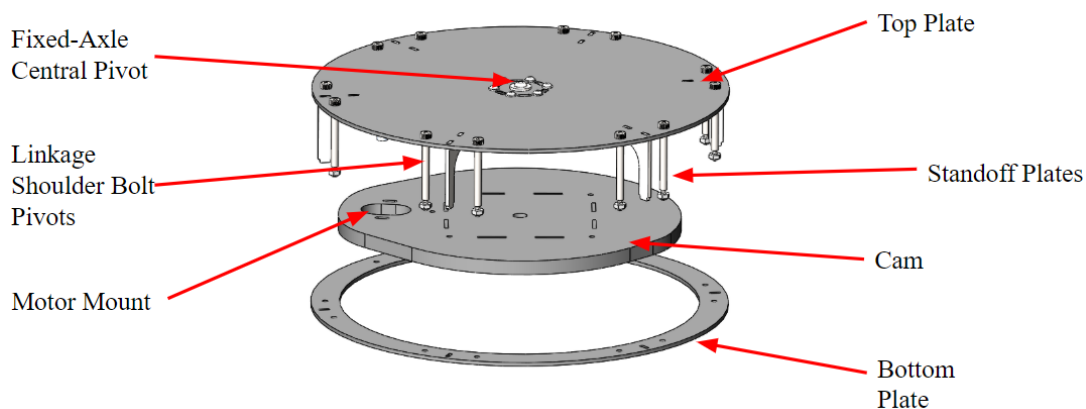
Figure 4.11: Motorized Metal Indexer Design

At the center of the top plate there is a central pivot fixed to the cam that the indexer rotates about. In addition, there is a hole pattern that allows for mating between a keyed versa-hub and the top plate for power transmission. The cam also has mating features that allow for the motor and superstructure tower to be fixed to it. All of the components of the Indexer were designed to be waterjet out of steel and assembled with COTS fasteners. This design ensures there is minimal machining required for the indexer and so that the system can be assembled with relative ease (see Chapter 7 for Manufacturing).

4.7 Indexer Analysis

4.7.1 Indexer Abuse Case: Loading and Fixturing

Continuing the abuse case presented in Section 3.4, the downward forces at the gripper were translated into a pure moment acting on the shoulder bolts that serve as the gripper's pivot points, shown in Figure 4.12.
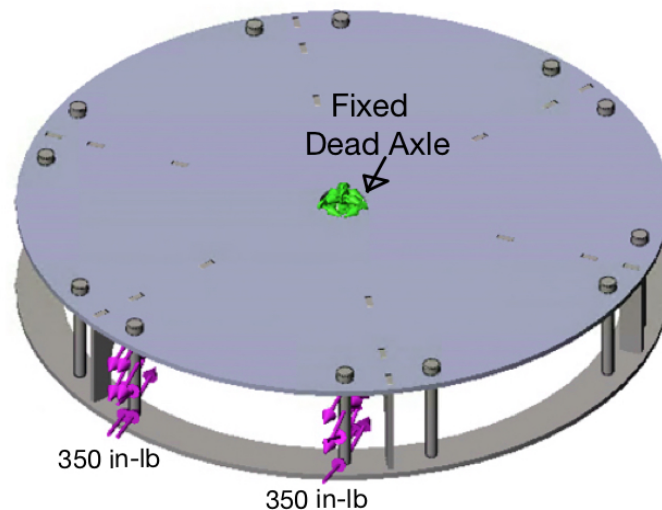
Figure 4.12: Indexer Loading (moment at pivot points) and Fixturing (dead axle pivot point)

The top plate is considered fixed due to it pivoting on a dead axle (a ½" solid steel rod in bearings). The bottom plate is considered fixed to the ends of each of the shoulder bolts (the bolts are tightened against the plate with locknuts), and take some of the bending loads.

4.7.2 Indexer Abuse Case: Hand Calculations

Similar to the gripper, the indexer could fail from tensile stress due to bending. The team simplified the indexer model by again assuming it to be a fixed beam but this time subjected to a moment at its tip. This moment is equivalent to the moment generated from the downward force at the tip of the grippers times the length of the gripper arms.

The team expected the failure to occur at the pivot point of the indexer, where the stress concentration is highest due to the pivot hole. Thus, the team performed the following analysis seen below in Figure 4.13 using a moment of inertia for just the top plate (assuming as a worst case that the bottom plate does not contribute at all to the bending resistance).
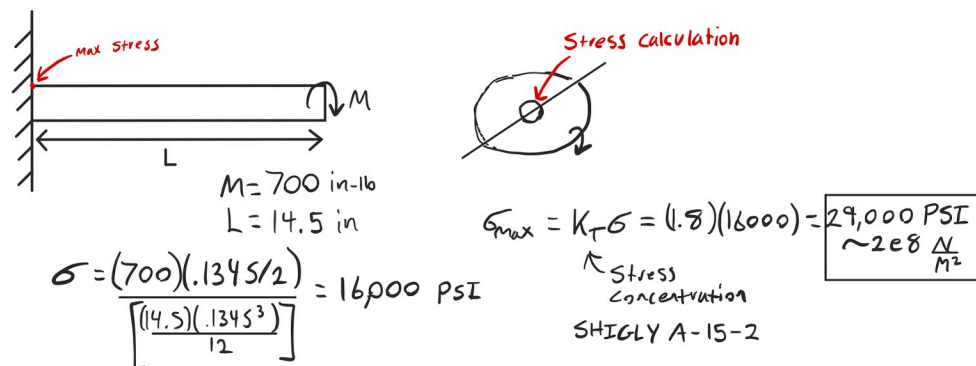
Figure 4.13: Indexer Hand Calculation using Fixed Beam with Applied Moment

The hand calculation shows a maximum stress of about $2*10^8$ Pa, which is a safety factor 1.8 relative to the tensile yield stress of the steel sheet ($3.52*10^8$ Pa). This safety factor is still above 1.5 and is sufficiently strong for this system and its limited life.

4.7.3 Indexer Abuse Case: FEA Results

The FEA on the indexer results shown below in Figure 4.14 align with the expected theory that the maximum stress will occur at the pivot where the hole creates a stress concentration.
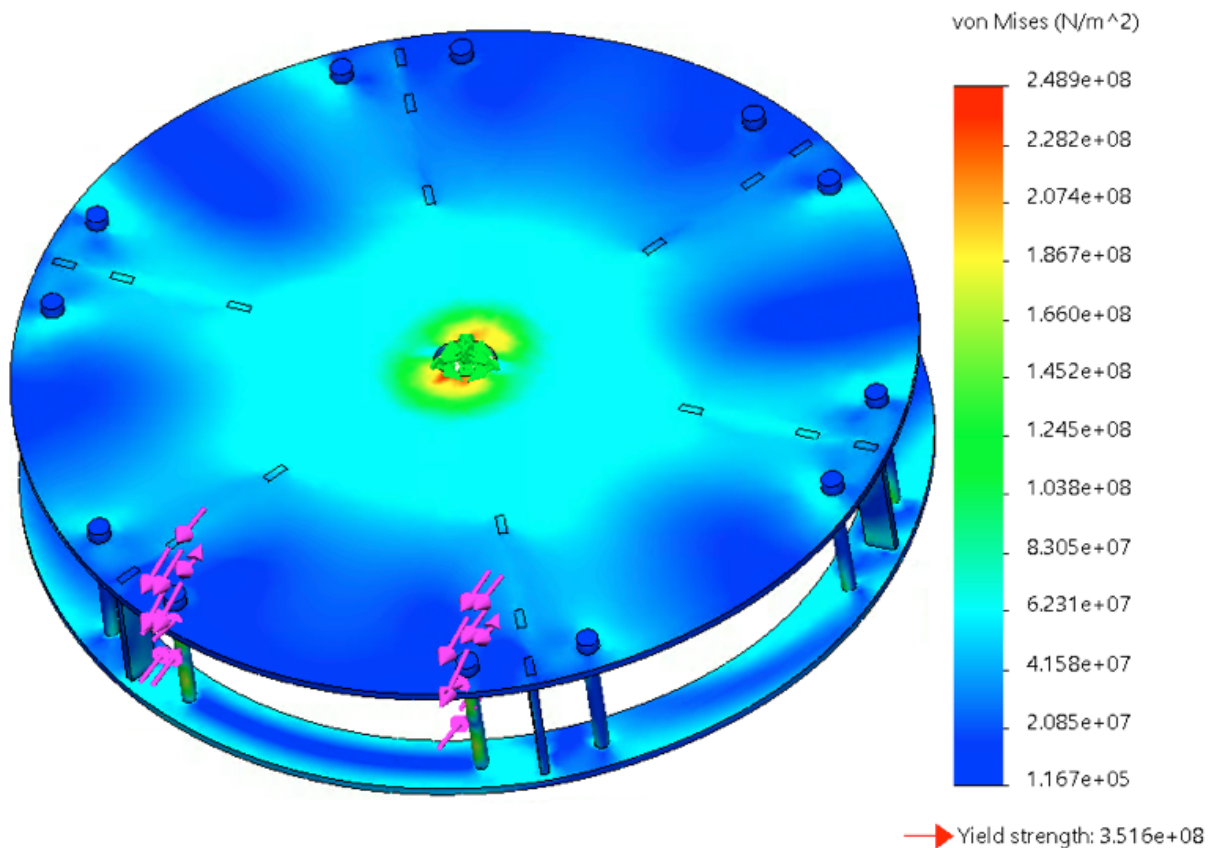
Figure 4.14: Indexer FEA Results show max stress of $2.49*10^8$ Pa, a 1.4 Safety Factor

The stress from the FEA is a bit higher ($2.49*10^8$ Pa) compared to the hand calculation ($2*10^8$ Pa) and this is likely due to the stress concentration. Also, the lower plate can be seen to be taking some of the moment load, helping reduce the stress seen by the top plate. This verifies the design, choice of material, and sheet thickness (10 GA Plain Carbon Steel, 0.1345in thick).

4.8 Indexer Conclusion

It was determined that the best way to achieve the desired characteristics for the loading, gripping, and ejection stages was to maintain the existing rotating indexer architecture but switch from a 2-stage to a 3-stage cam and tune the linkage geometry. These changes significantly improved the ease of loading, strength to hold the lettuce upright, and ability to eject the heart and excess leaves. From these design goals, a CAD sketch was made to parametrically define all the linkage and cam geometries based off limited inputs. This sketch was turned into a 3D models of a scale mockup, full scale mockup, and eventually a motorized metal prototype that successfully fulfilled all of the established requirements (see Chapter 8).

5. Superstructure Subsystem

5.1 Introduction

The team also focused on creating an improved base superstructure, shown in Figure 5.1, which is responsible for stabilizing the trimming system.
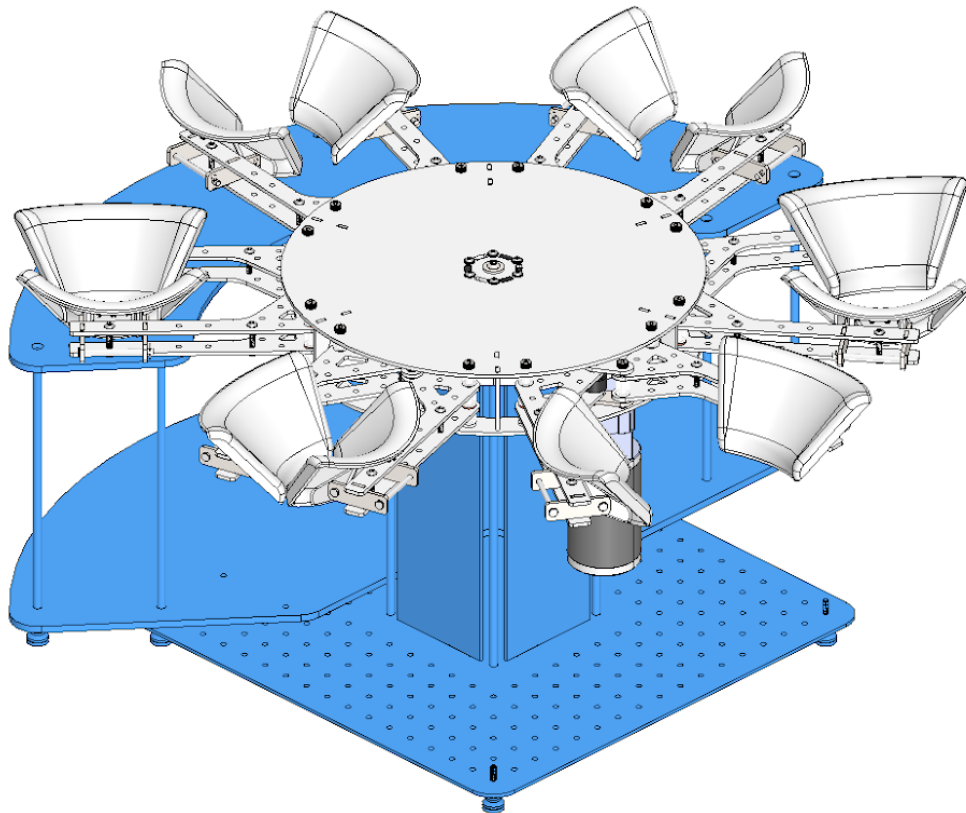
Figure 5.1 CAD Design highlighting Superstructure

The superstructure requires a large base to stabilize the system from tipping, however, the team hoped to make it compact enough such that the system could be easily moved. Additionally, it was critical that the base include mounting positions for the cutter, camera, and electrical equipment. Finally, it should feature a horizontal zeroing platform that lettuce can be pushed against during the loading stage such that the machine vision camera has a reference for measuring the diameter.

5.2 Supporting Structure

The supporting structure is made up of a baseplate, four tower plates, and four tower standoffs as shown in Figure 5.2.
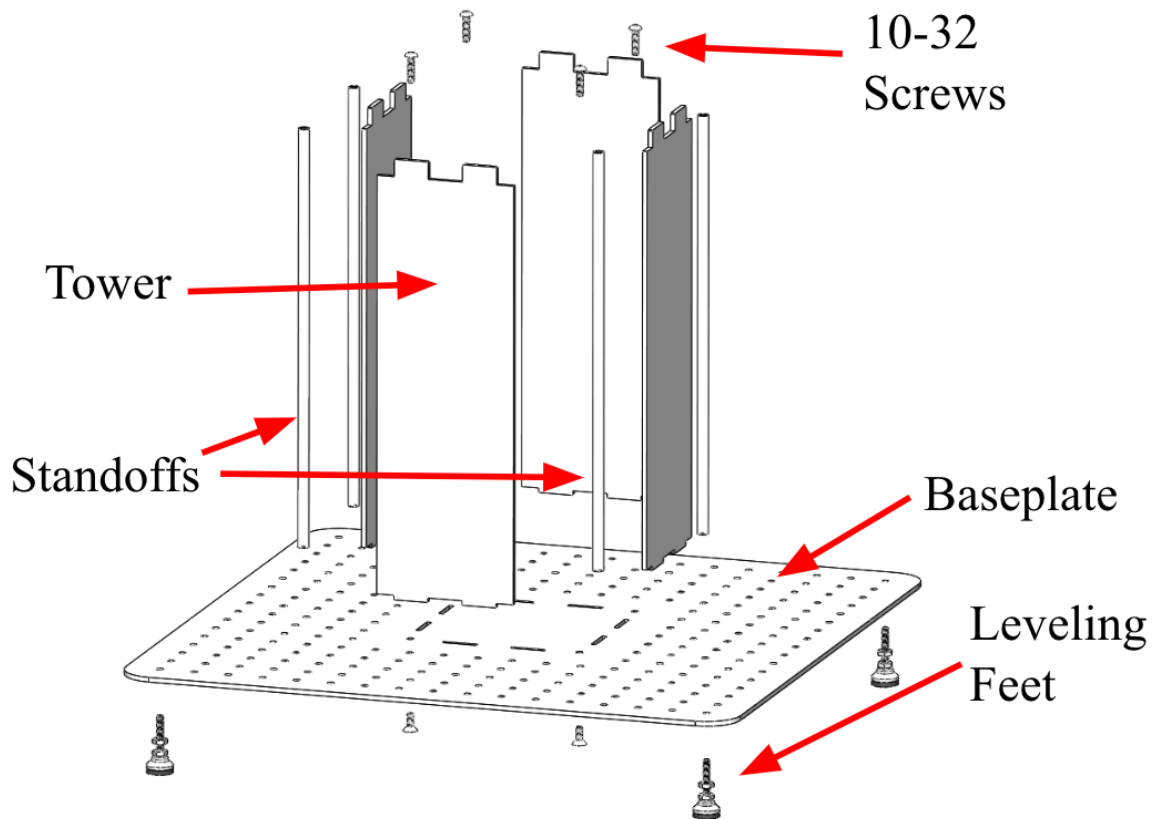
Figure 5.2: Supporting Structure Annotated Exploded View

The baseplate is 10 GA sheet steel approximately an 18 inch square, with rounded corners and a grid of holes allowing future components to be added. The baseplate also has a pattern of rectangular slots into which tabs on the tower plates fit. These four tower plates are wide, giving the connection between the baseplate and cam a large moment of inertia to stiffen the structure. The tower standoffs and screws are held in tension, compressing the tower plates into their slots and making the entire structure very rigid.

5.3 Horizontal Leveling Platform

The horizontal leveling platform's purpose is to be a known reference zero point such that the lettuce can be fully inserted until the stalk hits the platform, calibrating the stalk height so that a single camera in the vision system can measure the diameter of the stalk.

The platform (shown in Figure 5.3) consists of a lower plate that bolts to the baseplate and leveling feet, a series of tapped standoffs, and an upper plate to zero the lettuce.
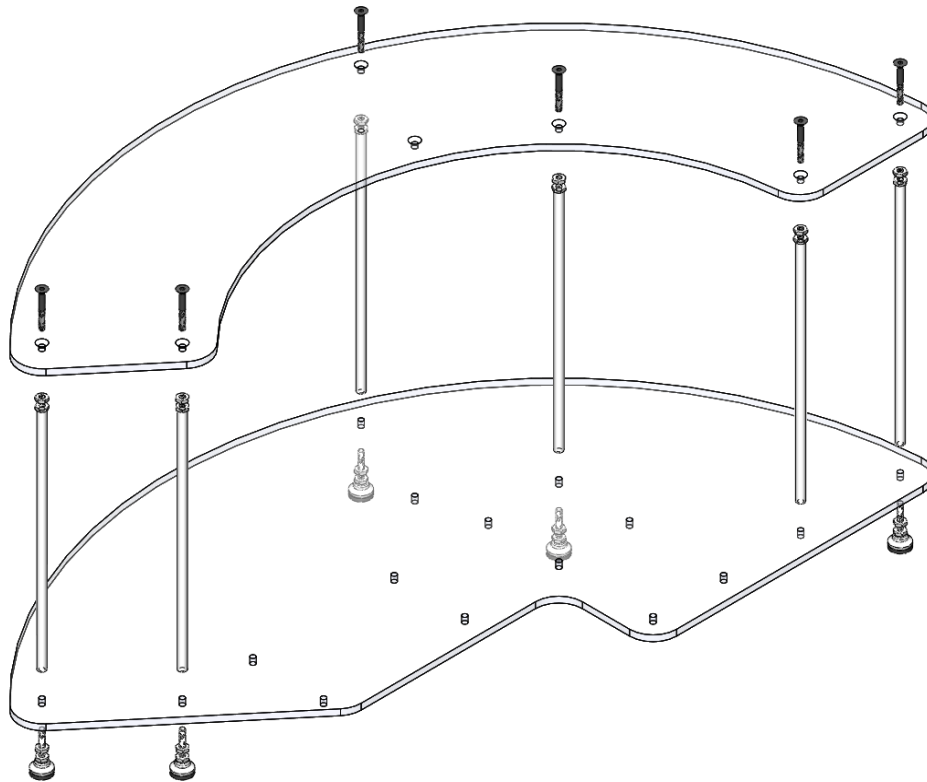
Figure 5.3: Horizontal Leveling Platform Annotated Exploded View

The upper and lower plates are made of ¼" polycarb, chosen for their robustness and ability to absorb impact rather than shatter. The plates could also have been made out of sheet steel like the rest of the system but by using plastic they strike a balance between being stiff enough to zero the lettuce but not so strong that someone would think they could lift the system by holding it there. The team did not want the lower plate to be used as a lifting point for the system, so by choosing plastic it serves as a clear indication that it is not structural and to lift from elsewhere.

The standoffs are tapped for #10-32 Flat Head Cap Screws to attach the top plate at a somewhat adjustable height relative to the lower plate and thus lettuce held in gripper cups. This screw and double jam nut arrangement means the height of the zeroing plate can be adjusted and locked to a desired height, allowing for tuning for specific species of lettuce or if harvesting smaller heads. Flat Head screws countersunk into the top plate ensure a flat surface for zeroing and cleaning.

5.4 Mounting for Cutting and Vision Systems

The cutting and vision systems, as stated in Chapter 2, were not in the scope of this senior design project since the Partner Farm already had functional components that met these needs. However, the team wanted to ensure that future teams could use the trimmer and add their own systems to it and as such the team added a hole pattern for #10 bolts across the baseplate. A simple adapter part could be made between a future designed vision or cutting system. The team did use the holes in the baseplate to mount an electronics box and horizontal leveling platform.

5.5 Conclusion

The Superstructure Subsystem, although simple, is incredibly important since it supports the indexer and future vision and cutting systems. The team built a compact but stable base that rigidly supports the cam. A horizontal leveling platform allows for camera height calibration. Holes in the baseplate provide opportunities for mounting electronics and future vision and cutting systems. Overall, the superstructure is strong, robust, compact, and a significant improvement over the farm's large and complicated existing structure.

6. Mechatronics Subsystem

6.1 Introduction

To drive the system and rotate it at a constant speed, a motor, battery, and control system is required in a mechatronics system as shown in Figure 6.1.
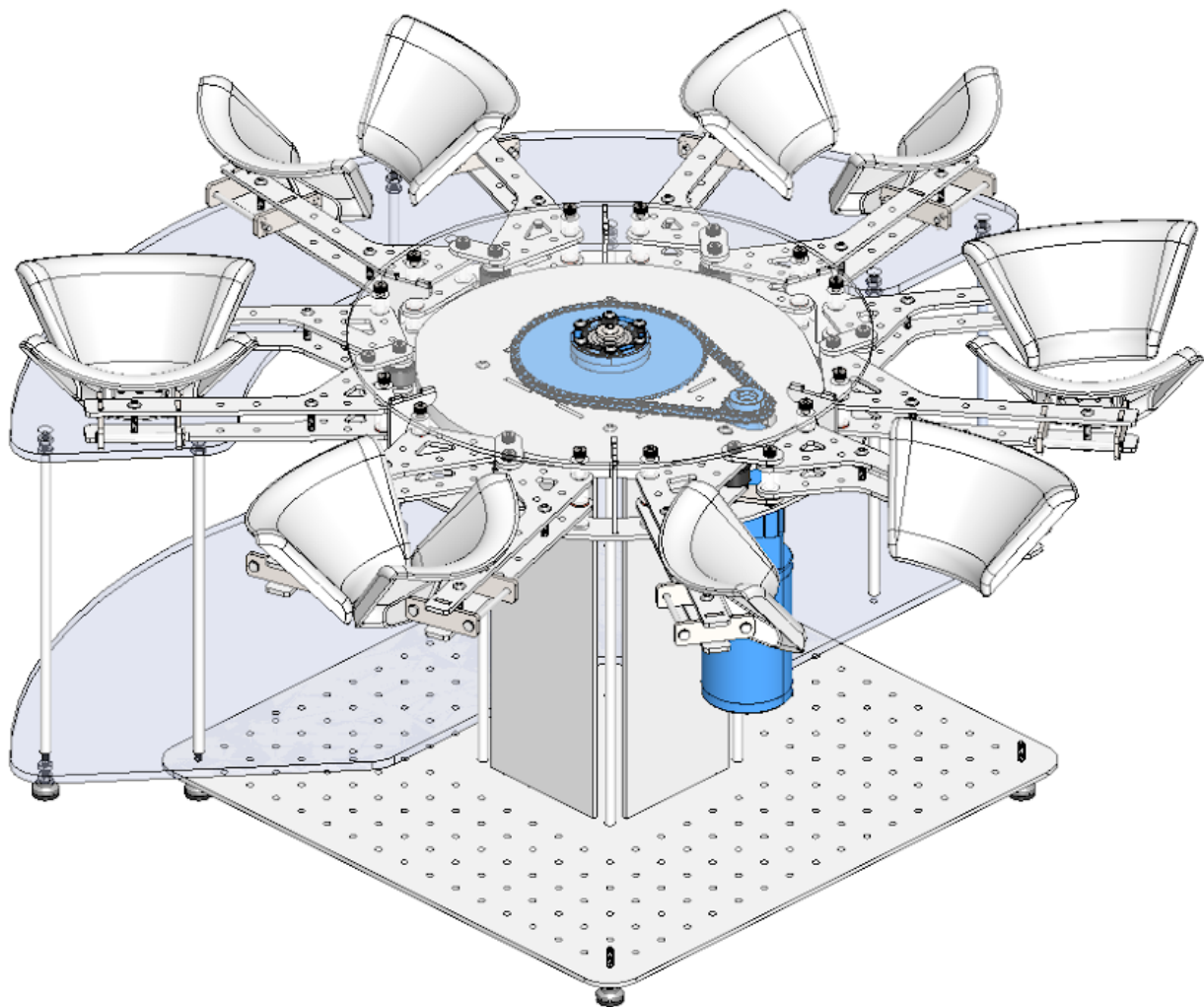
Figure 6.1: CAD Design highlighting Mechatronics

The motor must be properly sized and paired with a gear reduction such that it can run at the desired speed efficiently for long periods of time. An encoder and motor controller must be selected that can provide closed-loop velocity control to compensate for unexpected disturbances.

6.2 Kinematic and Dynamic Analysis of Cam and Linkage for Motor Selection

6.2.1 Introduction

The team needed to determine the size (power) and gearbox reduction needed for a motor to drive the rotation of the indexer to meet the required rotational speed while having enough torque to open the springs in the grippers and overcome any friction generated through the many rotating and sliding contact points. Thus, the team performed an extensive kinematic and dynamic analysis of the gripper linkages and cam profile to determine the torque requirements and thus select a motor.

6.2.2 Kinematic Analysis of Linkage

Before a dynamic analysis can be performed and torque requirements can be found, a kinematic analysis is necessary to establish how the required cam states translate into positions, velocities, and accelerations of the linkage and spring.

Kinematic Inputs: Cam Profile and Linkage Geometry

The primary inputs to the kinematic analysis are the cam profile and linkage geometry derived from the SolidWorks sketch (Figure 6.2). The sketch constrained the linkage and cam in the loading, gripping, and ejection states as described in 4.3.2, *Indexer CAM and Linkage Design*. The gripper's dimensions were driven by the dimensions of the lettuce, how much it would have to close for each state, and how much it could eject whilst not colliding with other grippers.
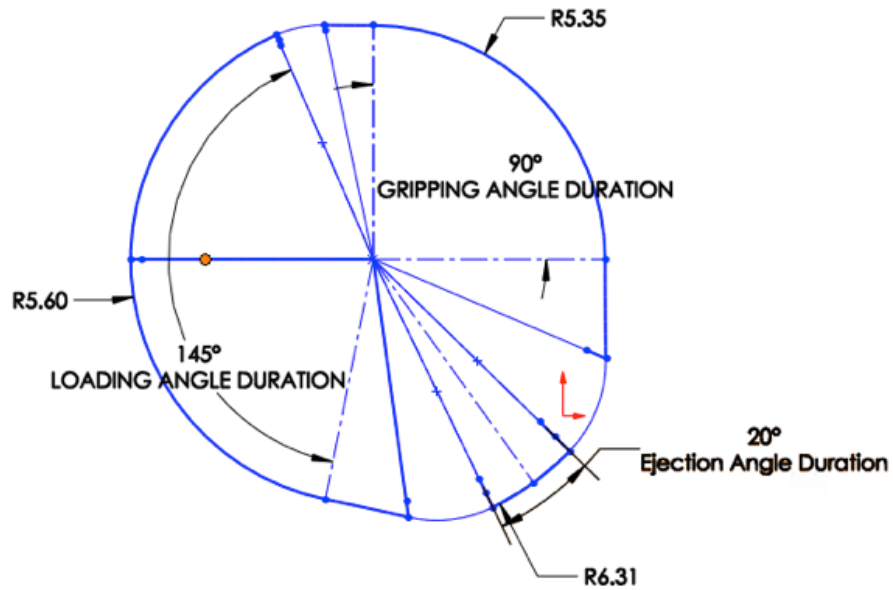
Figure 6.2: Cam Profile with Radiuses (in) and Dwell Angles (deg)

The cam profile was largely driven by the rotational speed requirements and trying to maximize the amount of dwell time spent in the loading and gripping statex. Together, these constraints fully defined the cam profile and linkage geometry (shown in Figure 6.3).
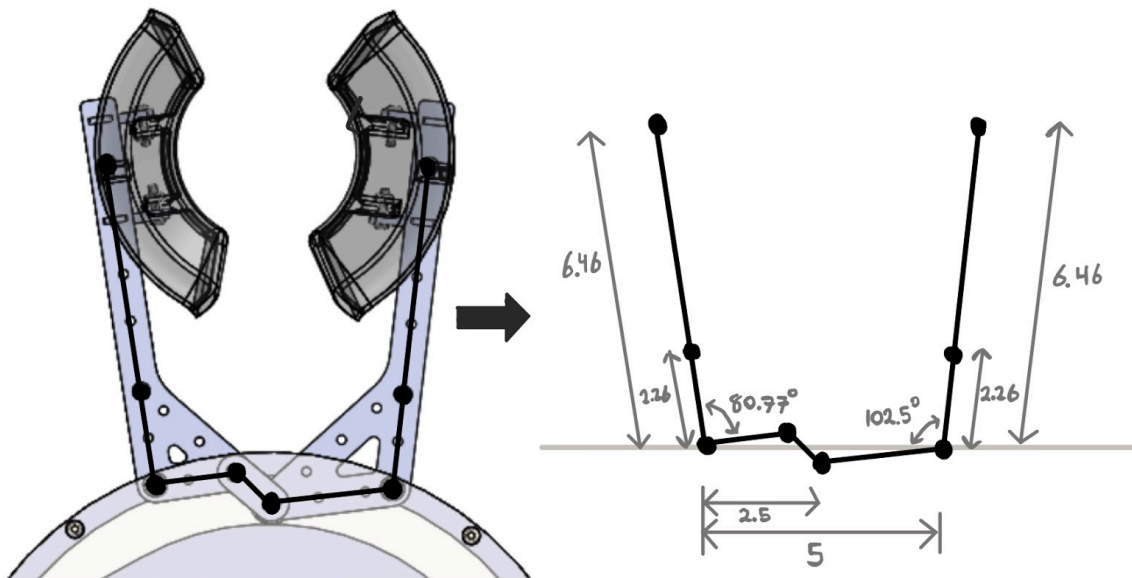
Figure 6.3: Stick Model of Linkage Geometry with Lengths (in) and Angles (deg)

With these geometries, and the required 5 rpm, the cam radius, and thus the displacement of the follower wheel on the linkage, as a function of time could be generated using MATLAB (Figure 6.4). The entirety of the MATLAB code can be found in Appendix F. This time-dependent displacement function was the primary input to the kinematic analysis from which velocity and acceleration functions were generated using numerical derivatives.
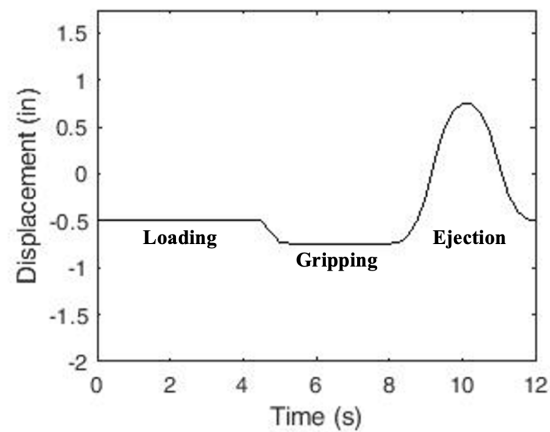
Figure 6.4: Cam Profile Radius (wheel displacement) vs Time input to Kinematic Analysis

Inverse Kinematics of Linkage for Position and Displacement Determination

Next, the team used inverse kinematics to determine the resulting linkage angles from cam profile inputs. A simplified sketch of the important shorter links attached to the follower wheel can be seen in Figure 6.5. These coupled links are driven by the cam's profile causing a radial displacement of the follower wheel, y [in].
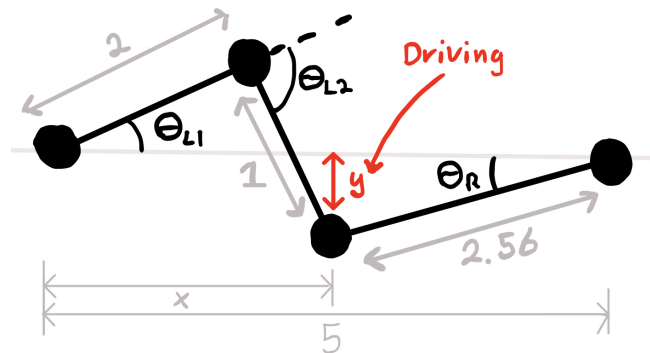
Figure 6.5: Simplified Linkage Kinematic Model (in)

The angle of the right link, Θ_R, can be found using Equation 1.

$$\Theta_R = \tan^{-1}(y/(5-x))$$ (1)

The angles of the left link are highly coupled and difficult to find but can be calculated using derived inverse kinematics Equations 2 and 3.

$$\Theta_{L2} = -\cos^{-1}((x^2 + y^2 - 2^2 - 1^2)/ (2*(2)*(1)))$$ (2)

$$\Theta_{L1} = -\tan^{-1}(y/x) - \tan^{-1}(1*\sin(\Theta_{L2})/(2+1*\cos(\Theta_{L2})))$$ (3)

Thus, a relationship was established between the radius of the cam and the angles of the linkage. This can be extrapolated outward with forward kinematics to derive the positions of the spring attachment points (blue dots) and linkage tips (red dots), seen in Figure 6.6, for the various gripper states (or any time-stamp in-between).

1. Loading   **2. Gripping**   **3. Ejection**
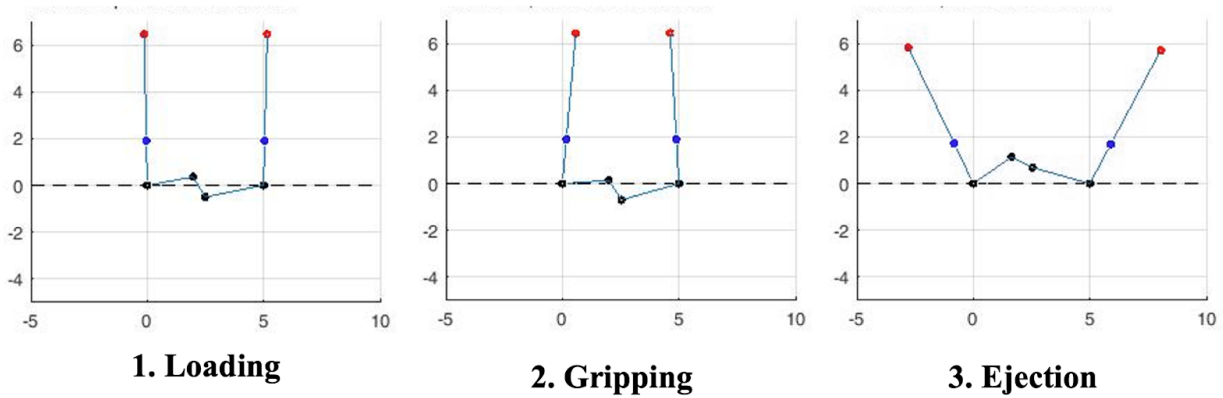
Figure 6.6: Simulated Gripper Positions for Various States (Position, inches)

Velocity and Acceleration of Linkage

With the modeled positions and time-dependent displacements of the points in the linkage, the instantaneous velocity and acceleration of these points can be found using discrete time-based derivatives as shown in Figure 6.7. Although this data is not explicitly needed for the torque derivation and motor selection, having an understanding of the velocity and acceleration seen by the spring attachment and tip points is useful as a sanity check that the gripper would not be "snapping" too fast between states, potentially causing unwanted and unplanned shock loading.
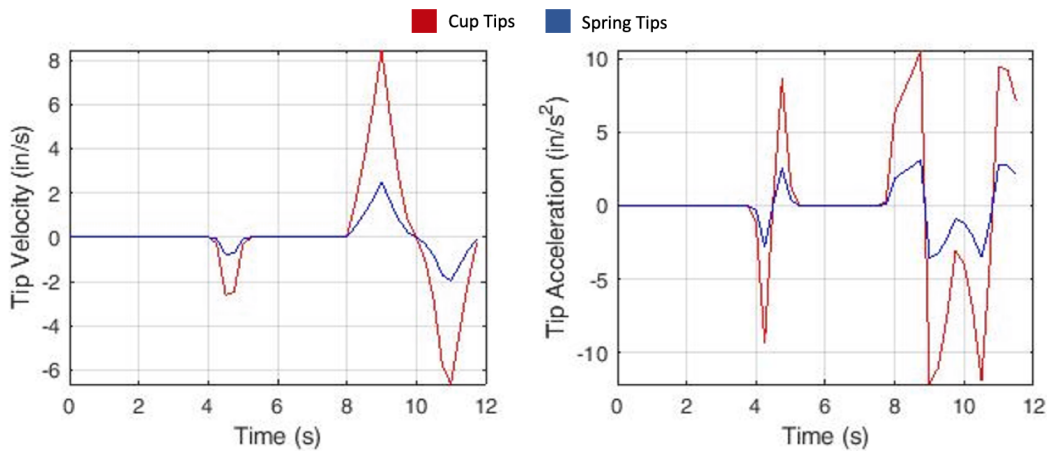
Figure 6.7: Velocities and Accelerations of Spring Attachment (blue) and Cup Tips (red)

As shown, the velocity and acceleration at the tip does not exceed 8 [in/s] or 10 [in/s^2], numbers that are reasonable and would not be characterized as a "shock."

6.2.3 Dynamic Analysis of Linkage

Forces due to Spring Displacement

The modeled displacement of the spring attachment points found in Section 6.2.2 can be used as an input, along with Equation 4 below to calculate the spring force of the gripper as a function of time. Assuming an idealized spring, the force, F [lbs], is equivalent to the displacement, x [in], times the spring constant, K = 7.26 [lbs/in].

Note the displacement is the total distance between the spring attachment points, thus including both the left and right linkage arms' displacements.

$$F_{spring} = K * x \qquad (4)$$

Thus, the spring force as a function of time can calculated. This force can then be translated to the restoring force of the wheel pressing on the cam and the gripping force of the cups pressing on the lettuce using the geometry of the linkage as a function of time as shown in Figure 6.8.
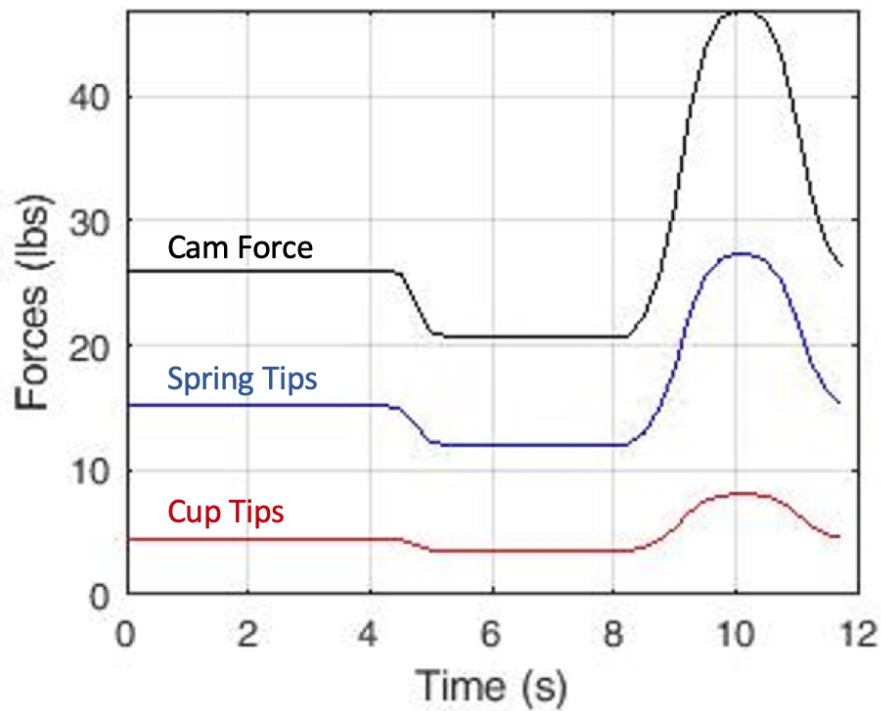
Figure 6.8: Force on Cam at Spring Attachment Points, and Cup Tips Over Time

Note that the force on the tips of the cups is lowest due to the 3rd class lever nature of the linkage, but that the gripping force is still about 5 lbs, large enough to prevent the lettuce from tipping or falling out but not too high that it'd crush the lettuce (see Section 2.4.3).

65

Torques due to Wheel Force on Cam

With the force on the cam calculated in Figure 6.8, the resulting torque generated due to opening the springs and the rolling resistance between the wheel and the cam can be calculated with trigonometry and taking the cam profile (and its instantaneous slope) as inputs. The resulting torque due to one gripper can then be summed at each moment to give the torque requirement for the whole system, shown in Figure 6.9.
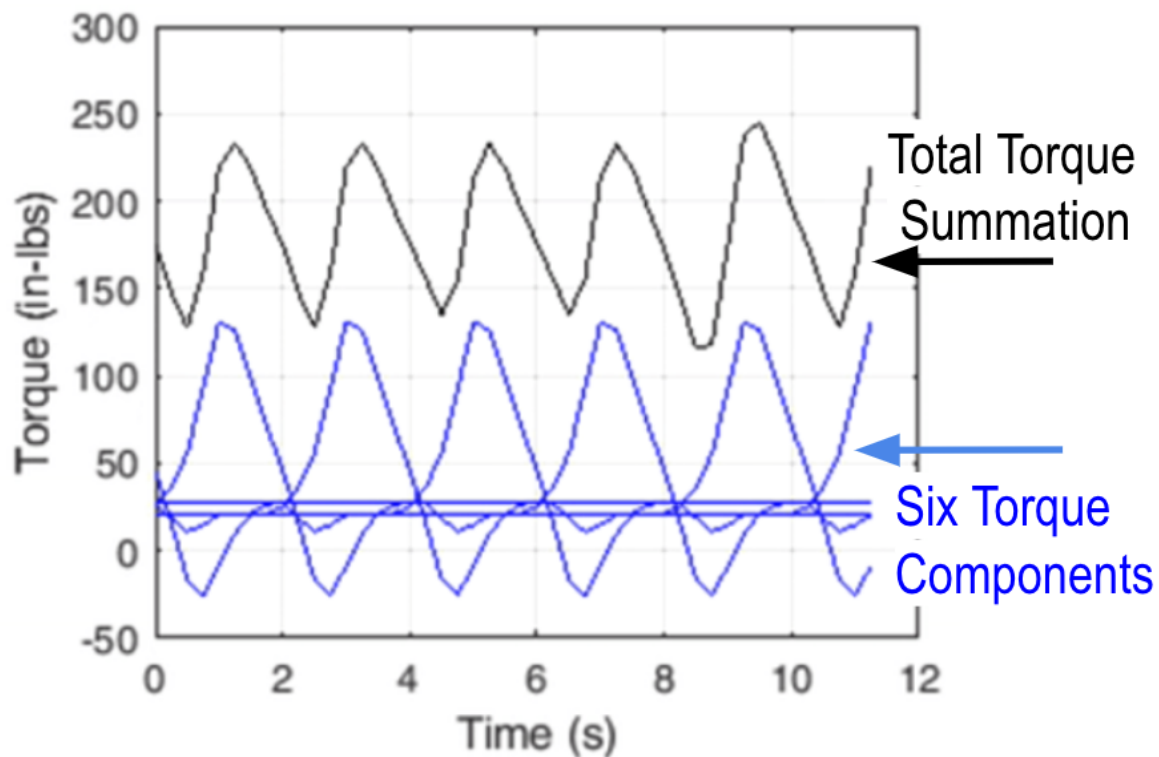
Figure 6.9: Total Torques Required to Drive Indexer

Finally, additional friction is present in elements such as the indexer pivot point, bearings, chain, gearbox, etc. but these were not calculated and will be overcome with a large torque safety factor over the estimated maximum of 250 in-lbs. Thus, the team plans to select a motor, gearbox, and chain reduction capable of delivering at least 1,200 in-lbs at a speed of 5 rpm.

6.2.4 Motor Selection: Power for Required Torque and rpm

With the required torque of 1,200 in-lbs and 5 rpm, this results in an output power requirement of ~70 Watts. Thus, the team needed to select a motor capable of at least 70 Watts, but ideally is rated for much high power at high voltages so that the team can run the motor at perhaps 50% voltage (i.e. 6V on a 12V rated motor) so that it will not overheat and have a longer total life. The team selected the CIM motor (Appendix G1) because it is capable of delivering ~150 W from 12V at its peak efficiency (~65%) meaning it can be scaled to only a 6V and deliver the required 70 W while still having plenty of leftover voltage and torque to overcome any unexpected spikes or efficiency losses.

To achieve the desired 5 rpm, the team has selected a 100:1 reduction with a planetary gearbox (CIM Sport, Appendix G3) that the CIM directly attached to. The output of this gearbox is a a hex shaft that can drive commercially available sprockets (16T to 66T) to further increase the reduction and provide some shock absorption between the indexer and the more-delicate planetary gears. This results in an overall reduction of 330:1, allowing the motor to run at ~2000 rpm, close to its peak efficiency rpm at a lower voltage.

Figure 6.10: Selected CIMSport Planetary Gearbox (80:1 reduction)

At first, the team used simple open-loop control, adjusting the input voltage via PWM to cause the system to run at 5 rpm. Disturbances resulted in unacceptable rpm variations, so the team

attached an inline optical shaft encoder (CIMcoder, Appendix G2) to the planetary gearbox to measure the motor's rpm so closed-loop control could be applied to vary the output voltage and maintain a constant 5 rpm.

6.2.5 Motor Selection Conclusion

Using the required states and dimensions of the lettuce, the team used a SolidWorks sketch to find the cam profile and linkage geometry. These dimensions, along with the 5 rpm requirement, were turned into positions, velocities, accelerations, and forces of any point on the linkage as a function of time by using inverse kinematics, discrete time-based derivatives, and an idealized spring force-displacement relationship. These forces were converted to a required torque of ~250 in-lbs for opening the 6 gripper springs and for overcoming wheel rolling resistances. Thus, with a safety factor of 2 and the 5 rpm a minimum required motor power of 70 W was determined. Finally, an affordable, easily mountable motor with a compact planetary gearbox and shock absorbing chain transmission were designed to give the CIM Motor an overall reduction of 330:1, allowing it ample enough torque to run at a lower voltage of ~6V and still have plenty of power to drive the system and maintain its desired rotational speed.

6.3 Electrical Architecture: Closed-Loop Control

6.3.1 Need for Closed Loop Control

One of the most important requirements for the system is that it can match the throughput of the current manual labor teams that are used at 30 hearts/minute. Through the workspace analysis performed in Chapter 2 it was found that having 6 grippers and therefore a speed of 5 rpm was ideal for maximizing loading opportunity and ease. Now that a motor and gearbox had been selected with sufficient speed and torque to drive the system it was necessary to develop an electrical architecture to accompany and ensure the requirement of 5 rpm is maintained.

Originally the system was designed to use open loop control to achieve 5 rpm. However, upon testing the system, disturbances caused by the gripper springs opening and closing caused the system's velocity to vary outside the tolerance of ± 0.5 rpm. Other disturbances including resistance torque added when loading the system also caused the system to slow. To account for these disturbances and maintain the required constant velocity, the team decided to implement closed-loop PID control. The selection of the speed sensing mechanism along with implementation and accompanying electronics will be discussed in the following sections.

6.3.2 Electrical Components Overview

The electrical components used to power and control the speed of the indexer and grippers consist of a 12V lead acid battery, a optical rotary shaft encoder, and a motor controller with built-in PID speed control. The components and electrical schematic are shown in Figure 6.11.
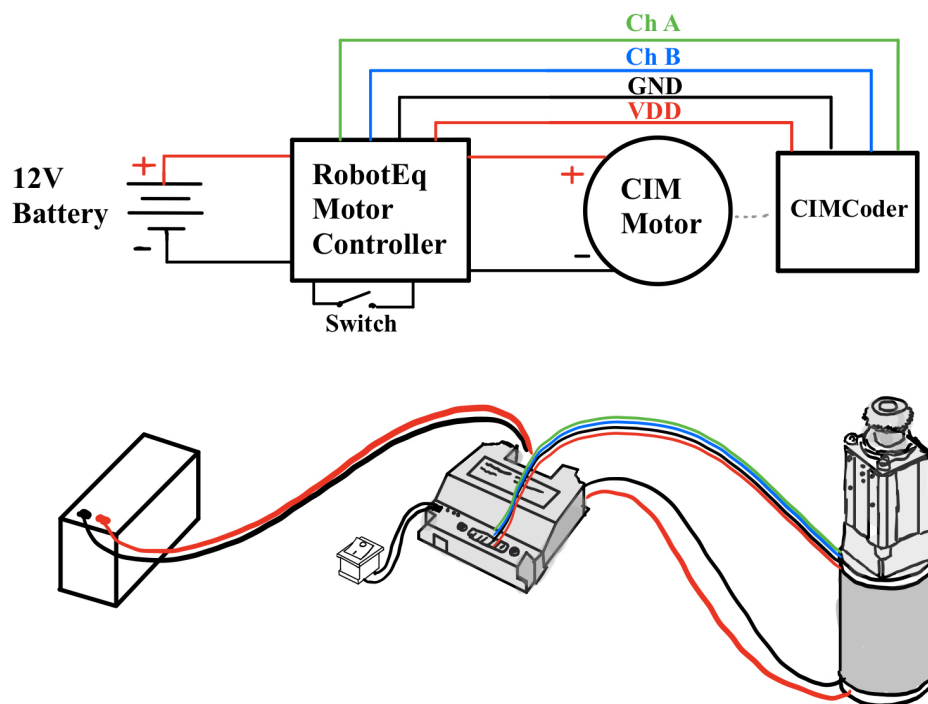
Figure 6.11: Electrical Schematic and Components

Although a system implemented in the field would likely connect to a tractor power system, the team chose to use a DC battery such that the machine could be easily transported. One 12 V, 8 AH, lead acid battery was selected as it could supply sufficient voltage and current while being relatively portabile. The battery is also low cost, very widely available, and easy to charge.

As previously mentioned it was necessary to implement closed loop control to maintain constant speed throughout use. To achieve this, an encoder was added in line with the CIM Motor. A RoboteQ SDC2130 controller processes the input from Channel A and B, calculating the velocity and adjusting power to the motor to maintain the desired speed.

6.3.3 Feedback Encoder: CIMCoder

The AndyMark CIMCoder was chosen because of easy interfacing with the AndyMark CIMsport gearbox and CIM motor. This incremental optical rotary shaft encoder was sufficient, as opposed to an absolute unit, since only velocity feedback was required. As shown in Figure 6.12 the CIMCoder mounts inline with the motor on the output shaft. Then the gearbox is assembled to the shaft after the encoder. In order to account for the width of the encoder it was necessary to mill off the back of the gearbox's adapter block to account for the width of the encoder (see Section 7.5.4).
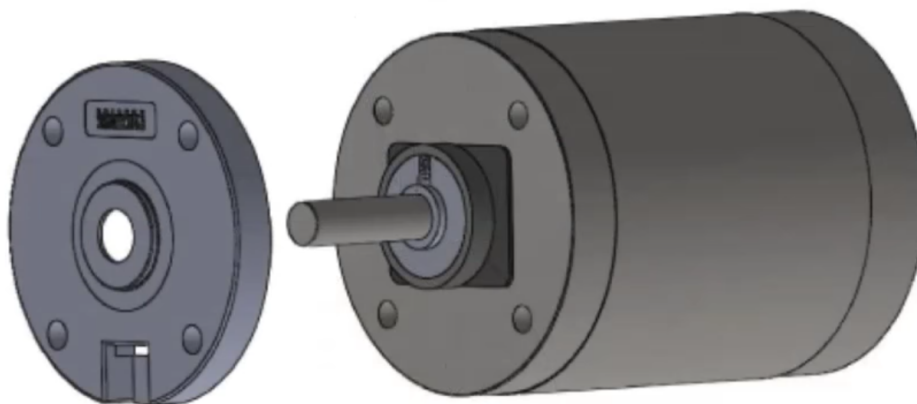
Figure 6.12: Assembly of CIMCoder onto Motor Shaft

The CIMCoder also comes with a cable for connecting the encoder to a controller. The cable has a 4 pin connector with the pinout shown below in Table 6.1.

Table 6.1: CIMCoder Connector Pinout

Pin #	Signal Type
1	Power +
2	Channel A
3	Power Ground
4	Channel B

6.3.4 Motor Controller and Software: RoboteQ

The RoboteQ SDC2130 Motor Controller was selected to perform closed loop control using encoder feedback. This off-the-shelf controller was selected primarily for its built-in PID control and the relative simplicity of set up and use. The 2130 model was chosen for its ability to run two motors up to 20 amps. Given the expected peak current draw, this provides a factor of safety of around 2. The controller is accompanied by RoboteQ's own software, facilitating setup and PID tuning. Finally, this controller was selected due to its availability, as it is commonly used in Santa Clara's Robotic Systems Laboratory.

6.4 Mechatronics Conclusion

To achieve smooth operation of rotating subsystems it required an in depth analysis of expected torque requirements throughout the entire rotation of the indexer and gripper subsystems. Based off of the required 5 revolutions per a minute a kinematic analysis was performed to calculate the displacements and in turn the velocity and acceleration of the grippers through the three different gripping states. Taking into account the spring constant of the selected spring along with the friction between the roller and cam surface it was possible to determine the required torque at any angular position. From there it was then possible to use the required torques along with the angular rotation to calculate the power output required of the motor. This allowed the team to determine that a 350 W CIM motor along with a 330:1 reduction achieved from a planetary

gearbox and chain reduction would be sufficient to rotate the indexer and grippers and would allow the motor to be operated at peak efficiency.

Once the motor and gearbox were selected it was determined that closed loop control would be necessary to account for disturbances the system experiences during operation. To achieve this the AndyMark CIMCoder and RoboteQ motor controller were selected for their easy and efficient packaging as well as the simplicity of implementation and tuning. All of this was powered off of a 12V lead acid battery that allowed for portability of the team's system and can power the system even during peak current draw. As discussed in Chapter 8, the Mechatronics subsystem successfully maintained the required 5 rpm and met all of its other design goals.

7. System Manufacturing and Assembly

7.1 Introduction

With the design and analysis completed for the gripper, indexer, superstructure, and mechatronics subsystems, the team's remaining work was to manufacture, assemble, and integrate the subsystems into the final overall metal prototype. Once built and brought-up, testing and verification were conducted to ensure all the requirements and the corresponding needs they addressed were satisfied.

Having created a CAD model of the entire system utilizing Design for Manufacturing (DFM) and Design for Assembly (DFA) practices, the manufacturing and assembly was quite straightforward. The majority of the parts were either waterjet milled steel, laser cut polycarbonate, turned shafts/spacers/standoffs, or Commercial Off-the-Shelf (COTS) components.

7.2 Waterjet Steel for Gripper and Indexer

7.2.1 Water Jetting Steel with Partner Farm

The team worked with the Partner Farm to complete the majority of the manufacturing for the most challenging and high-resource parts including the waterjet steel plates for the gripper linkage and indexer. The team sent completed DXF file drawings to the farm for both the team's system, which uses the mechatronics subsystem, and the Partner Farm's system, which uses their existing superstructure and hydraulic motors. The farm forwarded the files to a waterjet shop and the team picked up the parts a week later.

7.2.2 Cleaning and Painting Steel

The received metal was extremely rusty and needed to be cleaned and painted for weather-proofing, minimizing exposure to rust and dust particles, and improving the trimmer's aesthetics. The metal as delivered is shown in Figure 7.1.

Figure 7.1: Delivered Water Jet Pieces

The team used powered sanding and Scotch-Brite belts to clean away the majority of the rust, and small files or deburring tools to clean inside slots and holes. Once cleaned, the metal was spray painted with white Rust-Oleum Clean Metal Primer. Due to time constraints, only one coat was applied. If the team had more money and time, or was making official products, they would pay to have the system sandblasted for cleaning and powder coated to improve the quality and life of the system.

After the system was painted, the final preparation included using hand drills and reamers to remove the paint from the various holes had filled in, helping ensure proper clearances for assembly. A #9 drill bit was used for clearance holes for #10 screws and the 3/16" cotter pins in the gripper pivots. A 0.249" reamer was used to clear out holes for ¼" shoulder bolts. The bores for the oilite bushings in the shoulder bolts were not drilled or reamed so that the bushings could be press-fit in place.

With all the cleaning, painting, and drilling finished, the waterjet steel was ready for assembly.

7.3 Laser cut Polycarbonate for Zeroing Platform

The zeroing platform was designed and manufactured last because it was a low-risk item. It was made using laser cut ¼" polycarbonate plates held up with adjustable height feet and tapped standoffs. Polycarbonate was chosen as it is a rugged material that would not easily crack or fracture in the field. The adjustable feet and standoffs allow the platform height to be moved to a specified height, adjusted as necessary to accommodate different sizes or variants of lettuce heads, or for calibration of a future imaging system.

The polycarbonate plates were laser cut using a 250W laser cutter that could cut through the material in a single pass. The laser cutter also had a filtering system for containing and cleaning toxic fumes emitted from cutting polycarbonate and preventing them from being released to the atmosphere.

After laser cutting, the top plate was countersunk with a hand-held cordless power drill so that #10-32 Flat Head Cap Screws could be used to hold the top plate in place while remaining completely flat for a constant zeroing height.

7.4 Turned Shafts, Spacers, and Standoffs

7.4.1 Stainless Steel Shaft

The majority of the custom manufacturing with heavy machinery performed by team members used manual lathes to turn shafts, spacers, and standoffs for the indexer and superstructure. The central dead-axle shaft that the entire indexer rotates around had to be turned to length and both ends tapped for ¼"-20. No other shafts for the pivot points in the gripper linkage had to be turned since the system was deliberately designed to pivot about COTS shoulder bolts.

7.4.2 Plastic Spacers

This central pivot also needed custom acetal spacers turned to length to make the height stackup which includes the thickness of the #25 66T sprocket, sprocket hub, and plate/cam thickness align. These acetal spacers were parted off from longer, 2" spacer stock. The numerous nylon spacers in the gripper linkages were all designed to match their COTS length to minimize manufacturing.

7.4.3 Aluminum Standoffs

The standoffs for the superstructure central tower were left a nominal length of 12" and tapped on either end for #10-32. These standoffs were spray painted with a screw inserted so that the screw could be removed and the threads left intact and unpainted. The standoffs for the horizontal zeroing platform were turned to length and both ends tapped for #10-32 so that leveling feet could thread in from below and the flat head screws with nuts for adjustment could be threaded in from above.

7.5 System Assembly

7.5.1 Gripper Linkages and Cups

The individual grippers were assembled first, pressing the bushings and standoff plates into the linkage plates. The top and bottom halves of left and right gripper linkages were connected using tab and slots, held in compression by screws. After the tabs were inserted, the left and right sides of the grippers were connected along with the COTS spacers and follower wheel. The completed gripper subsystem is shown in Figure 7.2.

Figure 7.2: Completed Gripper Cup Assembly Attached to Indexer

Once the gripper subsystem was assembled, it was attached to the indexer using shoulder bolts and COTS spacers. The 3D printed gripper cups were then attached using cotter pins and clevis pins. Finally, the springs for the gripper cup and linkage were assembled.

7.5.2 Superstructure Base and Tower

The superstructure was built beginning with the cam, filing the paint out of the slots so the tabs of the tower plates could be hammered into it. The ½" round dead-axle shaft that serves as the dead-axle pivot for the indexer was arbor pressed into the hole in the cam and then bolted in from below. The standoffs were then affixed to the cam and used to pull the cam and baseplate towards each other to form a preloaded structure that was very stiff and stable (Figure 7.3).
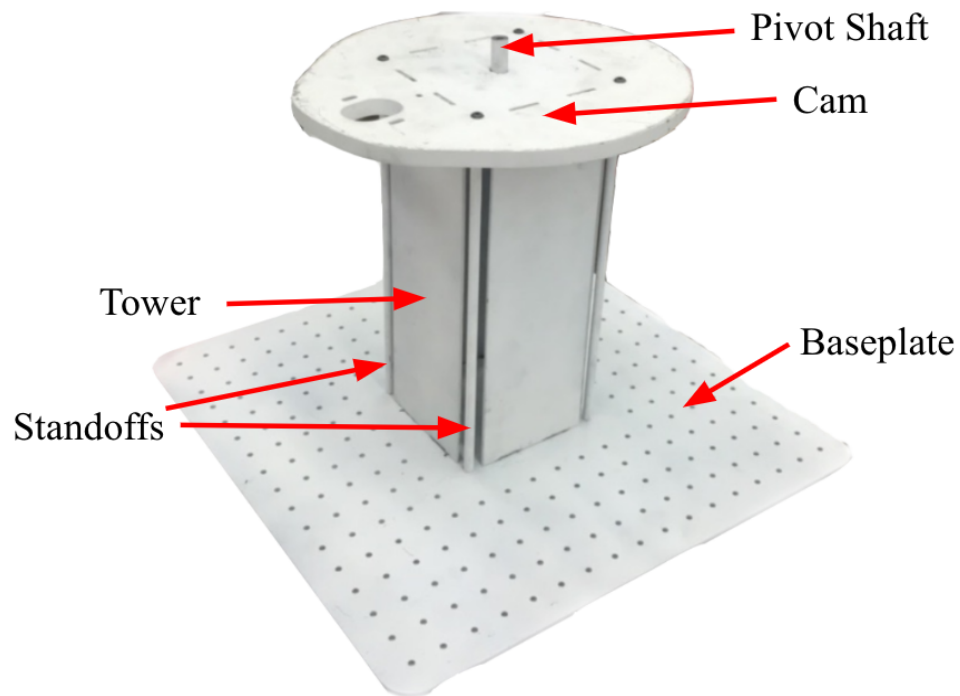
Figure 7.3: Assembled Superstructure with Pivot Shaft, Cam, Tower, Standoffs, and Baseplate

7.5.3 Indexer Plates

The indexer was assembled by attaching the lower plate to the top plate using the indexer standoff plates and gripper pivot shoulder bolts. Spacers were placed on this shaft and then the entire top plate with sprocket and its ball bearing were slid over this shaft.

7.5.4 Mechatronics Motor, Gearbox, and Encoder

The mechatronics subsystem was assembled beginning with preparing the Andymark CIM Sport Planetary gearbox by greasing all the internal gears and reassembling the gearbox (Figure 7.4).
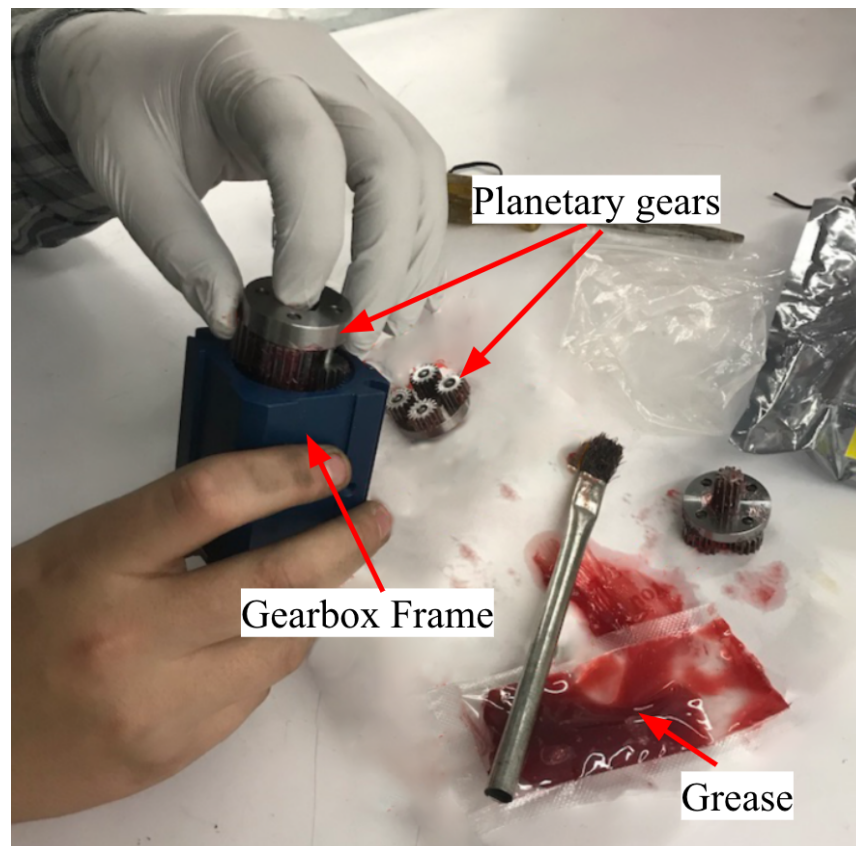
Figure 7.4: Greasing and Assembling Planetary Gearbox

As discussed in Section 6.3.3, the integration of the CIMCoder required the back of the gearbox's adapter block to be milled off by an amount equal to width of the encoder assembly so the CIM shaft and its pinion would be able to reach the input of the planetary gearbox. This milling down of the face of this aluminum block was done manually with a ½" endmill on a Bridgeport. Finally the CIMCoder components could be assembled onto the motor and gearbox.

The driving sprocket and custom acetal spacer were assembled with the shaft collar holding everything on. The motor, gearbox, sprocket assembly was then assembled onto the cam of the indexer (Figure 7.5).
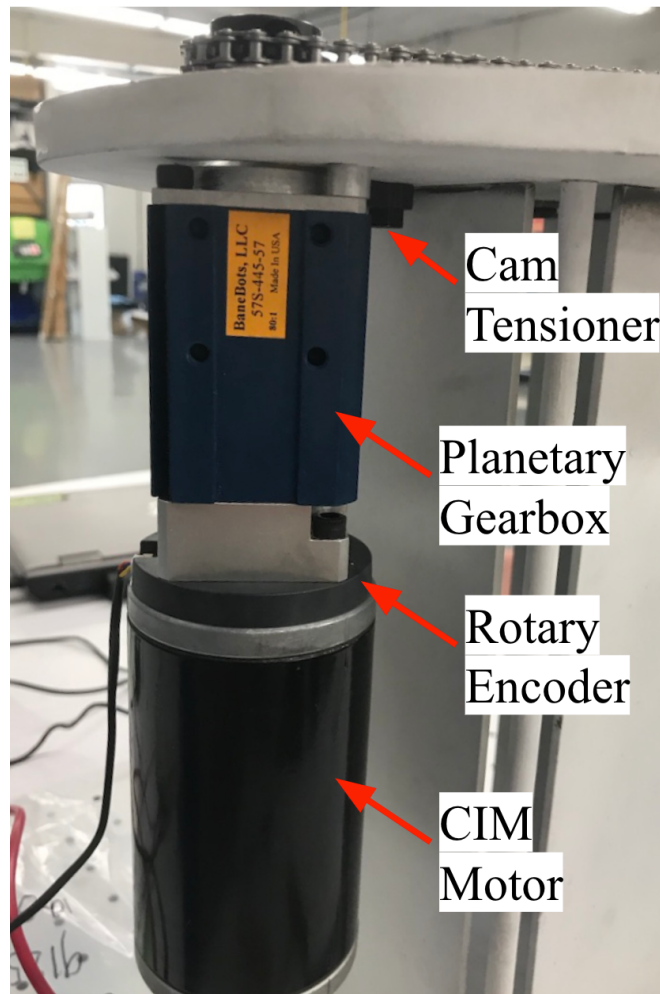
Figure 7.5: Assembled Mechatronics Motor Assembly

7.5.5 Mounting Mechatronics, Chain Transmission, and Indexer

The chain was made to length using a #25 chain breaker tool and then wrapped around the 2 sprockets. The small WCP cam was then spun with an end-wrench to push the entire motor-gearbox-sprocket assembly away from the large 66T driven sprocket, tensioning the chain (Figure 7.6).
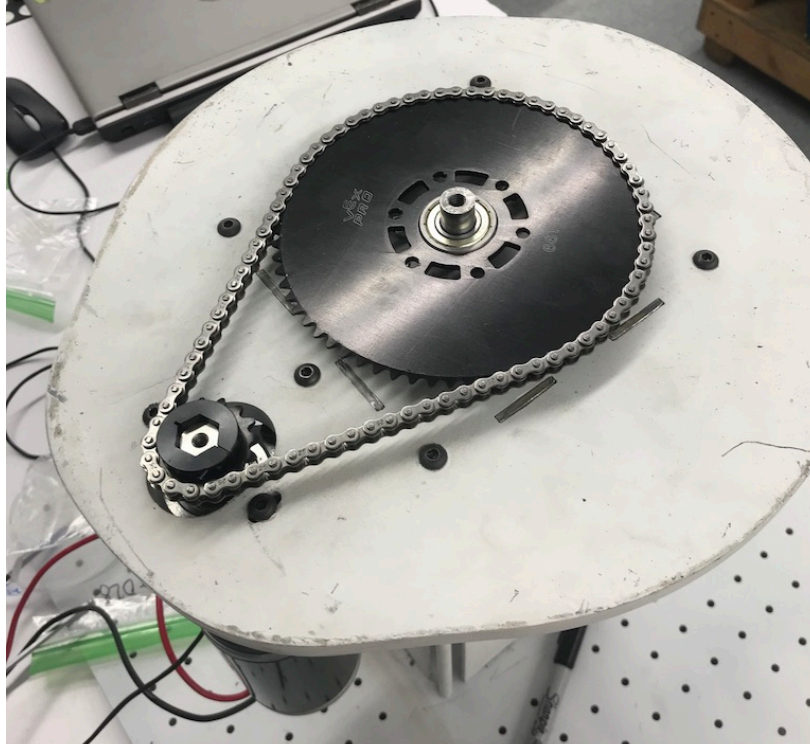
Figure 7.6: Assembled and Tensioned Chain Transmission

With the mechatronics system and chain mounted, the indexer top and bottom plate assembly could be brought in and placed over the 66T sprocket and sprocket hub. #8-32 bolts were tightened to secure the hub to the top plate and a ¼"-20 bolt from above pulled the entire top plate down onto the dead-axle central shaft. With this assembly, the indexer, superstructure, and mechatronics were complete, with the gripper and electronics needing to be added next.

7.5.6 Mechatronics Electronics Box

The electronics box which housed the RoboteQ motor controller, battery, and on-off switch was assembled (Figure 7.7). Holes were drilled into a clasping, weatherproof plastic box so the switch could stick out the wall and the box was bolted securely to the baseplate. Wires were run from the encoder and motor to the controller and from the controller to the switch and battery (wiring diagrams in Appendix G4).
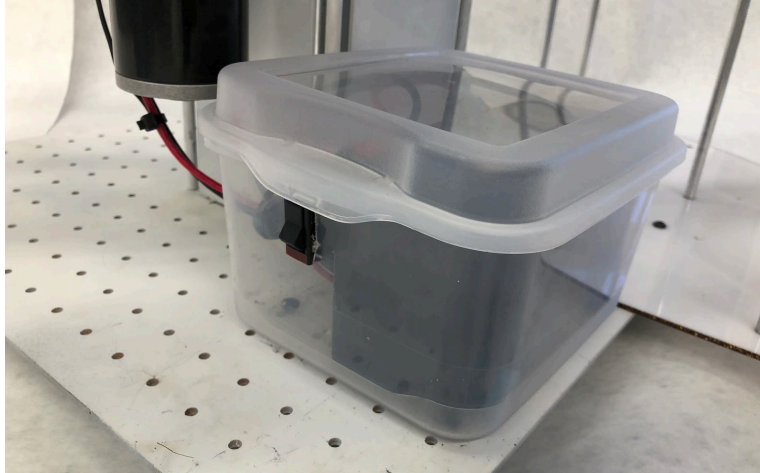
Figure 7.7: Electronics Box Holding Battery, Motor Controller, and Switch

7.5.7 Leveling Feet and Platform

Finally, the leveling feet were then mounted in each corner of the base and jam nuts adjusted so as to level the entire superstructure base plate relative to the table. The lower polycarbonate plate of the leveling platform was bolted onto the baseplate, and the level platform standoffs attached coming up from it, with more leveling feet below. Finally, the upper plate of the leveling platform was attached with the flat head screws and jam nuts (Figure 7.8).
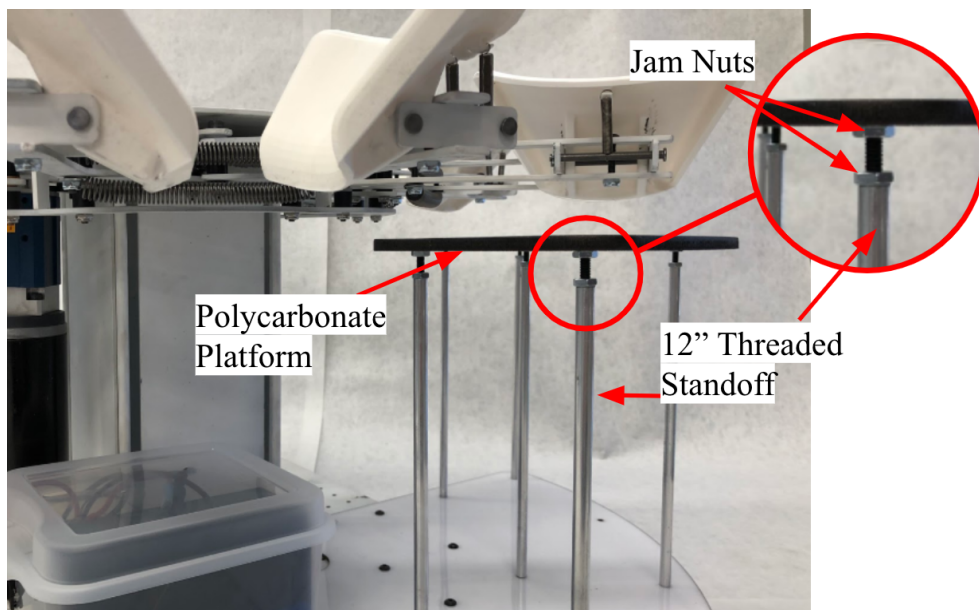
Figure 7.8: Leveling Platform with Screws and Nuts to Maintain Constant Height

The height of each screw was adjusted to level the entire platform and optimize the overall height to let the lettuce come in far enough that it would be securely gripped, while not coming in so far that it would easily tilt (due to a longer moment arm) when the stalk is trimmed by the blades of the farm's cutting system.

7.6 Integration and Bring-up

With all the components assembled, they could now be integrated and the entire system brought-up for subsequent testing and verification. This integration procedure involved mounting the grippers onto the indexer and connecting to the motor and encoder with the controller and its software so that the system could be spun under motor power at the constant 5 rpm.

7.6.1 Mounting Grippers to Indexer

The grippers were added one at a time to ensure each was assembled correctly and there were no introduced interferences with the operation of the system. First just one gripper, and then 3, and then all 6 were mounted and tested.
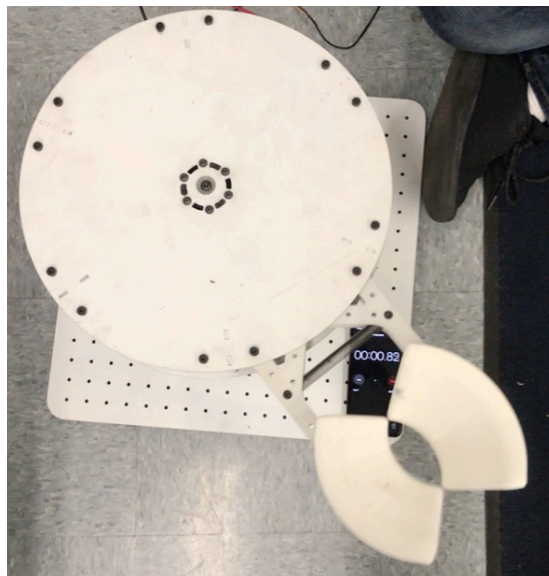
Figure 7.9: Single Gripper Mounted and Initially Spun
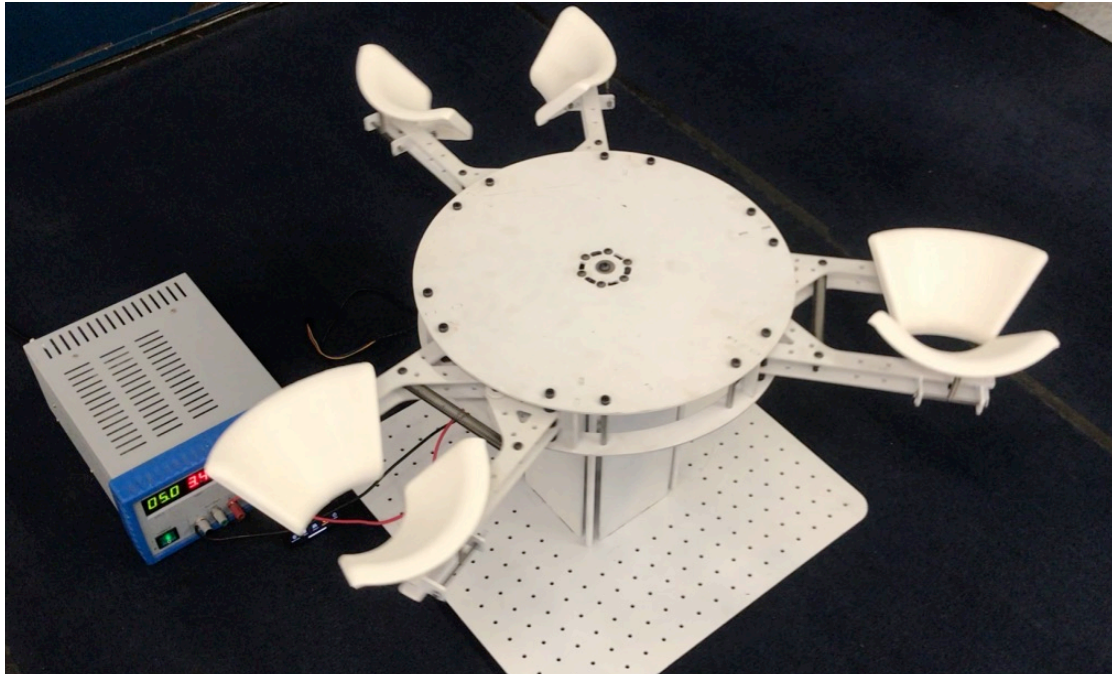
Figure 7.10: Three Grippers Mounted and Powered with DC Power Supply
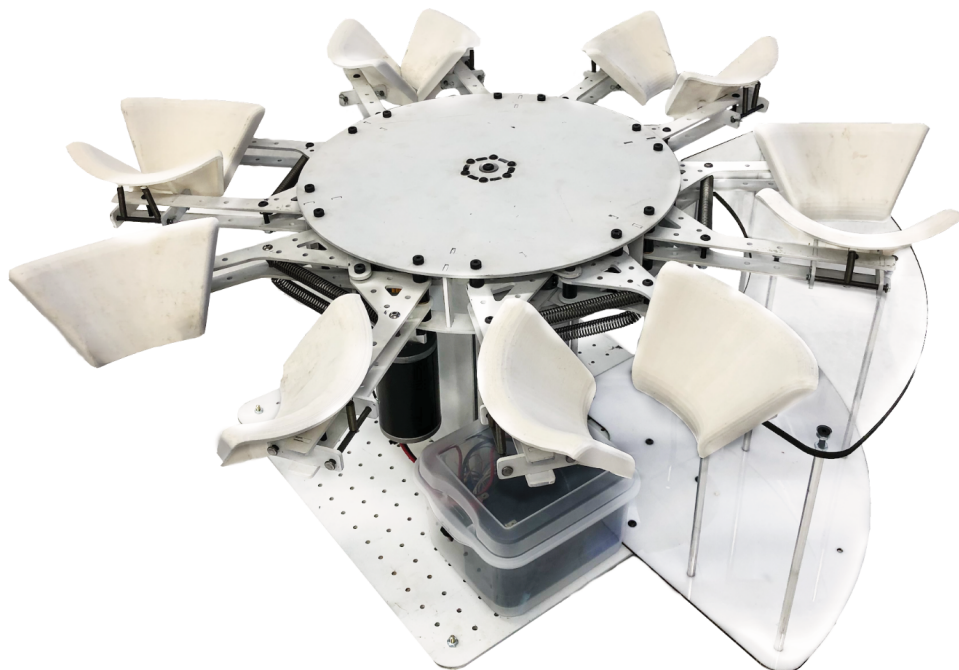
Figure 7.11: Final Assembled System with Battery and Mechatronics

7.6.2 *RoboteQ* Controller Software Setup and Tuning

RoboteQ also has downloadable software on their website that allows for quick and simple communication and tuning of the hardware. Once all the drivers are installed, also available on their website, simply connecting the controller to a computer using USB initiates communication between the software and hardware. Then to enable closed-loop speed control all that is required is the encoder pulse speed, specified under "Encoder" in the "Inputs/Outputs" controls, and "Closed Loop Speed" is selected under "Speed and Acceleration" in the "Power Output" controls as shown in Figure 7.12.
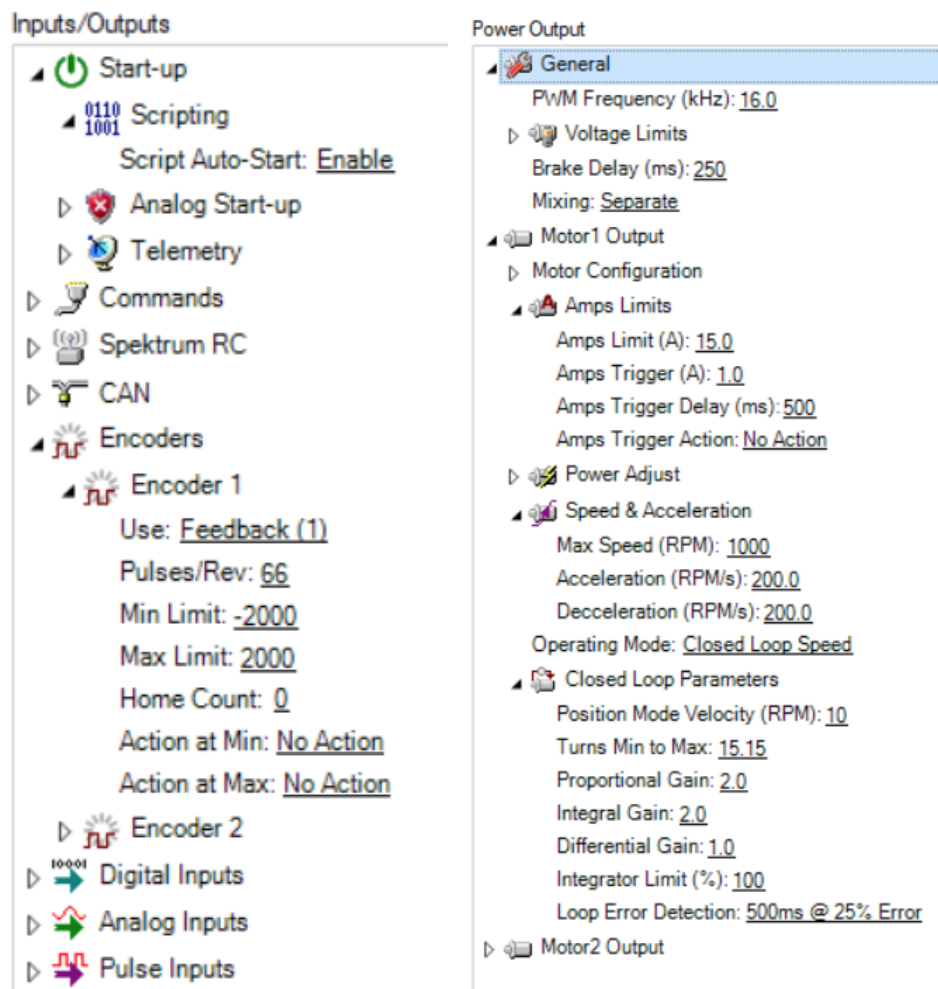
Figure 7.12: Software Settings for Encoder Feedback and Closed Loop Speed Control

The CIMCoder has a pulse rate of 20 pulses/revolution but to account for the 330:1 reduction and also to scale our speed from 0 to 1000 where 1000 corresponds to a speed of 10 rpm a pulse rate of 66 was specified. It is important to note that under "Speed and Acceleration," "Max Speed" should be set with the scale taken into account.

The performance of the system can be optimized by simply adjusting the Proportional, Integral, and Differential Gains under "Closed Loop Parameters" and the Acceleration/Deceleration Rates under "Speed and Acceleration." Again note that the Acceleration rates should be set with the scale taken into account. Once all of the desired settings are chosen, "Save to Controller" should be selected to download to the controller.

Once the settings were downloaded to the controller it was possible to manually adjust the speed using the "Run" control tab shown in Figure 7.13.
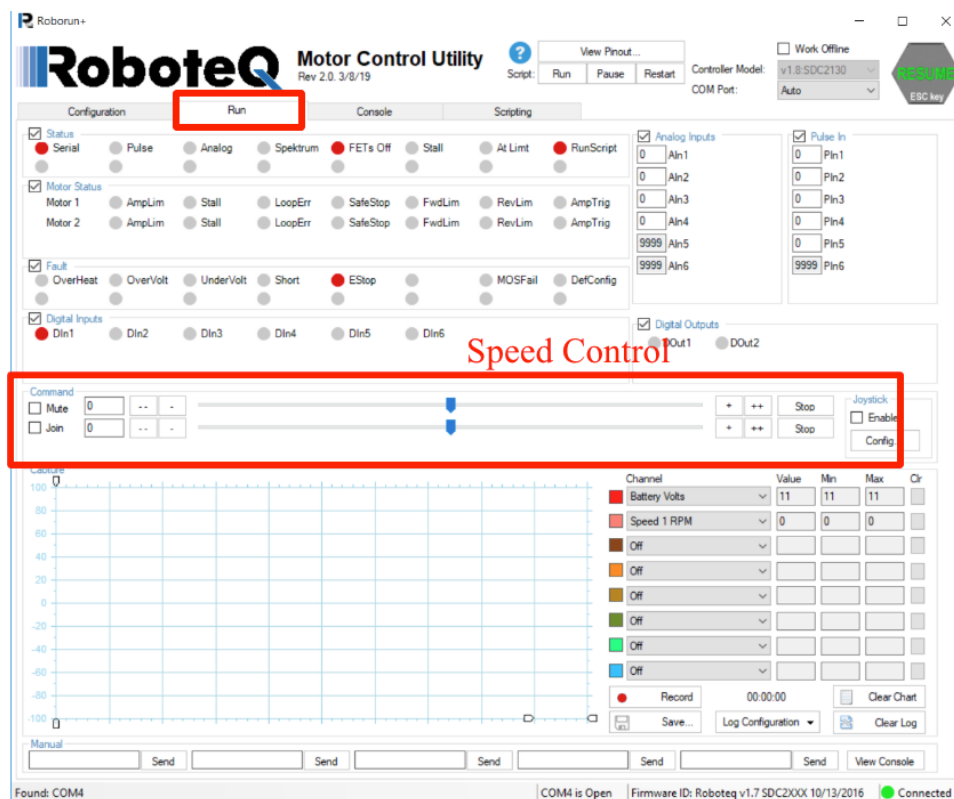
Figure 7.13: Software User Interface for Running the Motor

The controller also needed to operate autonomously without a computer connected to it. To achieve this, a script was written and saved to the controller under the "Scripting" tab. The script used to maintain a constant speed of 5 rpm is shown in Figure 7.14.
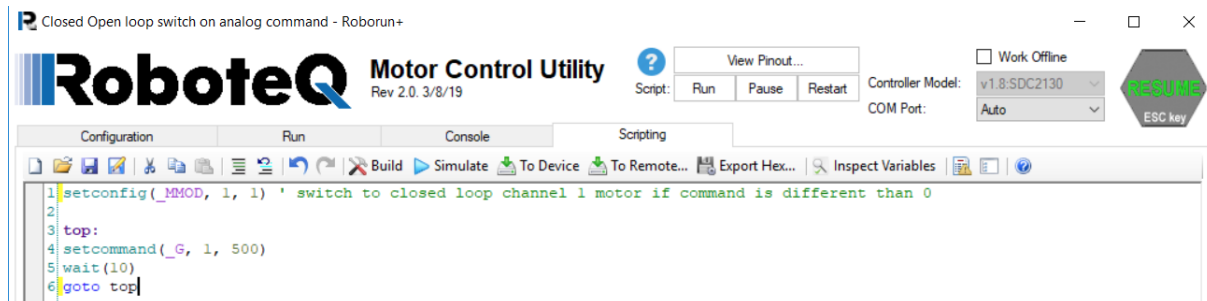
Figure 7.14: Script Downloaded to Controller for Autonomous Operation

The script simply tells the controller to operate in closed loop control mode and to maintain a speed of 5 rpm. The rest of the settings assigned under configuration will be maintained by the controller simply by selecting "Save to Controller" as stated previously.

7.7 Conclusion: System Assembled and Functioning

The design of the trimmer was done with ease of manufacturing and assembly in mind. All of the steel components were manufactured using water-jetting, the gripper cups were 3D printed, the leveling platform was laser-cut, and the remainder of the parts were off-the-shelf components. As a result of these design choices very little machining was required and the bulk of the work, once the components were received, was assembly and bring up.

Fasteners made the assembly straightforward. Starting from the baseplate the system was assembled working bottom up, first adding the superstructure tower, next the indexer cam and the mechatronics were attached, followed by the remainder of the indexer, and lastly the grippers. Once those components were assembled, the zeroing platform was attached to the baseplate and set to the desired height.

After the system was fully assembled the last step was to implement the closed loop control to achieve constant speed. This was done using an encoder inline with the output shaft of the motor to record the speed of the output shaft. Then, using this data along with a RoboteQ motor controller with built-in speed control, the system was tuned so that it could maintain 5 rpm and account for disturbances.

After all of the manufacturing, assembly, integration, and bring up, the system functions as expected. The motor drives the indexer, which rotates around the central pivot and forces the grippers through the different gripping states. However, the system be could not considered successful until it was verified to meet all of the original requirements.

8. Testing and Verification

8.1 Introduction

After building the system, the team performed a series of tests to thoroughly verify the original requirements. The determination of needs and how they were translated to requirements is discussed in Chapter 2 and is summarized in Table 8.1.

Table 8.1: Key System Requirements

Need	Requirements	Value	Tolerance	Units
Holds Lettuce Upright	Gripper Gripping Size	3	± 0.5	in
Rapid Loading	Gripper Loading Size	4.25	± 0.5	in
Full Ejection	Gripper Ejection Size	8	± 0.5	in
Consistent Stalk Height	Height Variation of Lettuce Stem	0	+ 0.00 - 0.25	in
Does not damage lettuce	Grip Strength	6	± 1	lbf
Constant Speed	Rotational Speed	5	± 0.5	RPM
Match Harvesting Rate	Lettuce Head Throughput	2	± 0.1	secs/head

The testing plan, shown in Table 8.2, illustrates the three test areas, Mechanical Dimensions, Loading and Gripping, and Throughput, and equipment utilized to test the system.

Table 8.2: Verification Testing Plan

Test	Equipment	Need	Expected Value	Units
Mechanical Dimensions	Calipers	Gripper Gripping Size	3	in
	Calipers	Gripper Loading Size	4.25	in
	Calipers	Gripper Ejection Size	8	in
Loading and Gripping	Tape Measure, Camera	Consistent Height of Lettuce Stem	0	in
	Force Gauge	Grip Strength	6	lbf
Throughput	Hall Effect Encoder	Rotational Speed	5	RPM
	Stopwatch	Lettuce Head Throughput	2	secs/head

8.2 Mechanical Dimensions

Each state (loading, gripping, ejection) has a required opening dimension between the cups to support the desired handling characteristics of easy, compliant loading, firm gripping, and full and complete ejection. As shown in Figure 8.1, gripping states were tested using calipers to measure the center to center distance of each of the gripping states.
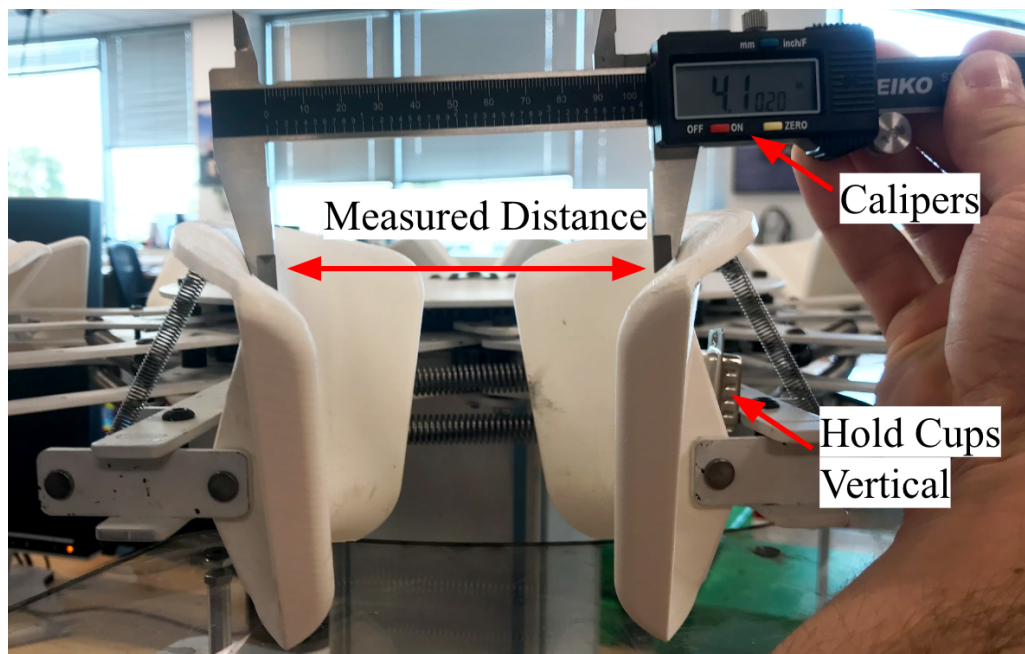
Figure 8.1: Verifying Gripping State Distance with Calipers

The distance between each state was measured a total of five times and the weighted average was found. The results of these tests are shown in Table 8.3.

Table 8.3: Gripper Dimension Verification Results

Need	Requirement	Tolerance	Units	Equipment	Trials	Result
Gripper Gripping Size	3	± 0.5	in	Calipers	5	2.76
Gripper Loading Size	4.25	± 0.5	in	Calipers	5	4.12
Gripper Ejection Size	8	± 0.5	in	Calipers	5	7.93

The results of the test show that the average measurement of gripper distances falls within the desired ± 0.5 in tolerance. In addition, there was less than 10% error between the final measurements and the initial CAD design, which meets the specification of each state.

8.3 Loading and Gripping

During the loading stage a lettuce head is pushed down between the two gripper cups until the stem hits the leveling platform. The lettuce stem must stay at the height of this leveling platform as future imaging systems will depend on knowing the height of the lettuce to determine the diameter of the stalk and thus the cutting location. To measure the consistency of lettuce height after loading, the team simulated regular use by loading lettuce in the loading stage. After the lettuce moved to the gripping stage, where lettuce will eventually be imaged and cut, the motion was paused and a measurement stick was used, as shown in Figure 8.2, to measure the distance of the stem away from the leveling platform.
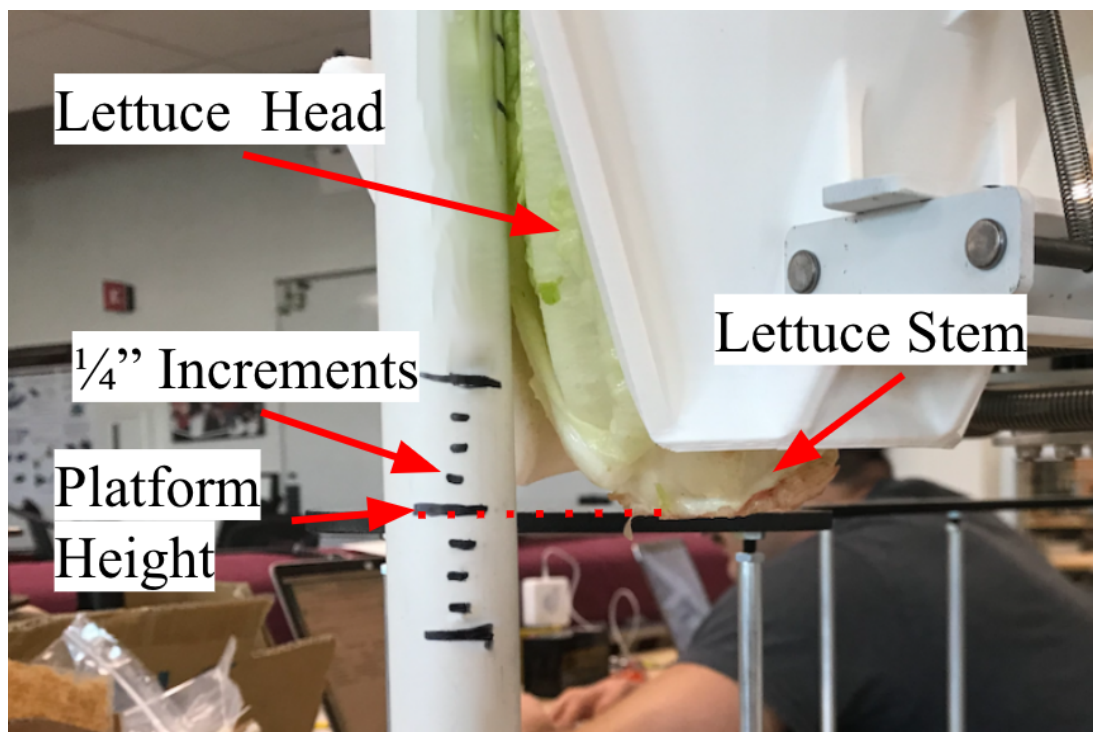
Figure 8.2: Leveling Platform Constant Height Verification with Measuring Stick and Camera

As shown in Table 8.4, 10 trials resulted in an average of -0.113 in below the leveling platform, falling within the desired tolerance of -0.25 in (data is shown in Appendix D2).

Table 8.4: Stalk Height Verification Results

Need	Requirement	Tolerance	Units	Equipment	Trials	Result
Consistent Stalk Height	0	+ 0.00 - 0.25	in	Tape Measure, Camera	10	0.11

Another critical requirement of the machine is that the lettuce is not damaged at any point during handling. As discussed in Section 2.4.3, initial lettuce force testing indicated that the system should not apply more than 6 ± 1 pounds. Although the springs were sized to prevent damage to the lettuce, the team measured the force of the springs using a force gauge, seen in Figure 8.3.
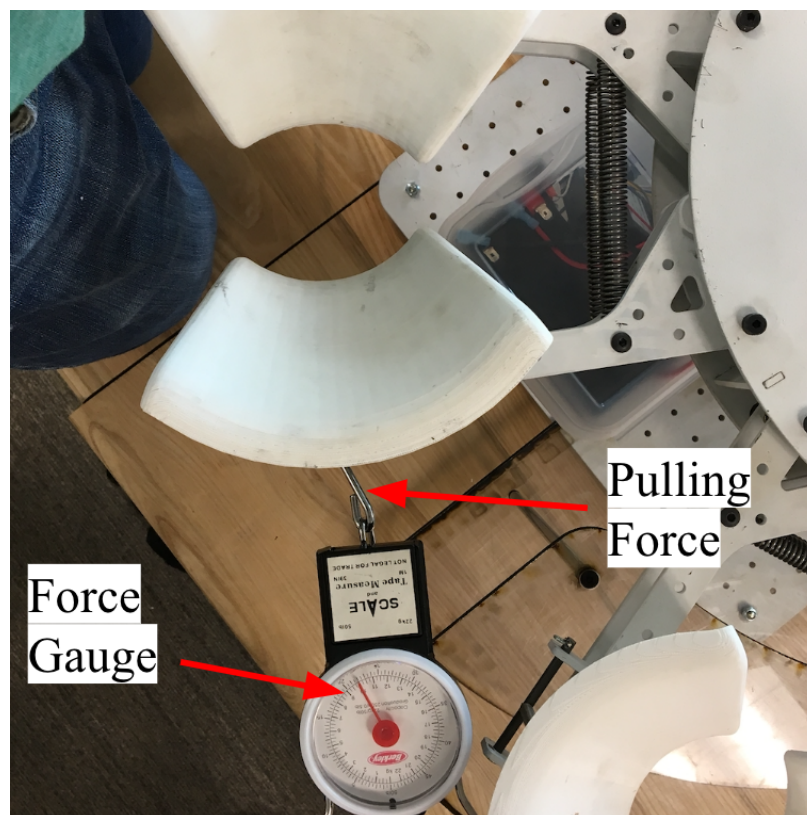
Figure 8.3: Gripping Force Verification with Force Gauge

As shown in Table 8.5, 10 trials resulted in an average force 5.5 lbf, meeting the requirement of 6 lbf. Data is shown in Appendix D2.

Table 8.5: Gripper Force Verification Results

Need	Requirement	Tolerance	Units	Equipment	Trials	Result
Does not damage lettuce	6	± 1	lbf	Force Gauge	10	5.5

8.4 Throughput: Constant Velocity with Closed-loop Control

One of the most important requirements is the system's ability to match the harvesting rate of the manual laborer team of 30 heads/minute which is a throughput rate of 2 secs/head. The system must also be easily loadable by a human; as discussed in Chapter 2, a design of 6 grippers and a requirement of a constant 5 rpm would allow for the desired throughput of 2 secs/head while maximizing loading time and minimizing overall size.

As shown in Figure 8.4, a stopwatch was used to measure 5 complete rotations to verify that the system was able to achieve the desired throughput.

Figure 8.4: Manual Stopwatch to Verify System Throughput

Data for 8 stopwatch tests is shown in the Appendix D3, and summarized in Table 8.6. The results show that the average rotational speed was 5 revolutions per minute, meeting the original requirement set by the team.

Table 8.6: Throughput Requirements Verification Results

Need	Requirement	Tolerance	Units	Equipment	Trials	Result
Constant Speed	5	± 0.5	rpm	Stopwatch	8	5

Since it was crucial that the rotations have a constant speed for ease of loading, sensing, and cutting further testing was needed to verify that the speed was always within the tolerance of ±0.5 rpm. Using the data recorded by the encoder it was possible to demonstrate that during the entirety of the rotation the systems speed is always within the range of 5 ± 0.25 rpm as shown in Figure 8.5, satisfying the requirement with a factor of safety of 2.
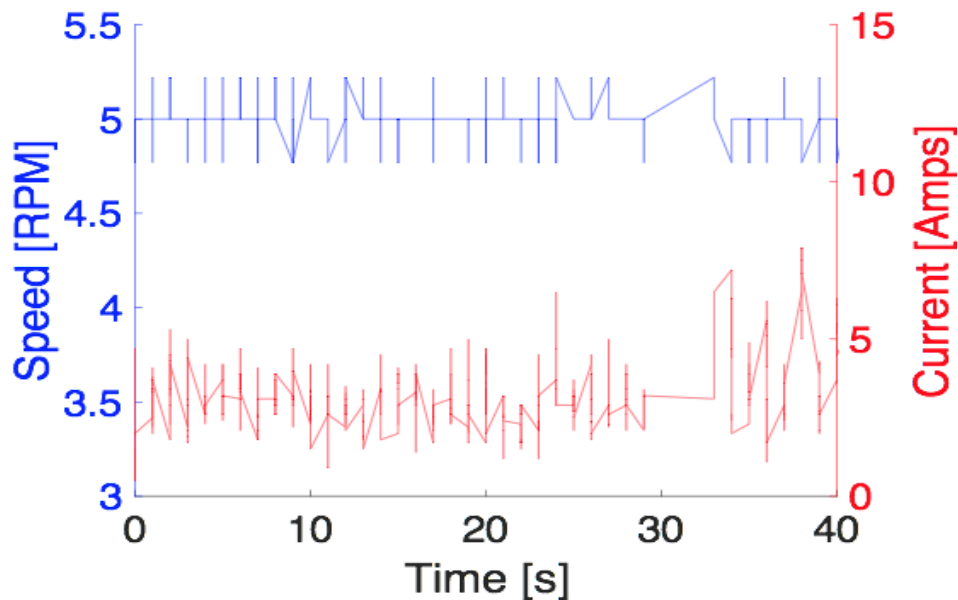
Figure 8.5: Speed and Current plot shows constant 5 ± 0.25 rpm

Using both a stopwatch and the speed data recorded by the encoder it was verified that the system met the goal speed and stayed within the tolerance of 5 ± 0.5 rpm. The results are shown in Table 8.7. Data is in Appendix D3.

Table 8.7: Constant Speed Verification Results

Need	Requirement	Tolerance	Units	Equipment	Trials	Result
Match Harvesting Rate	2	± 0.1	secs/ head	Stopwatch & Design	8	2

This speed, along with the design of 6 grippers, guarantees the system meets the required throughput of 30 heads/minute, or 2 seconds per head.

8.5 Gripper Lettuce Handling and Stiffness Testing

To further validate the design of the indexer and gripper subsystems it was crucial to test the system with actual lettuce and get customer feedback. Also physical testing allowed for the abuse case FEA analysis to be checked against the attributes of the physical system. This was done when the team visited the farm to test the gripper's abilities.

Through testing with many different sizes of lettuce heads, it was deemed that unexpected friction between the lettuce and the cups made loading difficult unless the lettuce was douched with water to lubricate the loading. This water douching would have been done anyway, to help insert the trimmed hearts into the bag, so now the partner farm simply has to reorder the series of steps in the harvesting process to douche the lettuce before this new automatic trimmer.

The gripper's ability to securely hold the lettuce was improved with the testing at the farm. Adding additional linkage and cup springs, shown in Figure 8.6, to each gripper allowed for a

slightly tighter, but still not crushing, hold on the lettuce so that it would not shift when cut by the blades.

Figure 8.6: Additional Linkage and Cup springs added to securely hold lettuce

Finally, testing revealed that the gripper system was sufficiently strong to withstand the aforementioned abuse case, as predicted, yet the deflection and stiffness that occurs such in loading was more than expected. The bushing-shoulder bolt interface was looser than predicted and caused more than ideal deflection. Such a deflection not only makes the product feel weak to a customer, but also causes performance issues with holding the lettuce at a precise height for the machine vision camera diameter determination. Future redesigns of the gripper should feature larger shoulder bolts and bushings, with the bushings further apart to resist moment loads.

8.6 Conclusion: Requirements Satisfied

After designing, manufacturing, and assembling a system to fulfil key requirements, it was critical to verify that the original requirements were actually satisfied. The primary needs and requirements that needed to be fulfilled included the geometry of the gripper states, stalk height consistency through the gripping stage, gripper force, and overall system throughput.

As discussed, the team verified these key requirements through controlled, quantitative tests measuring the specifications of the built system. The results of these tests are shown in Table 8.8.

Table 8.8: Verification Results Demonstrate Satisfied Requirements

Need	Requirement	Tolerance	Units	Equipment	Trials	Result	Satisfied
Gripper Gripping Size	3	± 0.5	in	Calipers	5	2.76	✓
Gripper Loading Size	4.25	± 0.5	in	Calipers	5	4.12	✓
Gripper Ejection Size	8	± 0.5	in	Calipers	5	7.93	✓
Consistent Height of Lettuce Stem	0	+ 0.00 - 0.25	in	Tape Measure, Camera	20	0.13	✓
Grip Strength	6	± 1	lbf	Force Gauge	10	5.5	✓
Rotational Speed	5	± 0.5	RPM	Hall Effect Encoder	8	5	✓
Lettuce Head Throughput	2	± 0.1	secs/ head	Stopwatch	8	2	✓

As shown, the system satisfied all of the original requirements and can be delivered to the partner farm. Next steps include developing the lettuce-imaging trimming system and incorporating it into the farm's overall harvesting process.

9. BOM and Cost Analysis

9.1 Introduction

In Chapter 2, it was explained that the School of Engineering provided the team with a $1,500 funding grant to facilitate the completion of the project. In addition, there was flexible funding available through Santa Clara's Robotic Systems Laboratory's Grant with the Partner Farm if needed. This chapter will review how both the budget was successfully used to complete the project and the cost breakdown for building one system.

9.2 Budget Utilization

Project funding covered three iterations of the system. Two wooden mockups were used to tune the cam profile and linkage geometries, and to get customer feedback. A third and final metal prototype included one fully stand-alone motorized prototype made for Romaine Robotics, and a prototype for the partner farm consisting only of the indexer and gripper subsystems. The costs of each of these iterations is shown in Table 9.1.

Table 9.1: Allocated Budget

Products	Cost ($)
First Wooden Mockup	91.30
Second Wooden Mockup	70.25
Romaine Robotics and Partner Farm Metal Prototype	1328.04
Total	1489.59

It can be seen from Table 9.1 that Romaine Robotics managed to come in just under $1500, all of which came from the School of Engineering funding grant.

9.3 Bill of Materials

In Table 9.2, the cost of building one complete motorized prototype is broken down. It should be noted that the cost of raw metal and water jetting was covered by the partner farm.

Table 9.2: BOM for Metal Prototype as Built

Product	Location	Part #	Qty	Qty/Unit	Cost/Unit	Cost	Subtotal
CIM Coder	Andymark	AM-3314A	1	1	42.00	42.00	42.00
CIM Sport Short Motor Block	Andymark	AM-3769	1	1	5.00	5.00	5.00
CIM Sport Gearbox	Andymark	AM-4008_080	1	1	96.00	96.00	96.00
CIM Motor	WCP	217-2000	1	1	32.99	32.99	32.99
1/2" Hex Bore 16T Sprocket	WCP	217-2642	1	1	7.99	7.99	7.99
1/2" Hex Bore 66T Sprocket	WCP	217-2628	1	1	15.99	15.99	15.99
#25 Chain (10' of chain)	WCP	217-2775	1	1	11.99	11.99	11.99
Clamping Shaft Collar - 1/2" Hex ID	WCP	217-2737	1	1	4.99	4.99	4.99
1.125" Bearing Bore Plastic VersaHub Spacer 1/2"	WCP	217-2591	1	1	2.99	2.99	2.99
WCP Cam	WCP	217-3431	1	1	4.99	4.99	4.99
0.500" ID x 1.125" OD Flanged Bearing	WCP	217-2731	2	1	2.49	2.49	4.98
DELRIN WASHER (2") 1/2" HEX ID	WCP	217-3265	2	6	6.99	1.17	2.33
Unthreaded Spacer Stock	McMaster	92377A213	10	1	10.07	10.07	100.70
1/4" Shoulder Bolt - Length 2-	McMaster	91259A104	12	1	1.65	1.65	19.80
10-24 Locknuts	McMaster	97367A111	36	50	9.72	0.19	7.00
Button Head Hex 10-32 Thread, 3/4" Long	McMaster	91255A269	6	50	12.20	0.24	1.46
Follower Wheel	McMaster	6831K42	6	1	23.57	23.57	141.42
Shoulder Bolt - Length 1-1/4"	McMaster	91259A544	12	1	1.15	1.15	13.80
Button Head Hex: 10-32 Thread, 1-1/8" Long	McMaster	91255A028	24	25	10.4	0.42	9.98
10-32 Locknuts	McMaster	90633A411	24	100	3.18	0.03	0.76
Oil-Lite Bushing 1/4 ID	McMaster	6338K411	24	1	0.67	0.67	16.08
1/16 Nylon Spacer	McMaster	90176A152	24	25	1.9	0.08	1.82
11/16 Nylon Spacer	McMaster	90176A163	6	25	2.99	0.12	0.72
9/16 Nylon Spacer	McMaster	90176A161	12	25	2.86	0.11	1.37
1/2 Nylon Spacer	McMaster	90176A159	12	25	2.81	0.11	1.35
7/16 Nylon Spacer	McMaster	90176A158	12	25	2.74	0.11	1.32
3/32 Nylon Spacer	McMaster	94639A445	24	1	1.93	1.93	46.32
Clevis Pin	McMaster	98306A116	24	25	10.19	0.41	9.78
Cotter Pin	McMaster	98335A031	24	100	5.76	0.06	1.38
8-32 Locknuts	McMaster	90633A009	6	100	3.23	0.03	0.19
Button Head Hex 8-32 Thread, 1" Long	McMaster	91255A199	6	50	15.5	0.31	1.86
#8 ID Steel Washer	McMaster	92141A009	6	100	2.00	0.02	0.12
Button Head Hex 1/4"-20 Thread, 5/8" Long	McMaster	91255A539	2	50	8.57	0.17	0.34
1/4 Washer	McMaster	93852A102	2	50	6.17	0.12	0.25
1/2 Rotary Shaft	McMaster	5947K13	1	1	10.62	10.62	10.62
Hex Screw - 10-32 Thread Size, 1/2" Long	McMaster	91253A003	4	100	11.18	0.11	0.45
Small Spring for Cup Angle	McMaster	9044K85	24	3	5.26	1.75	42.08
Large Spring for Closing Gripper	McMaster	9044K126	12	3	10.26	3.42	41.04
Swivel Leveling Mount	McMaster	6111K81	8	1	5.88	5.88	47.04
10-32 Thin Jam Nuts	McMaster	90480A195	12	100	1.89	0.02	0.23
10-32 x 1.25 Flat Head Screw	McMaster	91253A012	6	25	4.85	0.19	1.16
Polycarb Sheet 12x14 x 1/4"	McMaster	8574K43	2	1	26.17	26.17	52.34
Onyx Filament Spool	MkForged	F-MF-0001	1	1	189.00	189.00	189.00
Rust-Oleum Clean Metal Primer	H Depot	7780830	2	1	4.27	4.27	8.54
					TOTAL		1002.57

The total cost of building one system was just slightly over $1000. This is a very reasonable cost for the improved efficiency gained as a result of implementing this system.

9.4 Conclusion

Romaine Robotics successfully stayed under budget while performing multiple iterations to get to a final design. This was achieved because the team designed with cost in mind and did not make purchases without first observing what the effect on the allowed budget would be. This system also has potential for cost reductions in the form of bulk purchases, selecting cheaper materials, and standardization of parts. Even at the price of $1000, perhaps $3000 with the vision and cutters added, this is very reasonable considering the benefit the farm would gain through increased harvesting efficiency.

10. Business Plan

10.1 Introduction

The following Business Plan represents a hypothetical academic exercise that embodies steps the team could take to turn their proof-of-concept prototype into a profitable business.

10.1.1 Abstract

Team Romaine Robotics plans to partner with a corporation to sell their Automatic Romaine Lettuce Heart Trimmer via a robotics-as-a service sales model. The partner will leverage their existing network and system to handle the manufacturing, marketing, sales, distribution, and service of the product. Romaine Robotics will remain an independent design and development company specializing in compact, in-field farm automation equipment that still utilizes laborers to provide efficiency-increasing systems with a lower barrier to entry than fully-robotic expensive competitors.

10.1.2 Background: Problem, Market, and Predicate

Team Romaine Robotics has built an Automatic Romaine Lettuce Heart Trimmer which aims to address the growing labor shortage in the agriculture industry. This shortage, arsing due to improving standards of living and a changing political landscape, is causing farms such the team's Partner Farm in Salinas to be unable to fully harvest their crops before the lettuce rots in the field, wasting money, time, and water. The Partner Farm has expressed that if they could harvest more, they'd have the demand for and capacity to plant, grow, and sell more.

The romaine lettuce heart industry, despite occasional food safety concerns, is still a growing industry, with demand for lettuce increasing by 30% in the past 30 years [1]. In 2015, lettuce ranks second only to potatoes in annual eatings per capita and is a "$1.9 billion industry, ranking

first as the leading vegetable crop in terms of value" [5]. Of all lettuce consumption, 49% of lettuce consumption was leaf, which includes romaine and romaine hearts.

The current romaine heart harvesting process features crews of human laborers cutting and trimming the lettuce with handheld knives before placing the lettuce onto a conveyor belt that pulls the heads into a single stream line for packaging on the tractor. Time studies at the partner farm show laborers can perform the initial cut in about 1-2 seconds, but then about 4-10 seconds trimming, greatly slowing down the takt time (time per head) or production.

10.1.3 Company Goals and Objectives

Team Romaine Robotics seeks to establish itself as a leader in automated farm equipment, specifically targeting romaine lettuce hearts but eventually expanding to other equipment for different crops. By leveraging Silicon Valley robotics engineering expertise, the team members plan to build precise equipment featuring robotics, computer vision, and perhaps machine learning AI to automate harvesting and processing of delicate and complex crops previously thought impossible to automatically harvest.

The company hopes to establish itself as a valuable startup with a strong portfolio of products and patents that they can license out to partner corporations who would help with manufacturing, sales, marketing, distribution, and service. The company wants to remain independent and non-exclusive, reserving the right to partner with numerous corporations to enable reaching different types and depths of markets.

At this time, Romaine Robotics is seeking investment to expand their team and space to continue the design and development of their first flagship product, their Automatic Romaine Heart Trimmer.

10.2 Value Proposition and Product Description

The Romaine Robotics automatic lettuce trimmer is a machine for romaine lettuce farms suffering from labor shortage and the inability to fully harvest their crops. The automatic trimmer uses machine vision to quickly and accurately cut off the bottoms of romaine heads, so laborers only have to perform the initial cut, resulting in either more harvesting or equal harvesting with fewer laborers, alleviating the labor shortage. Compared to large and expensive robotic full harvesting systems, the Romaine Robotics machine merely trims, still utilizing the speed of laborers for initial cuts with a machine at a fraction of the size and cost, allowing it to be integrated into any work team. Compared to traditional manual trimming (see Table 10.1), the efficiency improvements can translate into savings on labor costs which directly improves the bottom line.

Table 10.1: Traditional vs Automatic Trimming Value Proposition to Farms

	Traditional Manual Trimming	**Automatic Trimming**
Time per Plant	10 seconds	5 seconds
# of laborers needed	12	6
Labor cost per hour	(12 workers)*($25/hr) = $300	(6 workers)*($25/hr) = $150
Machine cost per hour	0	$100 ($75 rental fee + $25 operator)
Total cost per hour	$300	$250
Hours per acre	15	15
Total Cost per acre	$4,500	**$3,750**
	$750/acre savings for farm	

At this time, the team has built a prototype featuring the Gripper, Indexer, Superstructure, and Mechatronics subsystems necessary to handle and control the delicate lettuce and move it through the computer vision and cutting systems that have already been developed by the Partner Farm. The Team now plans to reverse-engineer a custom vision system at a cheaper cost using an off-the-shelf RGB camera, linear actuators, and cutting blade systems.

10.3 Potential Markets

10.3.1 Romaine Lettuce and Expansion

At this time, the company is planning on targeting mid and large scale (multi-acre) romaine lettuce farms that could utilize their product to their full potential and rapidly increase their harvesting and thus production and sales rates. Sales to farms will begin in California and then Arizona, where the vast majority of romaine lettuce production is based. If successful, expansion could be taken to other states or internationally. With this conservative growth strategy, the team and its partner corporations will be able to meet production, sales, and service demands while ramping up.

10.3.2 Future Crops

The Team believes that beyond just romaine lettuce, their expertise and understanding of the market can enable the company to be successful manufacturing other in-field automation equipment for other crops that are delicate and difficult to harvest. Crops such as strawberries, asparagus, apples, berries are fragile or feature complicated harvesting procedures and thus like romaine lettuce are currently only slowly harvested by human laborers. Building automated picking, trimming, or processing equipment that is compact and implementable on existing tractors and in-field equipment can enable farmers to increase the efficiency of their harvesting operations without having to redesign the entire harvesting system architecture. Lowering the barrier to entry by providing equipment that does not completely replace, but rather empowers' human laborers is where Romaine Robotics sees their unique differentiator compared to previous automation attempts.

10.4 Competitors

Although a lot of research is being done in robotic harvesting/picking systems by various companies and universities shown around the world (summarized in Appendix G1), few competitors are publicly known to be working on automating romaine heart harvesting or trimming. The following benchmarking table highlights the value that the Romaine Robotics trimmer provides, specifically featuring a lower cost to operate and/or manufacture than all competitors.

Table 10.2: Benchmarking and Comparison among Romaine Lettuce Harvesting Systems

	Current Laborer Team	Partner Farm Robot Harvester	Taylor Farms Water Jet/Bandsaw	Romaine Robotics Trimmer
Output Product	Trimmed Romaine Hearts	Cut Romaine Heads	Cut romaine leaves (not hearts)	Trimmed Romaine Hearts
Cutting Method	Knife held by laborers. ~5 seconds spent trimming per head	Chopping blade on robot arm directed by overhead LIDAR	Water Jet or bandsaw 0.5" off ground slices 5 heads at once.	Spinning blades trim bottom of heads. Height determined by machine vision.
Output [product/minute]	30	30	100	30
Complexity (max 5)	1	5	4	2
Operators Needed [#]	0	3	4	1
Packers Needed [#]	2	2	6	2
Harvesters Needed [#]	12	0	0	6
Operating Cost (labor+utilities) [$/hr]	350	100	550	210
Cost to manufacture [$]	100	50,000	30,000	3,000

Thus, the Romaine Robotics Automatic Romaine Heart Trimmer utilizes its low manufacturing cost (discussed below in Sections 10.6 and 10.7) and its labor savings to provide a combined relatively low-cost and easily implementable product to improve farms' harvesting speeds and efficiencies.

10.5 Sales and Marketing Strategies

10.5.1 Corporate Partnership Licensing

As discussed in 10.1.3, the company hopes to partner with other corporations that already specialize in manufacturing, marketing, selling, and distributing farm equipment. A corporation, such as John Deere, that already has an international network and brand recognition would greatly accelerate the growth and sales abilities of Romaine Robotics and could certainly be worth whatever cut the partner corporation would take to cover the management and operating costs. Romaine Robotics hopes to form non-exclusive licensing deals with numerous corporations to enable the Team to reach different markets such as international regions or farm sizes.

Romaine Robotics will license the use of the Intellectual Property (IP) for its trimmer or other products to these partner corporations. Romaine Robotics will still own the IP and thus allow them to build up a product and patent portfolio that can make them a lucrative acquisition for a larger company hoping to add farm automation and robotics expertise to their business capabilities.

10.5.2 Sales to Farms: Robotics as a Service

Romaine Robotics proposes a Robotics as a Service Sales Model to reach the farms. Instead of outright selling, renting, or leasing the trimmer, the partner corporation will always own and be responsible for the equipment and the farmer only has to pay per day of use. This massively lowers the barrier to entry for farmers, who will not need to buy an expensive piece of capital equipment and can instead just pay for the use of the machine on the days they are harvesting. A low barrier to entry is key since farmers may be hesitant to try adjusting their tried-and-true process unless they can be shown clear results and returns for a minimal initial investment/trial period.

This approach also maximizes the availability of inventory and sales for the partner corporation. When one area is out of harvest season the farmers will want to return the equipment and then the corporation can redistribute and make sales with farmers in another region where the harvest is about to begin (example Salinas and Yuma harvesting seasons follow after each other). This minimizes the amount of equipment the partner corporation needs to build and service and maximizes their use and life throughout the year, addressing the issue of the "seasonality" of harvesting equipment.

10.5.3 Marketing, Branding, and Pitch

Sales of the equipment will be done via a Business-to-Business sales team. Leveraging the partner corporation's existing sales and distribution networks will allow this team to reach farmers and pitch the products. The product's ability to address the farmer's growing labor shortage while having a low barrier to entry and overall operating cost will be the major selling points of the pitch. The product may be rebranded by the partner corporation, such as the "John Deere Automatic Romaine Heart Trimmer (powered by Romaine Robotics)", as this brand recognition and loyalty will also serve as a positive characteristic and reflection of the product's quality and performance.

10.6 Manufacturing Plan

The manufacturing of the trimmer will be managed and overseen by the partner corporation, allowing them to leverage their existing manufacturing centers or relationships with contract manufacturers. The water jetting of the steel and machining of other custom components could easily happen overseas at lower cost before the parts are imported to a local plant for assembly, packaging, and shipping. Due to the compact nature of the trimmer, it can be shipped via conventional methods right to the farmer, with no need for a special delivery and setup team like other, larger capital equipment offered by competitors.

10.7 Product Cost and Price

As outlined in Chapter 9, the Bill of Materials for the motorized metal prototype had a total cost of about $1,000. Notably, this cost does include the raw material and water jetting of the steel plates, nor the cost of labor for powder coating and assembly of the system. Also importantly, this does not include the cost of the vision and cutting subsystems. However, these systems have already been developed by the team's Partner Farm and should not cost too much as a standard RGB camera, a small computer for simple vision processing, and a small linear actuator with off-the-shelf cutting blades would be sufficient. Also, note that the $1,000 cost of the metal prototype was quite high, using small-quantity packages from reseller McMaster-Carr, and could have been made much cheaper if the device was built at scale. Thus, with these components, manufacturing, and assembly costs, the Team estimates that a total cost for the product at scale would be about $3,000.

As discussed in Section 10.5, the product will be sold via a robotics as a service sales model, charging the partner farms a price per day used. Based on the amount of money saved to the farmer, $750/acre with an acre being harvested in a day, it is feasible that the the partner corporation could charge a service fee of about $600/day, thus still providing a savings value to the farmer of $150/day. This price and thus total company profitability is summarized below in Table 10.3.

Table 10.3: Pricing and Profitability

Item	Value
Cost per machine ($)	3,000
Income per machine per day ($)	600
Income per machine per year ($)	40,000
Estimate machines sold Year 1	20
Cost per year ($)	60,000
Income per year ($)	800,000
Profit per year ($)	740,000

With these profits, a portion of them would be distributed between the partner corporation and Romaine Robotics per the rates established in the IP licensing agreement. Because the partner is handling the manufacturing, marketing, sales, distribution, and service of the system it is likely that they take the vast majority of the profits to cover their operating costs. However, the income Romaine Robotics receives will still be sufficient to operate their engineering team and continue to design and prototype new products since they will have non-exclusive licensing deals with numerous partner corporations, allowing them to bring in a lot of steady, continual income for the design of any one product.

10.8 Service and Warranties

In addition to handling the manufacturing, sales, and distribution of the system, the partner corporation will also be responsible for managing service and warranties by leveraging their existing network of field technicians and customer service call centers. This will free Romaine Robotics up so that they can focus on designing the next version of the product or a new system for a different crop. If major issues arise in the design that is more than a minor service issue, the partner corporation will contact Romaine Robotics so a mitigation plan and redesign can be implemented if necessary.

Warranties shouldn't be a major issue since the farmer does not actually own the equipment, they merely pay for its use in the robotics as a service sales model. This model also enables the partner corporation to perform preventative maintenance and routine service during the periods in between harvesting seasons when the farmer returns the equipment.

Overall, the team plans to build a high quality product robust enough to withstand abuse from both users and the environment, minimizing the overall amount of service required.

10.9 Financial Plan and Investor ROI

At this time, Romaine Robotics is still developing a proof-of-concept prototype to demonstrate the technical feasibility of the Automatic Romaine Heart Trimmer. The Team is pursuing a first round of investing from friends, family, and angels to sustain the team's development for the next year as it finished the design, patent application, and manufacturing a production unit it can present to partner corporations to secure the licensing deals. This money will be used for buying SolidWorks licenses, paying engineering salaries, purchasing prototyping tools, parts, and equipment, and renting a space for design and development.

Investors will receive a return on their investment upon the establishment of the licensing deal and initiation of income from the sale of products once the design it complete. Although it is difficult to predict the exact ROI timeline as it is highly dependent on the terms of the licensing deal, initial estimates extrapolated from Table 10.3 show a positive return in about 3-4 years to be feasible. Thus, Romaine Robotics believes that the design and development of its Automatic Romaine Heart Trimmer and future potential crops will be successful and investors should get in early to maximize their ROI.

11. Engineering Standards and Realistic Constraints

11.1 Economic: Addressing Global Food Demand

The introduction of a robotic lettuce trimmer will help sustain and advance romaine lettuce harvesting, helping combat the increasing demand for romaine lettuce. The global population is expected to grow by over 2 billion by 2050, requiring agricultural production to double if it is to meet the increasing demands for food and bioenergy [1].

As shown in Figure 11.1, the production of romaine lettuce is growing rapidly, at a rate of almost 1 billion pounds per decade.
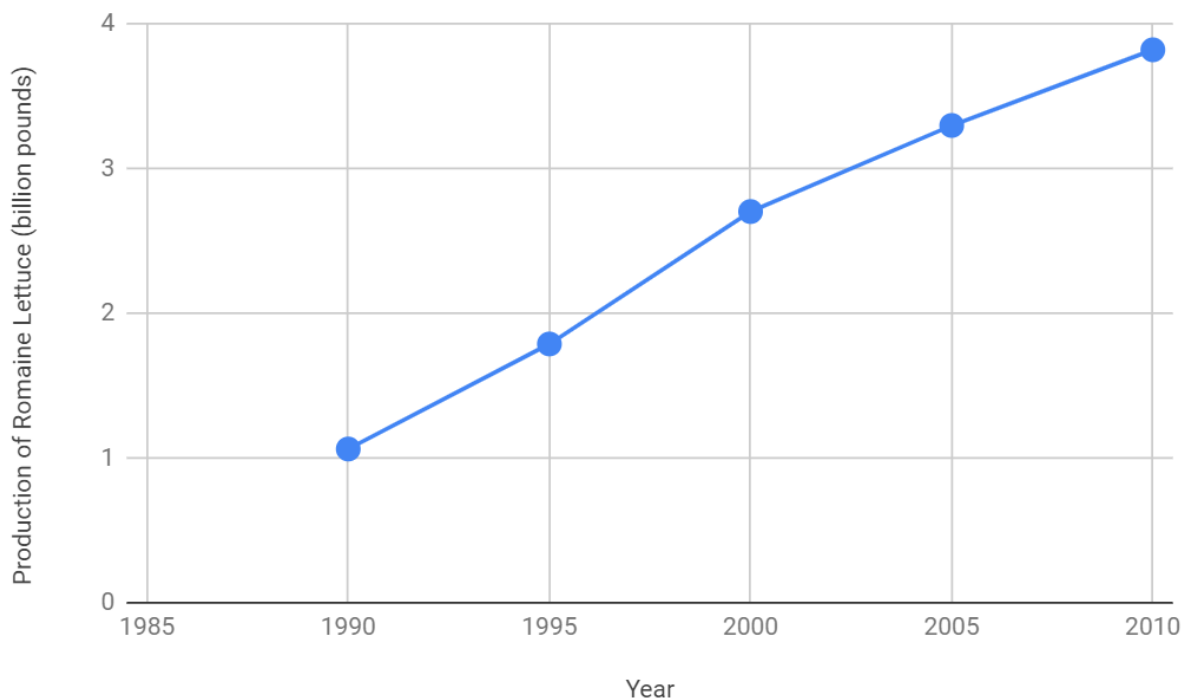
Figure 11.1: Increasing Romaine Lettuce Production [1]

11.2 Political: Growing Labor Shortage

Despite the growing demand of romaine lettuce, there is a shrinking labor force for romaine harvesting farms. This trend is illustrated in Figure 11.2, showing that the number of hired farmworkers has decreased by 22% in the last 30 years.
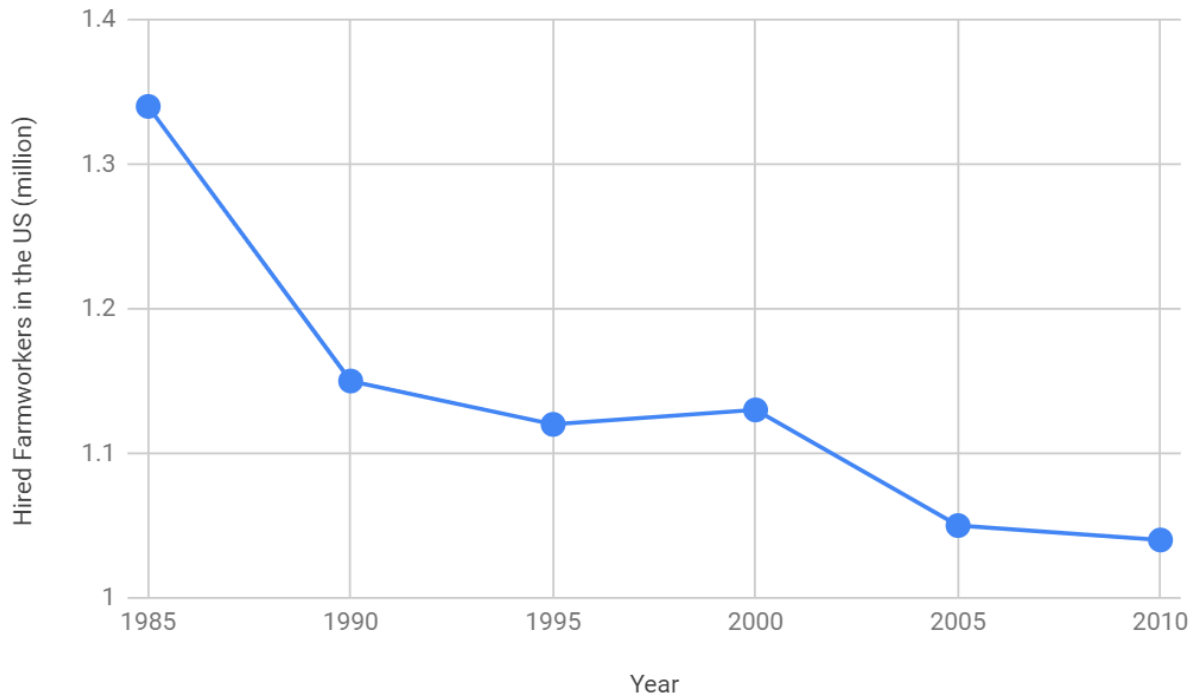
Figure 11.2: Decreasing Labor Availability in Agriculture [2] [3]

Although labor trends are very complex, restricted immigration is contributing to the labor shortage. Immigrants, both documented and undocumented, have historically made up a large component of the agricultural labor force. However, the United States is becoming more and more closed off, and many immigrants are finding other more desirable jobs. As the number of agricultural farm workers continue to decrease, automation will become more necessary.

11.3 Ethical: Alleviating Difficult Human Labor

Automating difficult tasks allows humans to work more interesting and fulfilling jobs. Although many believe robots are replacing jobs, a lettuce trimming system will not displace jobs but will fill a gap in employment. Agricultural labor is backbreaking work. Bending over in the field for hours on end is exhausting and can have serious health consequences. The Romaine Robotics trimmer creates a new operator job where the user can sit up in the tractor, out of the sun and dirt. Teams could have workers rotate through this positions, therefore alleviating the longevity of the difficult labor for all workers.

Additionally, by decreasing dependency on labor, food can be more reliably produced, helping to address food security. Furthermore, automation will allow farms to produce more yields with higher quality at lower expenses in a sustainable way that is less dependent on the labor force.

11.4 Health and Safety: Minimizing Human Contamination

A lettuce trimmer could improve produce safety throughout the harvesting process. Current harvesting processes have many workers directly handling romaine hearts. This process, seen in Figure 11.3, shows that produce is handled by multiple humans.
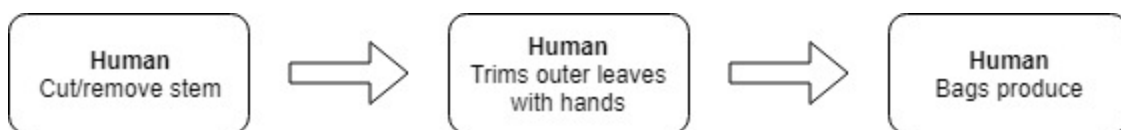
Figure 11.3: Current Romaine Heart Harvesting Process

Using this method, at least 3 workers will have handled the produce before it is ready to be sold. Any one person with dirty hands could contaminate the produce which could have serious consequences for the farm and romaine lettuce brand.

The team's trimmer reduces the number of workers handling the hearts directly. As shown in Figure 11.4, humans are removed from the trimming process.

Human Cut/Remove Stem	→	Conveyor Belt Moves Lettuce	→	Robot Trims Lettuce Leaves	→	Human Bags Produce
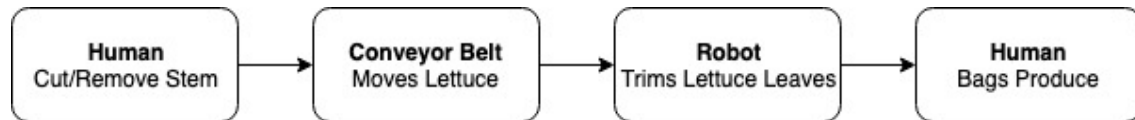
Figure 11.4: Lettuce Trimmer Harvesting Process

This new process for romaine heart harvesting with robotic trimming lets only 1 worker directly handle the hearts. Workers upstream from the robot handle the lettuce by their exterior leaves, which are removed by the trimmer. The hearts are supplied to the bagging and quality control worker without opportunity for human contamination. Ensuring sanitization with this single bagging worker is far easier than the sanitation of multiple workers.

11.5 Sustainability: Reducing Food Waste

The mechanically automated trimming reduces overall waste in harvesting by ensuring a consistent level of quality in trimmed romaine hearts. Previously, lettuce would rot in the fields because it could not be harvested in time [4]. By providing a reliable system that can provide a quantifiable harvest rate and is less dependent on labor availability, the number of wasted hearts can be reduced, increasing profits for farms and providing more food for those who need it.

12. Conclusion

12.1 Summary

The *Romaine Robotics* senior design team, contracted by a Partner Farm, redesigned a romaine heart trimmer to improve its ability to handle and control the lettuce during the trimming process, allowing it to be consistently sensed and cut. Fully implemented, the system has the potential to greatly increase the efficiency of the romaine heart harvesting process, enabling full harvests in the face of labor shortages and growing demands.

To redesign the system, the farm's needs were identified and translated into quantitative requirements with some given directly by the farm and others, such as the maximum gripping force, determined through experimentation. System design included FEA, hand calculations, kinematic analysis, and several iterative prototypes to prove concepts and obtain quality feedback from the customer. Finally, the team manufactured a full size metal prototype that can be incorporated into the partner farm's design.

System level testing verified that all requirements were met by the final design, including safely loading, gripping, and ejecting the lettuce while maintaining a constant rotational speed for the trimmer. The system has been accepted and integrated by the Partner Farm with their existing trimmer for field evaluation during a later growing season.

12.2 Future Work

The primary potential for future work resides in the design, manufacturing, assembly, and tuning of vision and cutting systems for the motorized metal prototype the team built and delivered to the SCU Robotics Systems Lab. The vision system could be designed with an off-the-shelf camera and computer using custom machine vision recognition software to measure the diameter of the stalk. The cutting system might use spinning blades like the Partner Farm, but instead use

a smaller and cheaper linear actuator to achieve the necessary ± 0.5 in of vertical adjustment needed for trimming.

Other future work could include redesigning the entire harvesting process from the ground up, as opposed to just adding an in-line trimmer. Investigating the Partner Farm's robotic harvester and finding ways to make it cheaper, faster, and produce higher yields could be a better long-term research project.

12.3 Lessons Learned

Through this Senior Design project, the team learned the importance of project and time management and having frequent meetings both as a team and with our advisor and customer to confirm the direction and results of work. Understanding the difference between requirements and specification, verification and validation, and the overall design process from investigation to completion proved insightful. Working with a client and deciphering their underlying needs was extremely engaging and the team now feels more confident in their ability to work with customers in industry. Finally, communication skills improved through the immense amount of writing and presenting required for the thesis and conference. Overall, the team really enjoyed the Senior Design project and is excited to go forth with this new knowledge into their careers and beyond.

References

Cited

[1]   U.S. Lettuce Statistics. Economic Research Service. U.S. Department of Agriculture. January 2011. http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?document ID=1576.

[2]   Farm Labor. Economic Research Service. U.S. Department of Agriculture. November 2018. https://www.ers.usda.gov/topics/farm-economy/farm-labor/#size.

[3]   Martin, Philip, Jackson-Smith, Douglas. "An Overview of Farm Labor in the United States." Rural Connections. https://wrdc.usu.edu/files-ou/publications/pub__1454925.pdf.

[4]   Partner Farm (Name under NDA)

[5]   AGMRC.org: "Lettuce Market Information" https://www.agmrc.org/commodities-products/vegetables/lettuce

Consulted

[6]   Huffman, W., 2014, Agricultural Labor: Demand for Labor, Encyclopedia of Agriculture and Food Systems, Academic Press, Ames.

[7]   Richard, B., 2014, "Robot innovation brings to agriculture efficiency, safety, labor savings and accuracy by plowing, milking, harvesting, crop tending/picking and monitoring," Industrial Robot, Vol 41. Pp 493- 499.

[8]   The Produce Nerd, Cited 2018, Harvesting Romaine Lettuce. https://www.youtube.com/watch?v=PnRLW0h6cb4.

[9]   Ramsay Highlander Inc, Cited 2013, Ramsay Highlander Inc. Ramsay Highlander's Top and Tail Mechanical Harvester https://www.youtube.com/watch?v=KKgG7hCmACM.

[10]   Maconachy, Frank J., Offerdahl, David, Garnett, Chris. 2006. "Lettuce Harvesting Method." United States. 6,996,964 B2.

[11]   Ottaway, James N. 1996. "Lettuce Harvesting Method and Apparatus to Perform the Same." United States. 5,560,190.

[12]   Ramsay Highlander Inc, Cited 2013, Ramsay Highlander Inc - Mechanical Water Jet Harvester. https://www.youtube.com/watch?v=t6p3G9pkFc4.

[13]   Maconachy, Frank J., Offerdahl, David. 2007. "Water-Cutting Harvesting Apparatus and Method Therefore." United States. 2009/0077940 A1.

[14]   Cho, S. I., Shin, D. J., and Kim, Y. Y., 2000, "Development of Lettuce Harvesting Robot System for Automated Plant Factory," IFAC Proceedings, Vol 33. Pp. 39-44.

[15]   Franka Emika, 2018, Franka Emika Panda - Automated Robotic Arm User Manual. https://frankaemika.github.io/docs/.

Appendix A: Need Finding and Establishing Requirements

A1: Interviews with End-Users

Customer: Leslie Torrance   **Interviewer(s):** Andrew Torrance
Address: Phone Interview   **Date:** Oct 8
Current Uses: Eating, Cooking
Type of user: Consumer

Question/Prompt	Customer Statement	Interpreted Need
Consumption of lettuce habits	Two romaine hearts a month. Makes salads, big leaves	Convenience Large leaves
Knowledge of lettuce brands	None in particular. Cheap	Low Price
How to identify Quality	Looks fresh. No wilted leaves	Transported with care
Value added to product with robot harvesting	Would not care	Low price
Labor shortage or replacing labor	Dislike less jobs, but would buy hand picked if supports laborers	Harvesting does not replace labor
Food Safety	Not worried about it	
Conservation of Resources	Uses "imperfect produce" in favor of efficiency	High efficiency farming

Customer: Judy Culberson
Address: Phone Interview
Current Uses: Eating, Cooking
Type of user: Consumer

Interviewer(s): Chuck Culberson
Date: Oct 8, 2018

Question/Prompt	Customer Statement	Interpreted Need
Consumption of lettuce habits	Variety bought each week. Salads, iceberg, greenleaf, spring mix	Convenience
Knowledge of lettuce brands	Earthbound, Taylor Farms	None
How to identify Quality	No browning or wilting	Transported with care
Value added to product with robot harvesting	Same Value	None
Labor shortage or replacing labor	Mixed feelings, doesn't want work replaced	Harvesting does not replace labor
Food Safety	Possibly could improve	Sanitary Foods
Conservation of Resources	Would support if it saved resources	High efficiency farming

Customer: Rose Borst
Address: Phone Interview
Current Uses: Eating, Cooking
Type of user: Consumer

Interviewer(s): Jonathan Borst
Date: Oct 8, 2018

Prompt	Customer Statement	Interpreted Need
Consumption of lettuce habits	Used to buy 3 a week but now buys pre-washed mixes	Buying lettuce must be convenience
Knowledge of lettuce brands	Brand not important	Lettuce must be inexpensively harvested
How to identify Quality	Look for "organic" and freshness	Lettuce must look clean
Value added to product with robot harvesting	Does not affect decision	Lettuce must be inexpensively harvested
Labor shortage or replacing labor	Not bothered, farm labor is hard	Lettuce is harvested easily
Food Safety	Robot Harvest may be more sterile	Lettuce must be safe to eat
Conservation of Resources	Would feel better about brand	Lettuce must not waste resources

A2: Interviews with Lead Users (Customer / Partner Farm)

Customer: Stephen L   **Interviewer(s):** Andrew Torrance
Address: In Person Interview   **Date:** Oct 12, 2018

Question / Prompt	Customer Statement	Interpreted Need
Production yield	Partner Farm harvest 2 million hearts a day, with about 1.5 passing quality and being shipped	System should operate at least as fast a human crew
		System should produce as high yields as a human crew
Company operations in Winter	Company moves to Yuma (500+ miles south) from November to February	System must be transportable to Yuma for winter harvesting
Thoughts on robotic automation?	Even if robot produces the same yield as current humans, the easier work would convince more laborers to come to Partner Farm (instead of competition) and thus still be extremely valuable	System could operate similar to human crew if labor is easier on workers
	Automated equipment (easier work) would allow for 2 shift days	System should be able to operate for 2 shifts per day
Labor shortage	25% of laborers are H2A temporary agricultural workers	System should be usable by any skill or language-level worker
Overall scalability / limiting factors on more production	If harvesting increased, they could easily grow, cool, package, and ship more	Harvesting is the limiting factor in the overall production

Customer: Daniel L
Address: In Person Interview

Interviewer(s): Andrew Torrance
Date: Oct 12, 2018

Question / Prompt	Customer Statement	Interpreted Need
Labor shortage (Aging workforce)	Aging workforce in packaging. Young vacuum tube operator is 68. Computer automated and pre-programmed "recipes" for cooling plants is used by "MAC Coolers", also more efficient	Automation in more than just harvesting
Packaging and shipping tact times	3 hearts per bag. (XX hearts per box). 56 cartons (boxes) per pallet. 24 pallets into one vacuum, produced by 6 crews (~20 people) in 1 hour	Necessary output form factor of system
Freshness	Cooling via hydrociller or hydrovac (34 min). Takes produce from 60-65 °F to 45°F. then ice injectors to bring to 33-35 °F	Crops must be quickly cooled
	Product can't get wet to keep fresh	Product cannot be wet
	Plants never held over from longer than Friday -> Monday	Crops must be quickly shipped
	Each 1.5 hour uncooled leads to 1 day off shelf life	Crops must be quickly cooled
Traceability / food safety	Traceability critical, done with stickers on bag/boxes and barcodes on pallets.	Necessary output form factor of system
	Tracing location, type of plant, equipment use, time harvested and cooled, people harvesting, moving, cooling, shipping, etc.	Traceability
	Conduct mock recalls to test traceability system	Traceability
Availability of electricity for automation	Solar powered facility produces 96-98% of plant electricity. Stored w/ Tesla Batteries. Save money on peak time costs	Lots of electricity available (ex. battery powered robot?)

Question / Prompt	Customer Statement	Interpreted Need
Robot overview	Water sprays blade to clean off leaves, soil, and reduce friction	Crops look clean and fresh in package
		System uses limited water
	Soft robot "cow udder" end effector grabs top of lettuce	Crops should not be crushed or damaged
	Robot harvests 1 plant at a time from the row	Individual measuring and harvesting to ensure accuracy
	Robot harvest 3 columns of plants	Interface with field configuration
	Soft robot end effector pneumatic control causes time limitations	Reduce limiting factors to increase speed of system
		Crops should not be crushed or damaged
	Delta robot configuration to position end effector (XYZ)	End effector positioning
Determining where and height of cut with LIDAR system	"Torpedo ski" ground reference tells how planter bed is above tractor wheels. Hydraulics make trailer stay level (+- 1°) and at same height relative to "ground" (+- .25)	Robot base frame stays constant relative to ground
	LIDAR scans in line scans of 1mm X-spaced pulses. Encoder on trailer treads make lidar pulse scan every 1mm Y-spacing	Scanning / marking of plant locations should be independent of driven distance/speed
	LIDAR scans used to measure X-Y location centers by forming triangles and projecting down onto ground to find clustering of inward-facing leaves. Plotted in a heat map	Scanning should locate centers of plants
	No machine learning used	Potential for machine learning to improve scanning accuracy (ex. predict where next plant "should" be to ensure fewer complete misses)

	LIDAR scans measure Z position of top of plant. Tells robot to cut at X % of plant height.	Cut height determined by percentage of plant height
	Operator can push buttons to trim height of a whole column if they see consistent error in one direction	Operator can use UI and skill to adjust system, not completely automated
	Plant diameter should be 25-32mm	Plant diameter should be 25-32mm
	Humans squeeze/look at top of plant to see density of heart. Tighter heart -> cut higher	Heart density correlates to ideal cut height
	Stump diameters indicate if cut too high/low	Stump diameter correlates to ideal cut height
	Wind (>20mph) creates noisy LIDAR scans (dust)	Scanning/vision should work in all conditions

Question / Prompt	Customer Statement	Interpreted Need
Retrimming	Humans holds top of heart and takes additional cuts to trim off extra leaves	Retrimming frequently needed, but adds time to harvesting
	On robot system, human puts plant in cup and slides over blade to try to trim to specific diameter. Not that accurate	Retrimming frequently needed, but adds time to harvesting
	Automatic retrimming system is currently their 3rd priority, working on it when they get a chance	Potential for Automatic retrimming system
	If the robot always cut low, they would have 95%+ yield, but then every plant would need trimming	Potential for Automatic retrimming system
Labor shortage	Will keep getting worse, lots scared by politics right now. Driving push towards automation	System should be automated to assist with the labor shortage crisis
	Formerly automated for cost savings, now automating to meet demand	System should be automated to assist with the labor shortage crisis
	Farm has to pre-pay in cash at beginning of day to laborers ($13.25 / hr)	System should save farm for paying for the high cost of labor
	Payroll at end of week pays on amount of crops harvested (piece rate leads to about ~$16-17 / hr)	System should save farm for paying for the high cost of labor
	Labor cost directly goes into cost per box of product	System should save farm for paying for the high cost of labor
	Box sold for $10-12, labor about $4	System should save farm for paying for the high cost of labor
	No punishment if workers are hungover or don't come to work. they take who they can get	System should save farm for paying for the high cost of labor
	Humans do 8 cuts/min / person. 12 cutters on a crew.	System should operate at least as fast a human crew

Question / Prompt	Customer Statement	Interpreted Need
Traceability / food safety	Robots make traceability just as easy as current methods	Traceability
	Robot cleaned everyday with chlorinate water on food-contacting surfaces (gripper, cutter, conveyor, trimmer, bagging station)	Food safety
Previous prototype	Ring pushes outer leaves down/away then blades comes up under and cuts/picks up plant. Damaged neighbors, spread mud, hard to package multiple on a trailer, speed issue (human triggered, no LIDAR)	System must be automated and not need human skill to operate
		System must not damage crop or its neighbors
	Ability to place onto conveyor is hard	System must funnel crops into a single stream for processing and packaging
Ski issues	Affected by plant, might ride on leaves or get wedged up on a badly planted crop	Ground reference must be accurate in all field conditions
	affected by soil (wet vs dry). needs to work in all conditions	Ground reference must be accurate in all field conditions
Thoughts on going completely automated (ethical vs business)?	"we're a for-profit company" we will do whatever produces the most	System must produce profit for the company
Production speeds and yields	Robot does 30 cuts/min / robot. Currently 1 (eventually 4) robots per system	System should operate at least as fast a human crew
	1-5% of human cuts don't end up in bag	System should produce as high yields as a human crew
	20% of robot cuts don't end up in bag	System should produce as high yields as a human crew
	Romaine hearts in general produce lots of food waste. Most leaves left on ground	System should dispose of undesired leaves
Potential for side-imaging	Hard to see stump/stalk, lots of leaves	System could examine stalks to automatically check its own accuracy
Thoughts on smaller robots	Need to interface with rest of packaging, cooling, shipping	System must package products in pallet format cohesive with greater

working in parallel?	operations. Has to get on a truck and shipped in big pallets	shipping operations
Pull up entire plant and trim later (like Taylor farm mechanization)	Have to keep clean, Taylor farms waterjet sprays water and mud everywhere (OK since they chop and wash and make salads). Taylor farms bandsaw cuts many at once (inability to adjust to each plant height). Partner Farm romaine hearts only washed by consumer, have to look clean to be purchased	Product must look clean and fresh to be purchased by consumers
Cut multiple plants at once?	Plants growing in outer columns tend to grow outward angled (to get more sun), meaning perfect horizontal cutting doesn't usually work	Each column of crops should be cut individually to account for planting or field variations
Washing plants?	Takes too much water, water has to be sanitary (see E Coli breakout this year)	Product should not be washed

A3: Farm Visit Photos

Figure A.1: Laborer Harvester Knife

Figure A.2: Three Romaine Hearts as would be bagged together

Figure A.3: Romaine Cut Stem (too low, still a large head)

A4: Product Needs-Metric Correlation Matrix

#	Needs	1 Succesful Yield Percetage	2 Unit manufacturing cost	3 Total mass	4 Head trim rate	5 Minimum lettuce intake rate	6 Water Resistant (IPX4) Resistant rom any direction to spray nozzle	7 Solid Ingress Protection (IP3X) Finger and tools can not touch moving components	8 Time to train new operator	9 Machines overseen by one operator	10 Systems total height	11 Systems footprint	12 Time required to clean	13 Force at blade contact point	14 Minimum lettuce that can be in queue	15 Minimum number of cut diameter presets
1	**Romaine heart is not damanged**	X														
2	Romaine heart is cut at perfect height first time	X												X		
3	The cut is clean	X												X		
4	The cut is flat and perpendicular to stalk	X														
5	**The system is versatile**															X
6	The system can process variety of lettuce types															X
7	The system can process variety of crops															X
8	**The system lasts a long time**						X	X						X		
9	The system is servicable						X									
10	The system is durable						X	X								
11	The system is water resistant						X									
12	The system is dust resistant							X								
13	The system is reliable								X							
14	**System is easy to use**								X							
15	System's behaivior is easy to adjust								X							X
16	System's operation is easy to learn to use								X							
17	System's user interface is easy to understand								X							
18	Sytstem's user interface is visually appealing											X				
19	Sytstem's user interface is functionally appealing	X				X					X	X				
20	System is controllable remotely										X					
21	The system is ready to use upon delivery								X							
22	The system can operate with minimal to no human supervision									X					X	
23	**The system is economical**		X													
24	The system is affordable		X													
25	The system is cost saving compared to alternatives		X													
26	**The sytem is efficient**				X	X									X	
27	The system is fast				X	X									X	
28	The system is scalebale															
29	**The system is safe**							X								
30	Operator is safe when system is used properly							X								
31	Operator is safe when system is used improperly							X								
32	The system does not introduce dirt or pathogens to product													X		
33	The sytem is light			X												
34	The system is compact										X	X				

A5: Product Needs Prioritized
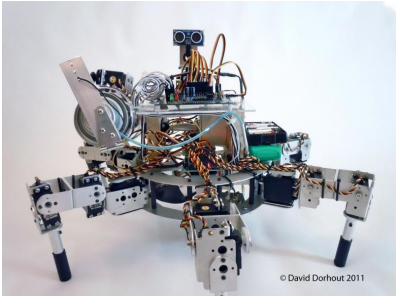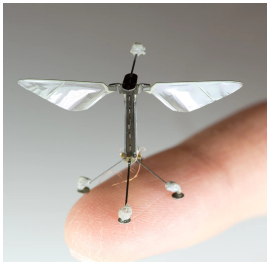
Need	Priority (0-5)
Romaine heart is not damaged	5
Romaine heart is cut at perfect height first time	3
The cut is clean	3
The cut is flat and perpendicular to stalk	4
The system is versatile	3
The system can process variety of lettuce types	2
The system can process variety of crops	1
The system lasts a long time	5
The system is serviceable	4
The system is durable	4
The system is water resistant	4
The system is dust resistant	4
The system is reliable	5
The system is safe	5
Operator is safe when system is used properly	5
Operator is safe when system is used improperly	3
The system does not introduce dirt or pathogens to product	5
The system removes dirt or pathogens from product	2
System is easy to use	4
System's behavior is easy to adjust	3
System's operation is easy to learn to use	2
System's user interface is easy to understand	2
System's user interface is visually appealing	1
System's user interface is functionally appealing	1
System is controllable remotely	1
The system is ready to use upon delivery	2
The system can operate with minimal to no human supervision	3
The system is economical	4
The system is affordable	3
The system is cost saving compared to alternatives	4
The system is efficient	4
The system is fast	3
The system is scalable	3

A6: Existing Agriculture Robots

Table G.1: Agricultural Automation Robots in Research or Development

Name and Manufacturer	Descriptions
Iron Ox Lettuce Robot[13]	Purpose: Transplanting lettuce between trays in a greenhouse Technologies: ● Robotic arm on a track ● Stereo Camera ● Custom gripper to lift pods
MIT Robot Gardener [14]	Purpose: Maintain soil humidity and pick ripe fruits Technologies: ● Robot arm on a iRobot Roomba drivebase ● Sensors in each plant wirelessly call robot when needed
Agrobot SW6010 [15]	Purpose: Detect and pick ripe strawberries Technologies: ● Tractor with sensors and robot arms ● Adjustable dimensions fit planting configurations
Wageningen UR Cucumber Harvester [16]	Purpose: Autonomous cucumber harvesting Technologies: ● Used autonomous vehicle, manipulator, an end-effector, a camera based visual system ● Identifies ripeness of each cucumber ● Uses the difference in spectral reflectivity to discern the cucumber from the similarly colored leaves
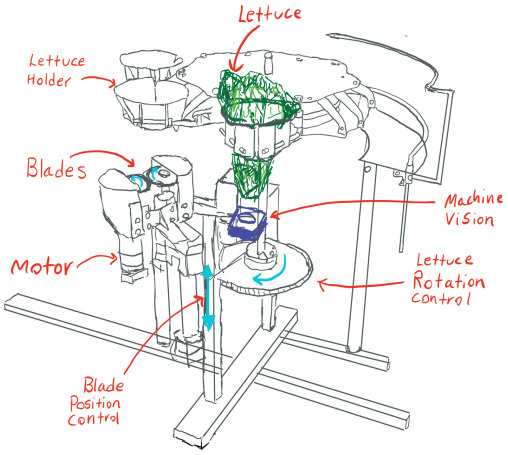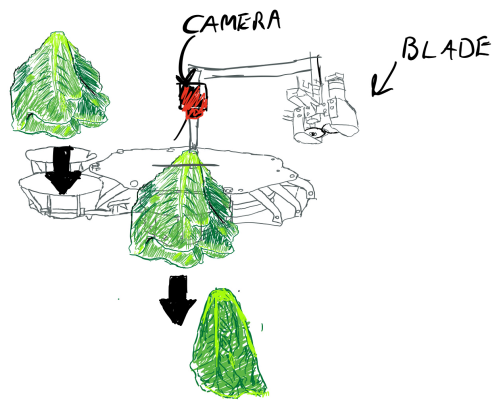
Sweet Pepper Harvester [17]	Purpose: Autonomous sweet-pepper harvester Technologies: ● Uses cameras and illumination to calculate fruit position ● Uses 6 DOF robotic arm with end effector that has gripper and integrated cutting tool
Berry Nice Harvester [18]	Purpose: Determines ripeness of the fruit using a 3D stereo camera to detect color. Technologies: ● Travels on a rail system. ● Uses robotic arm to reach out and snip the stem. Harvesting a berry every 8 seconds.
Rosphere [19]	Purpose: Collect data over uneven terrain with little impact Technologies: ● Moves by swinging a mass internal to the sphere adjusting the center of mass ● Uses sensors and camera to collect data of field conditions ● Wirelessly relays this info
Lettuce Thinner [20]	Purpose: Kill weeds while also killing off lettuce plants that are growing too close to another plant Technologies: ● Uses computer vision and AI to detect lettuce and weeds ● Based on collection of data makes decision about best treatment for each plant ● Uses 90% less herbicide

Aquarius [21] 	Purpose: Monitor soil moisture conditions and water plants accordingly Technologies: ● Uses drive system to move along rows of plants ● Path is set by operator ● Uses moisture sensors in soil ● Uses 30 gallon water tank to accordingly water plants
Prospero [22] 	Purpose: Work as group to plant seeds and apply herbicide Technologies: ● Uses combination of group and swarm theory ● Walks autonomously in any direction while avoiding obstacles ● Uses sensor to identify if a seed has been planted in an area ● Digs hole in soil and places seed in hole ● Communicates with swarm to deliver information about where seeds have been planted
Nursery Plant Mover [23] 	Purpose: Transport plants around nursery Technologies: ● Receives commands wirelessly from tablet application ● Autonomously navagates nursery and locates plants slotted for relocation ● Uses two grippers to squeeze and pick up plant
SwagBot [24] 	Purpose: Track and herd cattle Technologies: ● Uses sensors and cameras to navigate hazardous terrain ● Senses and sprays unwanted plants and weeds ● Interfaces with cloud to transmit herd status data ● Herds animals away from dangerous areas
RoboBees [25] 	Purpose: Wide range of application including pollination and weather, climate, and environmental monitoring Technologies: ● Can fly and navigate through air ● Currently still requires connection to external power source ● Uses microelectromechanical technologies to get in small form factor

Appendix B: Design Brainstorming and Concept Selection

B1: System Architecture Concepts

Table B.1: System Architecture Concepts

Concept	Photo
Top Loaded Indexer The indexer uses a cam mechanism to open and close the cups depending on the angular position. The cups open as they rotate over a metal frame, allowing laborers to drop lettuce heads into the cup, letting the stem of the lettuce sit on the metal overhang. The cup closes on the lettuce head and continues to rotate until a camera system images and uses the blade position control to move the rotating blades to the ideal cut location.	
Inverted Lettuce Input A cup design that allows lettuce to be inserted upside down. The inside heart of the lettuce would fit in the middle of the cup while the outer leaves would fall to the sides. The lettuce stem would be sensed and cut using machine vision and rotary blade system. When the stem is cut in the right location, the heart would fall through the cup and the outer leaves could be disposed.	

Spring Loaded Indexer This system utilizes spring loaded grippers to grab the head of the romaine lettuce. Blower is positioned above loading gripper to blow away outer leaves and allow for improved loading of the heart. Indexer of grippers rotates around central position while saw blades adjust height to cut lettuce at correct vertical position.	
Horizontal Blades with Linear Queuer This system replaces the rotational loading and ejection with a linear queuing system. It uses a slanted aluminum grate, possibly with actuated rollers, to feed the lettuce hearts to the saw blades. Saw blades are positioned horizontally and use overhead sensing to adjust their horizontal position.	
Iterative Trimming Approach Rather than trimming based off one diameter measurement and an estimate/algorithm for the required cut height, this iterative trimmer will use multiple passes, measuring the diameter each time, and only letting the heart through when it is guaranteed to be a good trim. More "closed-loop" compared to the currently developed "open loop" idea. This may perhaps be necessary to accommodate different species, varieties, and time of year.	
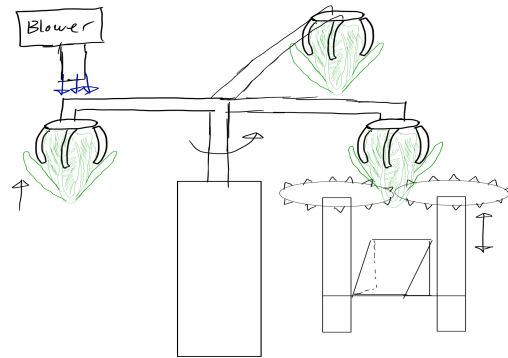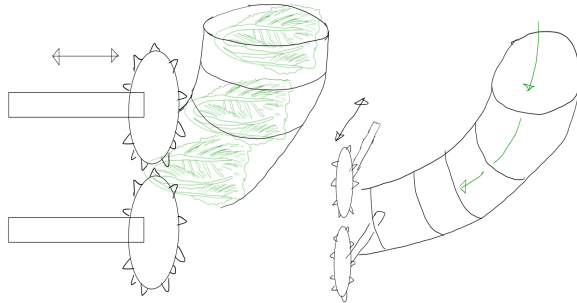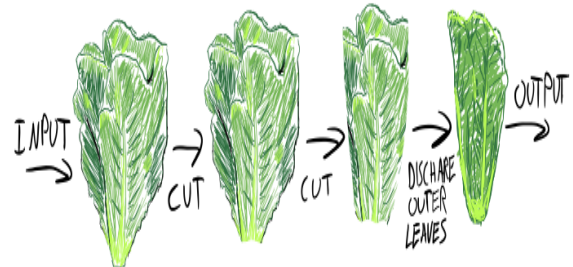
B2: Gripper Cup Selection

Table B.2: Gripper Geometry Concepts
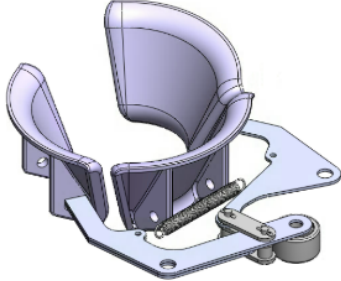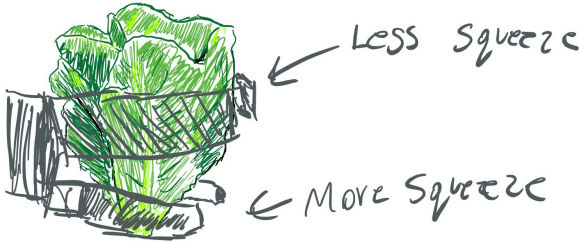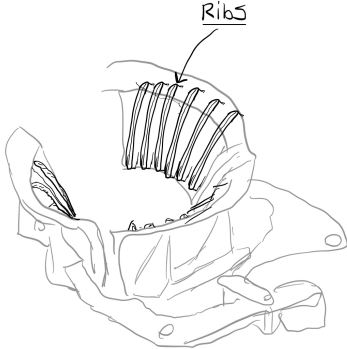
Concept	Photo
Conical (current implementation) Conical cups on a pivoting rod slightly adjust their angle to match the plant. The outer 2 cups are actuated in and out by the follower wheel on the cam. Struggles to eject the plant.	
Two level An upper gripper lightly holds the head leaves for initial loading while a lower applies high grip strength where the trimming occurs and vein cracking is less likely.	
Many fingers Many small fingers grab the plant from multiple locations to improve the pressure distribution, but at a higher cost, complexity, and worse durability.	
Ribbed Breaks up a smooth conical surface into one composed of many small ribs, be they rigid or compliant, with the aim of distributing the pressure by allowing veins to protrude into the gaps between the ribs and avoid crushing.	

Table B.3: Gripper Material Concepts

Concept	Photo
Hard plastic (current implementation) 3D printed or similar hard plastic does not conform at all to the organic texture or protruding veins of the romaine head.	
Compliant Silicone Silicon, or a similar compliant, rubber-like material, could offer better conformance around the plant while being more durable than an air or foam-based gripper material concept.	

		Compliant Foam	

Compliant Foam

A compliant foam, such as those found in bedding, is designed to conform and apply even pressure around irregular, organic, shapes. However, it could have issues with durability as the foam could potentially rip easier.

Air bag

A closed bag filled with a fixed volume of air that could be pushed (bag is compressed or rolled by the cam) into the gripper-side of the bag. Would offer the most compliance but might be less durable and manufacturable than simpler designs.
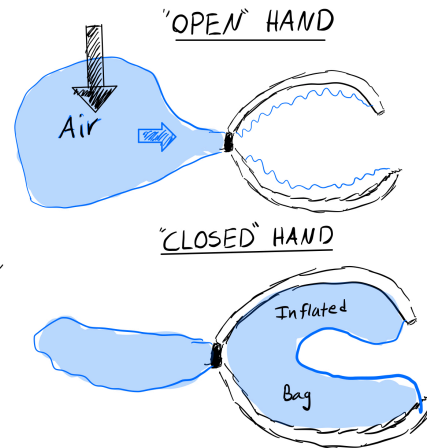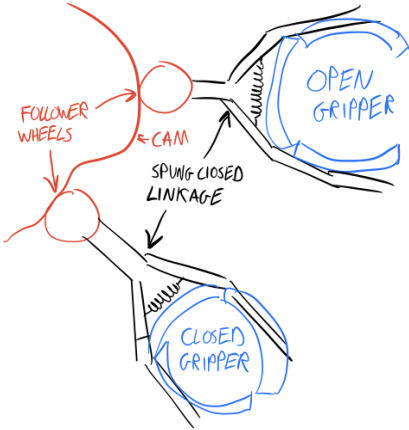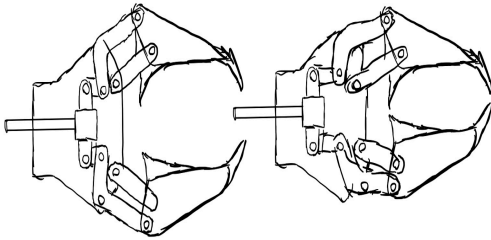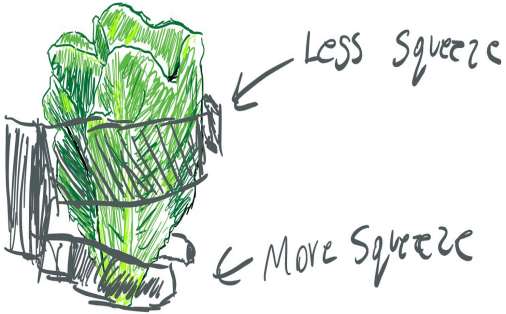
Table B.4: Prioritization Matrix for Criterion Weighting

	Criterion	FACTOR
1	Loading	25
2	Ejection	25
3	Grip Strength	10
4	Pressure Distribution	25
5	Low Cost	5
6	Durability	5
7	High Manufacturability	5
SUM		100

B3: Gripper Linkage Selection

Table B.5: Actuating Linkage Concepts

Concept	Photo
Cam Driven Actuation The method currently employed by the partner farm's existing trimmer prototype. A linkage with fixed pivot points is driven by a wheel that follows along the edge of a fixed cam. As the cam's radius changes, the wheel's position changes relative to the linkage pivot points thus driving the linkage to either open or close the gripper.	
Two Sided Gripping Linkage An alternative method of gripping the lettuce heads. The side grips of the mechanism could be cups, similar to previous designs. The mechanism has no springs and could squeezing the lettuce equally on each side. This could help the lettuce stay vertical instead of falling to either side.	
Two Level Grip The mechanical gripper uses springs to hold the lettuce in place. The bottom of the lettuce could be held more tightly because the area is less delicate. Doing so would also help align the lettuce to be vertical, improving stem cuttings. The top of the lettuce could be held with a larger surface area that has a less stiff spring constant since it is more delicate and varies more than the bottom of the lettuce.	

Pulley Gripper A simple cable system could be set up that would be able to squeeze the lettuce to hold it while cut. The benefit of this system is that it is simple, it requires no complicated linkage. The pulling could be mechanically automated as the cup spins.	
Pneumatic Cylinder Gripper Actuation Uses actuating pistons to engage grippers, rather than the current system's follower wheels and cam. Firing and timing on pistons controlled by solenoids (perhaps driven with relays). This allows for individualized firing of each plant, perhaps required if multiple trims (iterative approach) is needed. Also, the pistons can have pressure and stroke length easily adjusted for a highly modular machine. This can allow for quick adjustment during a prototyping phase or preset adjustments tuned for different species, varieties, and time of year.	
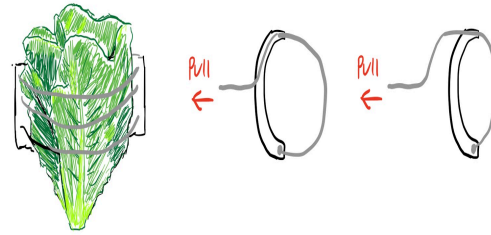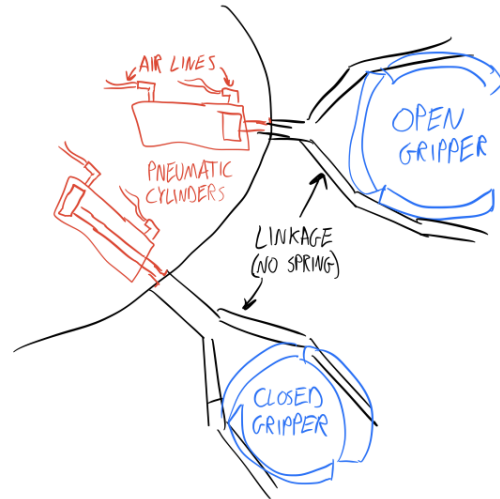
Table B.6: Gripper Cup Selection Scoring Matrix

Concepts		Weighting Criteria (Weights)							
Gripper Geometry	Gripper Material	Loading (25%)	Ejection (25%)	Grip Strength (10%)	Pressure Distribution (10%)	Low Cost (5%)	Durability (15%)	Manufacturability (10%)	SUM
Conical (Reference)	Hard Plastic (Reference)	4	5	5	1	4	5	5	430
Conical	Compliant Silicone	3	5	4	3	4	4	5	400
Conical	Compliant Foam	3	4	4	3	5	3	5	365
Conical	Air Bag	2	2	2	5	2	1	2	215
Two Level	Hard Plastic	5	4	4	2	3	5	4	415
Two Level	Compliant Silicone	4	4	4	4	3	4	4	395
Two Level	Compliant Foam	4	3	4	4	4	3	4	360
Many Fingers	Hard Plastic	2	2	1	4	2	3	3	235
Many Fingers	Compliant Foam	1	1	1	4	3	1	3	160
Ribbed	Hard Plastic	4	5	4	2	3	5	4	415
Ribbed	Compliant Silicone	3	5	3	4	3	4	4	385
Ribbed	Compliant Foam	3	4	3	4	4	3	4	350

Appendix C: Team and Project Management

C1: Hardware Timeline
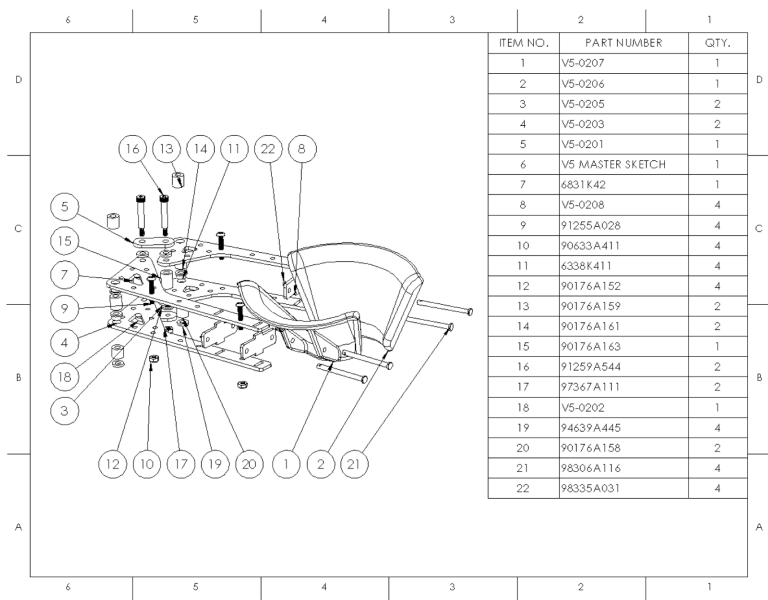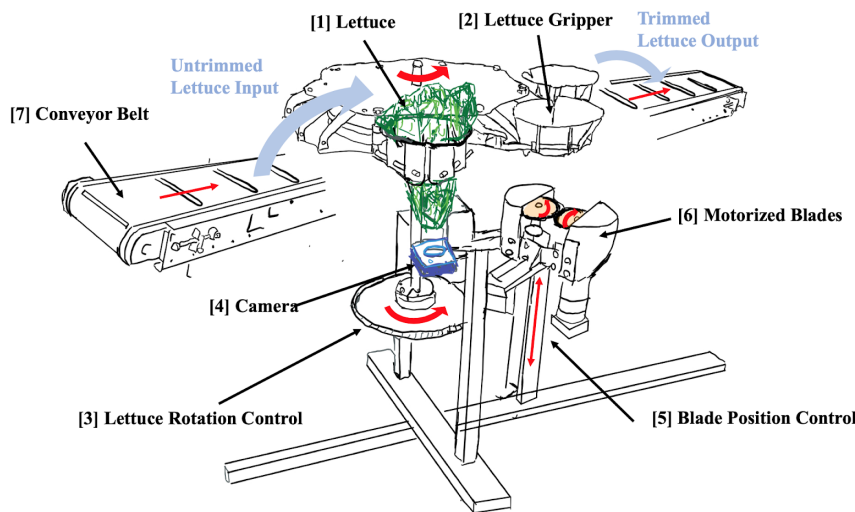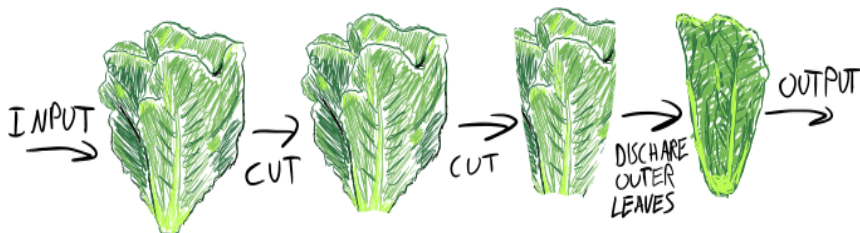
Table C.1: Hardware Timeline

Action	Scaled Mock Up	Wooden Prototype	Metal System
CAD	11/17/18 ✓	01/20/19 ✓	03/07/19 ✓
Drawings	11/19/18 ✓	01/28/19 ✓	04/09/19 ✓
Materials Ordered	11/21/18 ✓	01/28/19 ✓	03/15/19 ✓
COTS Parts Ordered	11/21/18 ✓	01/28/19 ✓	03/15/19 ✓
Machined Parts	11/25/18 ✓	02/04/19 ✓	04/24/19 ✓
Assembly	11/26/18 ✓	02/05/19 ✓	04/25/19 ✓

C2: Overall Project Gantt Chart
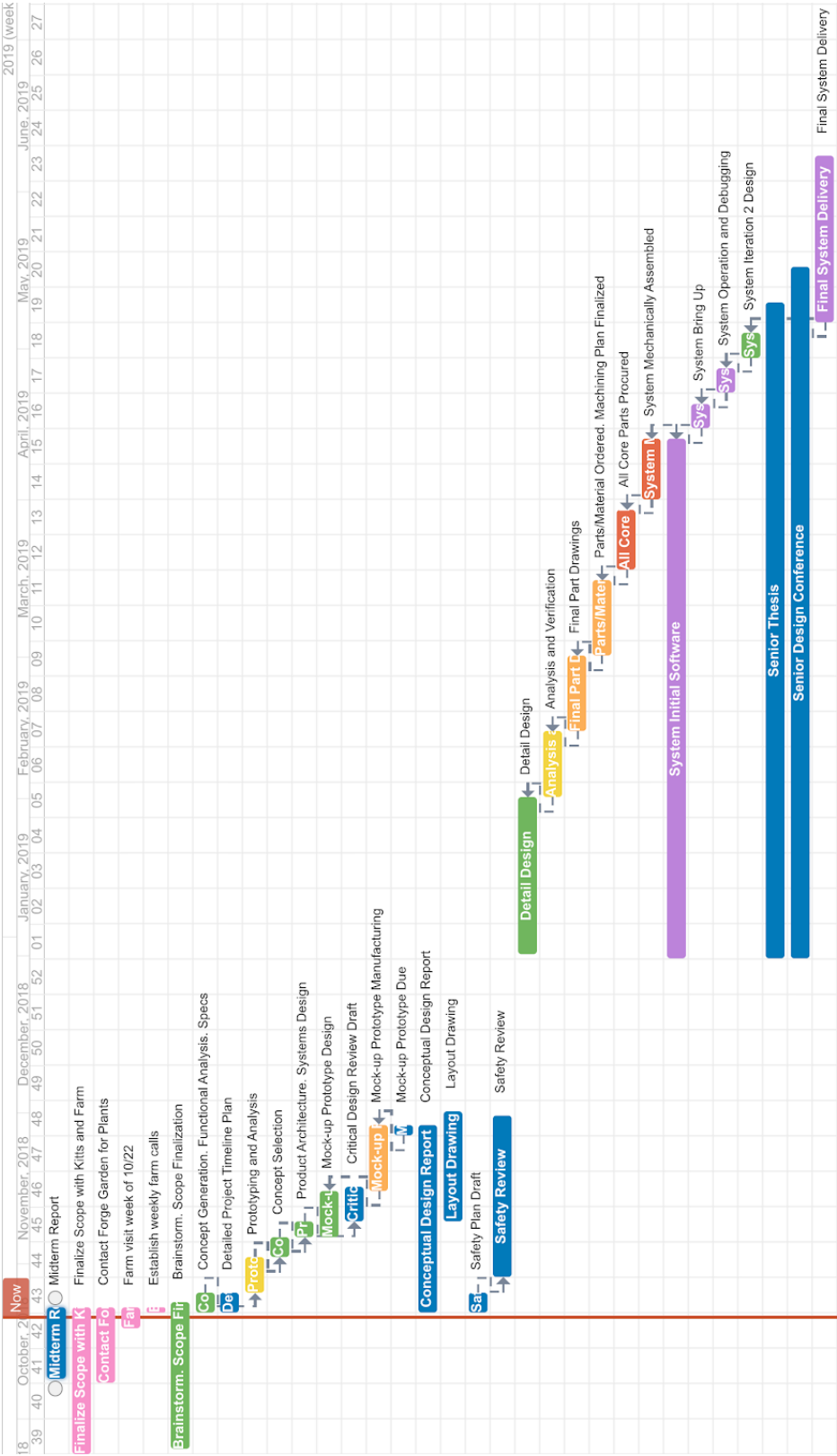
C3: Selected Team Member Drawings for Art Requirement

Andrew Torrance *Gripper Annotated* *Exploded View* *Technical Drawing*	
Jonathan Borst *Annotated System* *Level Sketch*	
Chuck Culberson *Iterative Romaine* *Lettuce Trimming* *Sketch*	

C4: Safety Report

The following section breaks down any and all potential safety risk concerns specific to each stage of the project.

Manufacturing

The manufacturing of the robotic trimmer may involve shop tools such as a mill, lathe, drilling tool, and bandsaw. To mitigate risks, the team will follow the Safety requirements established for manufacturing locations (Machine Shop, Maker Lab, Robotics Lab, and any other SCU Laboratories) including access requirements, hours of operations, and work alone procedures. Work will not be conducted if anyone feels unsafe. Thick gloves will be worn if there are sharp edges that have not been filed off.

Assembly

Assembly of the project will involve wrenches, ratchets, screwdrivers. Closed toe shoes and pants will be worn at all times. Any spot welding done will be under supervision and following procedures in the Machine Shop. During assembly, any electrical components will be unplugged. Any springs incorporated into the design will be installed using safety glasses. Heavy objects will be lifted by multiple people with proper technique. The pinch points will be address by including covers to prevent people from getting hands into those areas and training on use of the device to avoid these situations.

Test/Operation

The team will follow the Safety requirements established for each testing location. Force analysis for a head of lettuce will be conducted at CSA Moog under the supervision of Catherine Borst (cborst@moog.com). Testing of the mechanical systems will be done in

the RSL under supervision of Dr. Kitts (ckitts@scu.edu) and at the Partner Farm under the supervision of the head automation engineer. The trimmer involves rotating mechanical parts such as a shaft and top carousel that mechanically opens and closes cups via a cam mechanism. These systems have the potential to be powered with motors using wall power. No electrical components will be designed, any components used will be off-the-shelf. Voltages would be stepped down using a transformer or similar approved device (system voltages will not exceed 50V). An emergency stop button will be placed nearby and during testing nobody will be allowed within a 5 ft test zone ensuring safety.

Display

During display, only trained team members will be allowed to operate or demonstrate the working mechanisms of the system. Otherwise, the system will be unplugged and will be a static structure.

Storage

The project does not have any energy storage systems or pressurized fluids or gasses that could be dangerous to store. During storage, the system will be disconnected from any wall power and the emergency brake will be engaged.

Disposal

The mechanical trimmer will not be disposed, it will be implemented with our partner farm. However, should the system need to be disposed of, motors and electrical sensors will be recycled according to e waste standards. The remainder of the system will be a steel alloy and can be recycled or reused as needed. No batteries or chemicals are used in the system so there is no concern for toxic or specialty waste disposal.

C5: Risk Mitigation

Risk	Consequence	Probability (0-1)	Severity (1-10)	Impact (P*S)	Mitigation Strategy
Inability to buy material and parts	Can not manufacture prototypes	0.02	10	0.2	Design with readily available materials and parts. Buy any hard to acquire items well in advance
Unclear Requirements	Partner Farm is not satisfied with the design	0.1	9	0.9	Maintain regular communication, including trips to the farm, phone calls, and emails
Funding is not acquired	Can not purchase materials or parts	0.05	8	0.4	Apply for multiple sources of funding and have strategy for limited funding project
Group member has personal emergency	The members design tasks do not progress	0.01	7	0.07	All group members are involved and aware of the design of the subsystems
Not able to test with partner farm	Unable to verify designs quality	0.2	4	0.8	Work with Forge garden to make full lettuce heads available and have backup plan for cutting mechanism
Large fire that causes SCU campus to be shut down	Do not have access to machine shop or design center, pushing schedule back	0.3	2	0.6	Have alternative methods for designing and manufacture available.
Deadlines for other classes conflict with project deadlines	Project deadline is missed resulting in design schedule being pushed back	0.3	2	0.6	Emphasize as a team not procrastinating work in other classes or on the project
Lettuce has massive recall	No longer is funding or need for project	0.4	1	0.4	Designing project with multiple applications in mind

Appendix D: Verification Data

D1: Mechanical Dimensions

Table D.1: Caliper Measurements of Gripper Positions

Trial	Gripping	Loading	Ejection
1	2.7	4.1	8.1
2	2.8	4	8.2
3	2.6	4.15	7.8
4	2.8	4	7.8
5	2.9	4.25	7.75
Average	2.76	4.1	7.93
Std Dev	0.11	0.11	0.20
CAD Measurement	3	4.25	8
%Error	8.00%	3.53%	0.88%

D2: Stem Height and Gripping Force

Table D.2: Stem Height Measurements

Stem Height	
Trial	**Result**
1	-0.25
2	-0.125
3	-0.125
4	0
5	-0.125
6	-0.25
7	0
8	-0.125
9	-0.125
10	0
Average	-0.113
Std Dev	0.092
Ideal	0

Table D.3: Stem Height Measurements

Gripping Force	
Trial	**Result**
1	5.5
2	6.3
3	6.2
4	6.5
5	5.2
6	6.7
7	6.0
8	5.4
9	5.5
10	6.1
Average	5.94
Std Dev	0.510
Theoretical	6
%Error	0.01

D3: Rotational Speed and Lettuce Head Throughput

Table D.4: Rpm and Takt Time Measurements

Time for 5 Revolutions and Takt Time		
Trial	**Result**	**Takt Time**
1	59.97	1.999
2	60.02	2.001
3	59.93	1.998
4	59.92	1.997
5	59.97	1.999
6	59.98	1.999
7	60.02	2.001
8	59.97	1.999
Average		1.999
Std Dev		0.001
Theoretical		2
%Error		0.05%

Appendix E: Mechanical Drawings
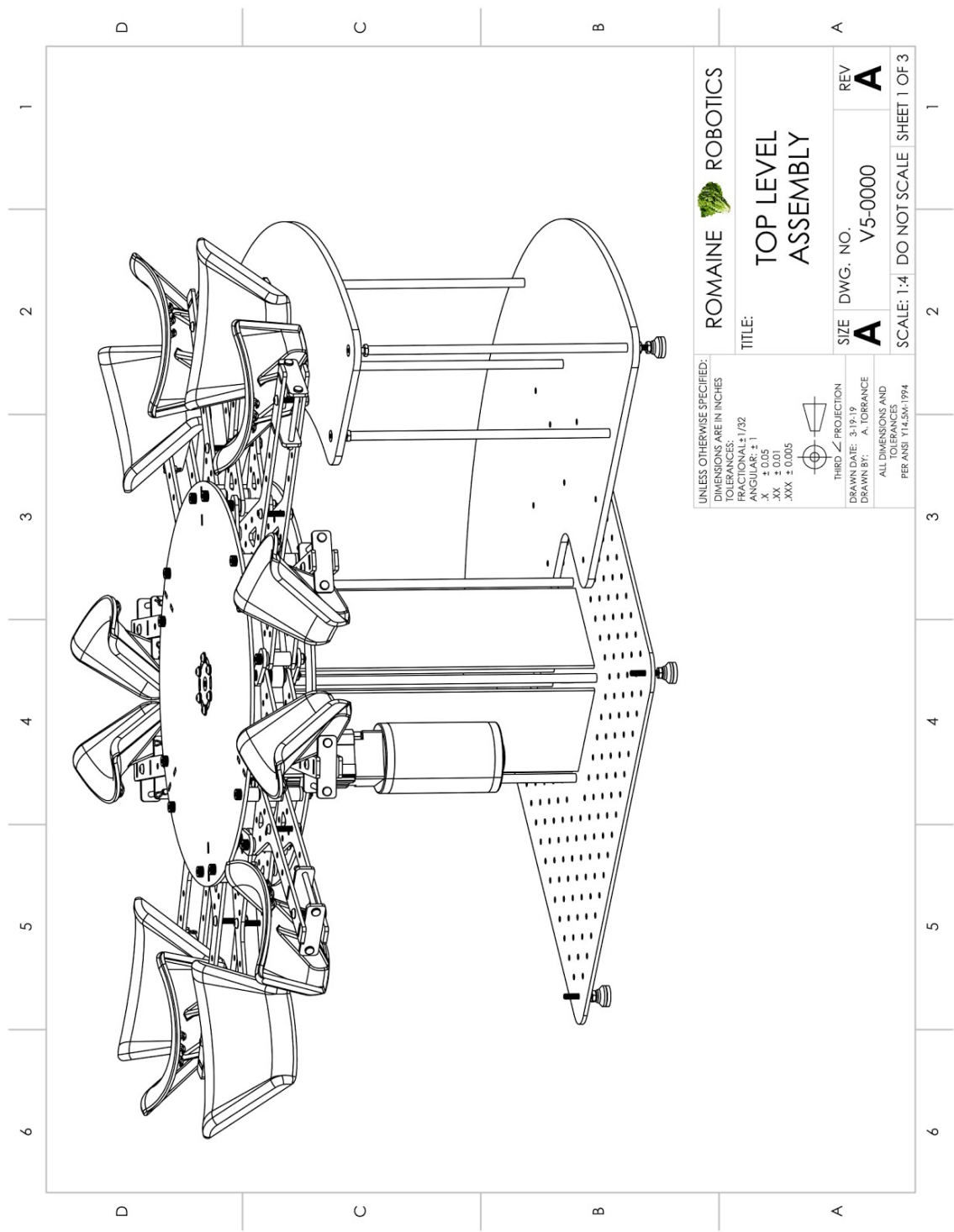
Figure E.1: V5-0000 Top Level Assembly

E1

ITEM NO.	PART NUMBER	QTY.
1	V5-0100	1
2	V5-0200	6
3	V5-0300	1
4	V5-0400	1
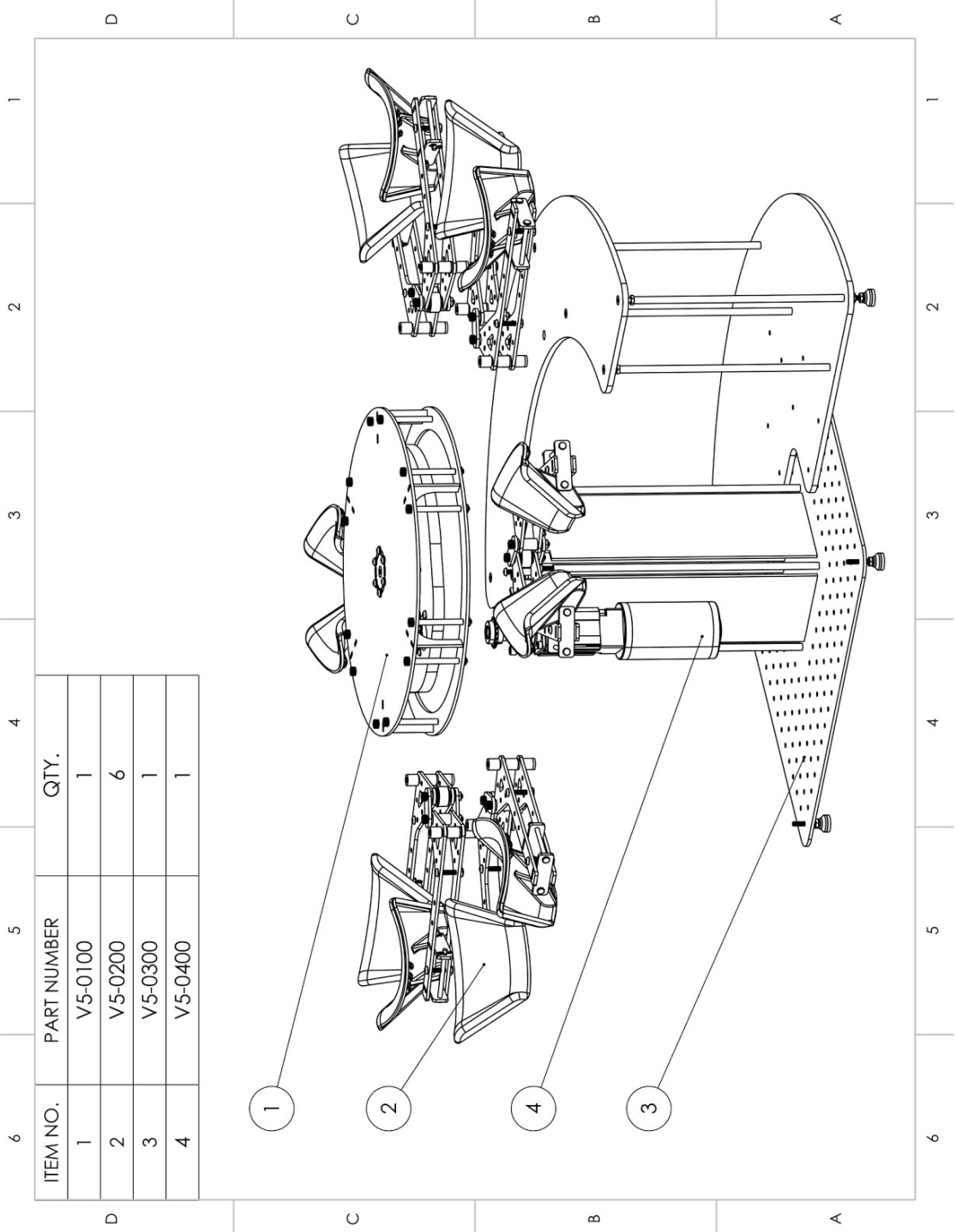
Figure E.2: V5-0000 Exploded Top Level Assembly
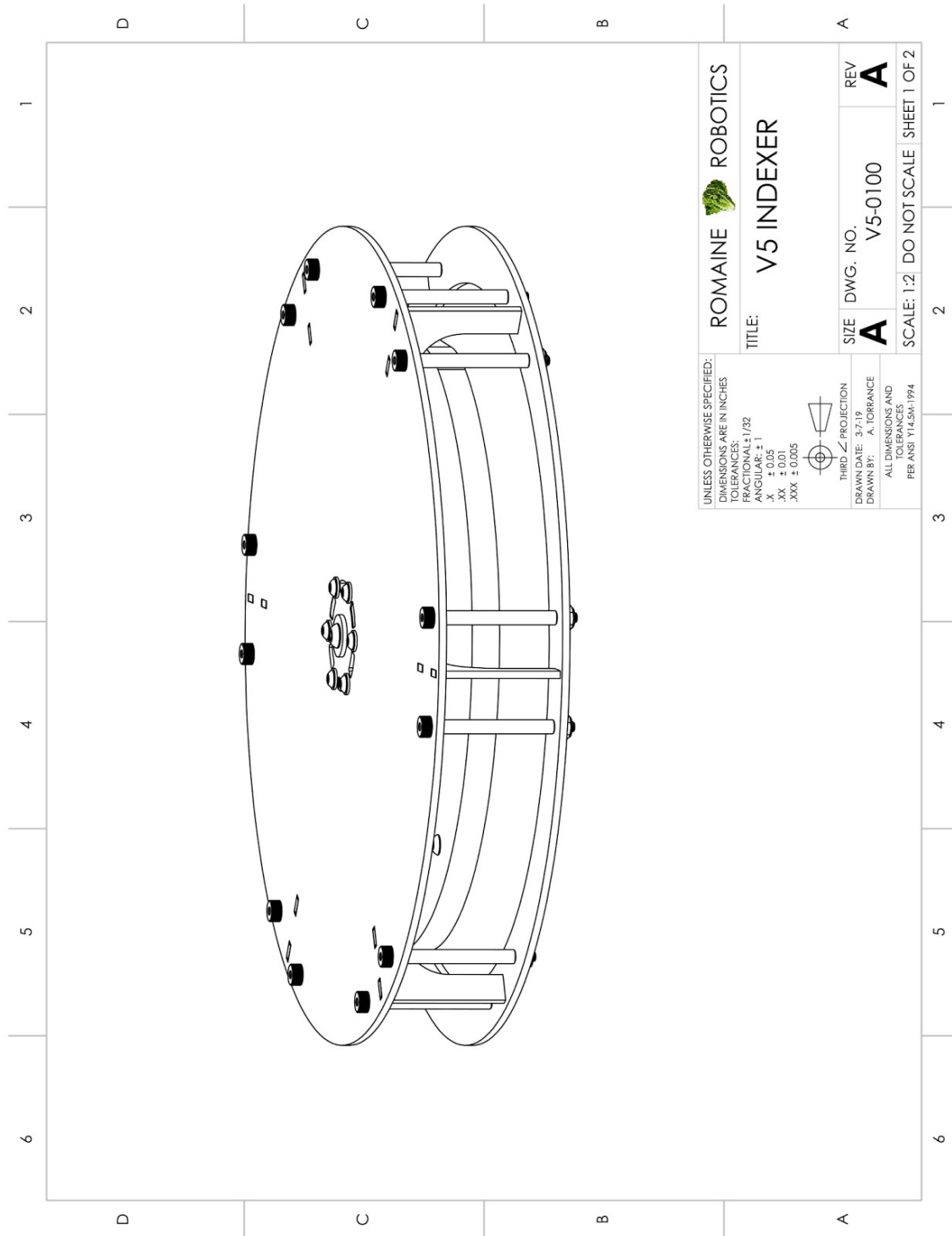
Figure E.3: V5-0100 Indexer Assembly

ROMAINE ROBOTICS

TITLE:

V5 INDEXER

SIZE	DWG. NO.	REV
A	V5-0100	**A**

SCALE: 1:2 | DO NOT SCALE | SHEET 1 OF 2

ITEM NO.	PART NUMBER	QTY.
1	V5-0101	1
2	V5-0102	1
3	V5-0106	1
4	93852A102	2
5	91255A539	2
6	#25 66T 1.125 Bore AL Plate Sprocket (VP 217-2628)	1
7	91259A104	12
8	V5-0103	1
9	97367A111	12
10	CAM WCP 217-3431	1
11	SD Chain Paith	1
12	#25 Chain Inner Link	41
13	#25 Chain Outer Link	41
14	VersaHub 1.125 Bearing Bore 0.50 Wide (VP 217-2591)	1
15	V5-0104	1
16	91255A199	6
17	90633A009	6
18	0.50 ID 1.125 OD 0.313 WD Flanged Bearing 217-2731	2
19	92141A009	6
20	91255A269	2
21	V5-0105	6

Figure E.4: V5-0100 Exploded Indexer Assembly

ROMAINE ROBOTICS

MATERIAL: PLAIN CARBON HR STEEL

THICKNESS: 0.5IN THICK SHEET

QUANTITY: 1

NOTES:

SEE V5-0101 SD.DXF FOR UNSPECIFIED GEOMETRY
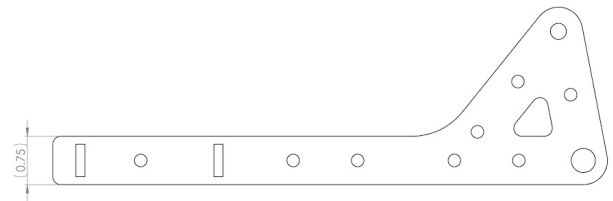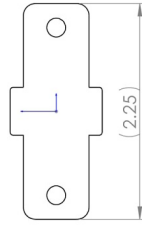
DIMENSION INCLUDED FOR REFERENCE [INCHES]
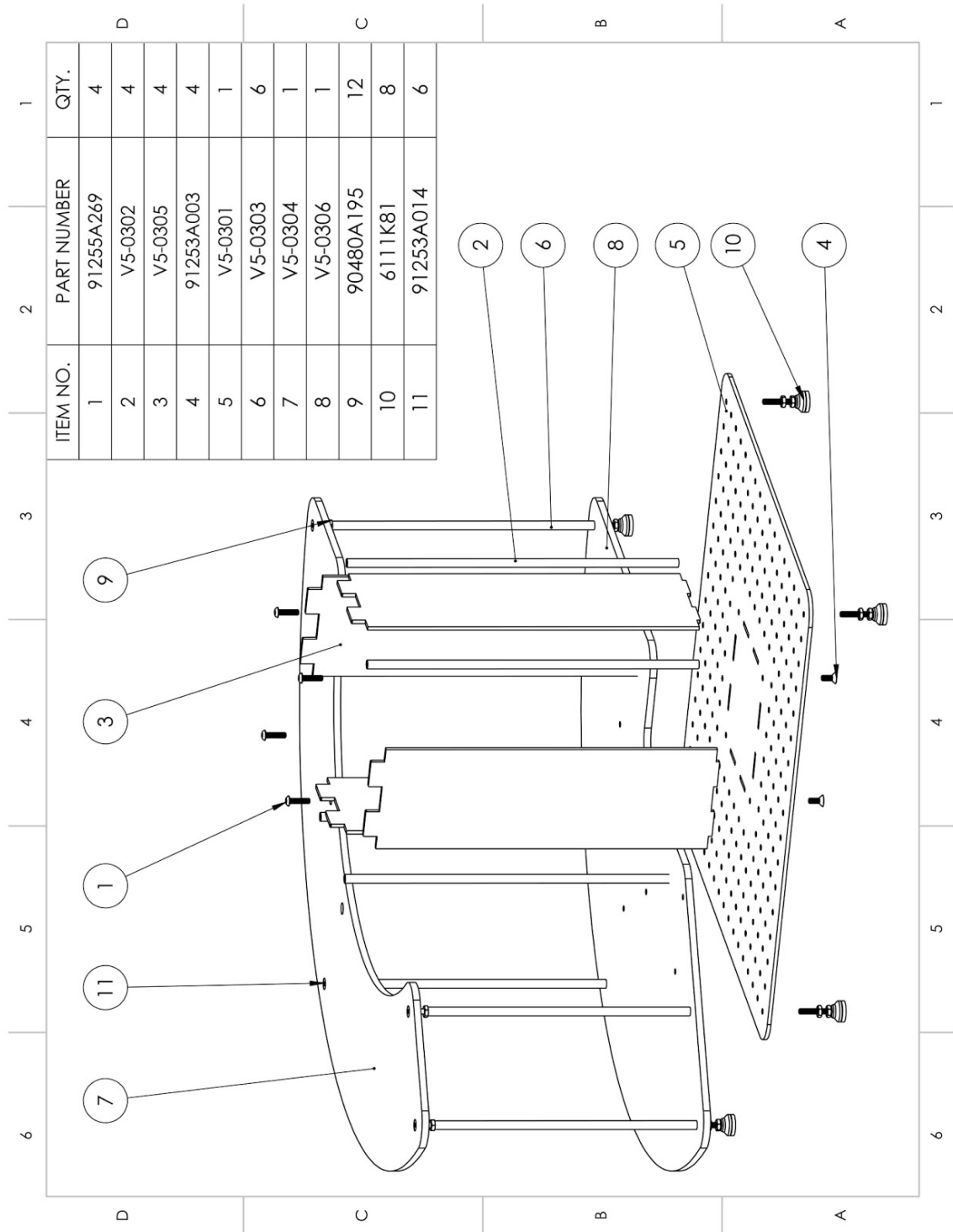
(∅ 0.50)
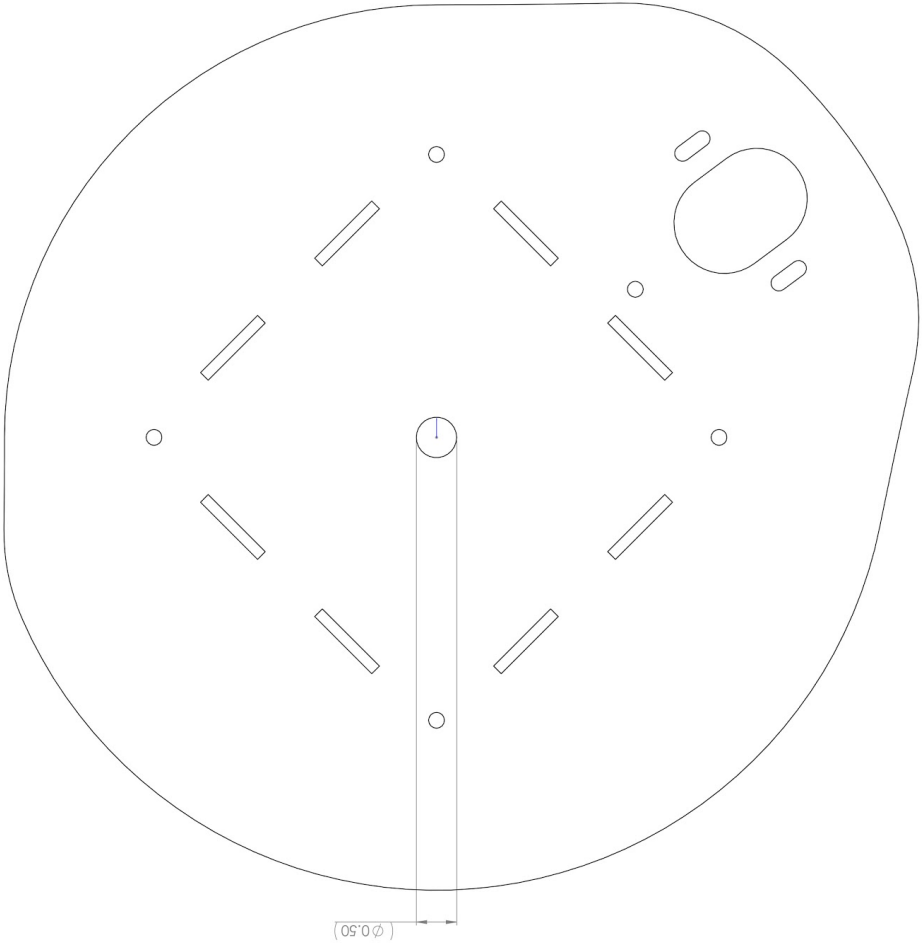
Figure E.5: V5-0101 Cam

Figure E.6: V5-0102 Top Plate

ROMAINE ROBOTICS

MATERIAL: PLAIN CARBON HR STEEL

THICKNESS: 10 GA SHEET

QUANTITY: 1

NOTES:

SEE V5-0102 SD.DXF FOR UNSPECIFIED GEOMETRY

DIMENSION INCLUDED FOR REFERENCE [INCHES]

(⌀ 14.50)

ROMAINE ROBOTICS

MATERIAL: PLAIN CARBON HR STEEL

THICKNESS: 10 GA SHEET

QUANTITY: 2

NOTES:

SEE V5-0103.DXF FOR UNSPECIFIED GEOMETRY
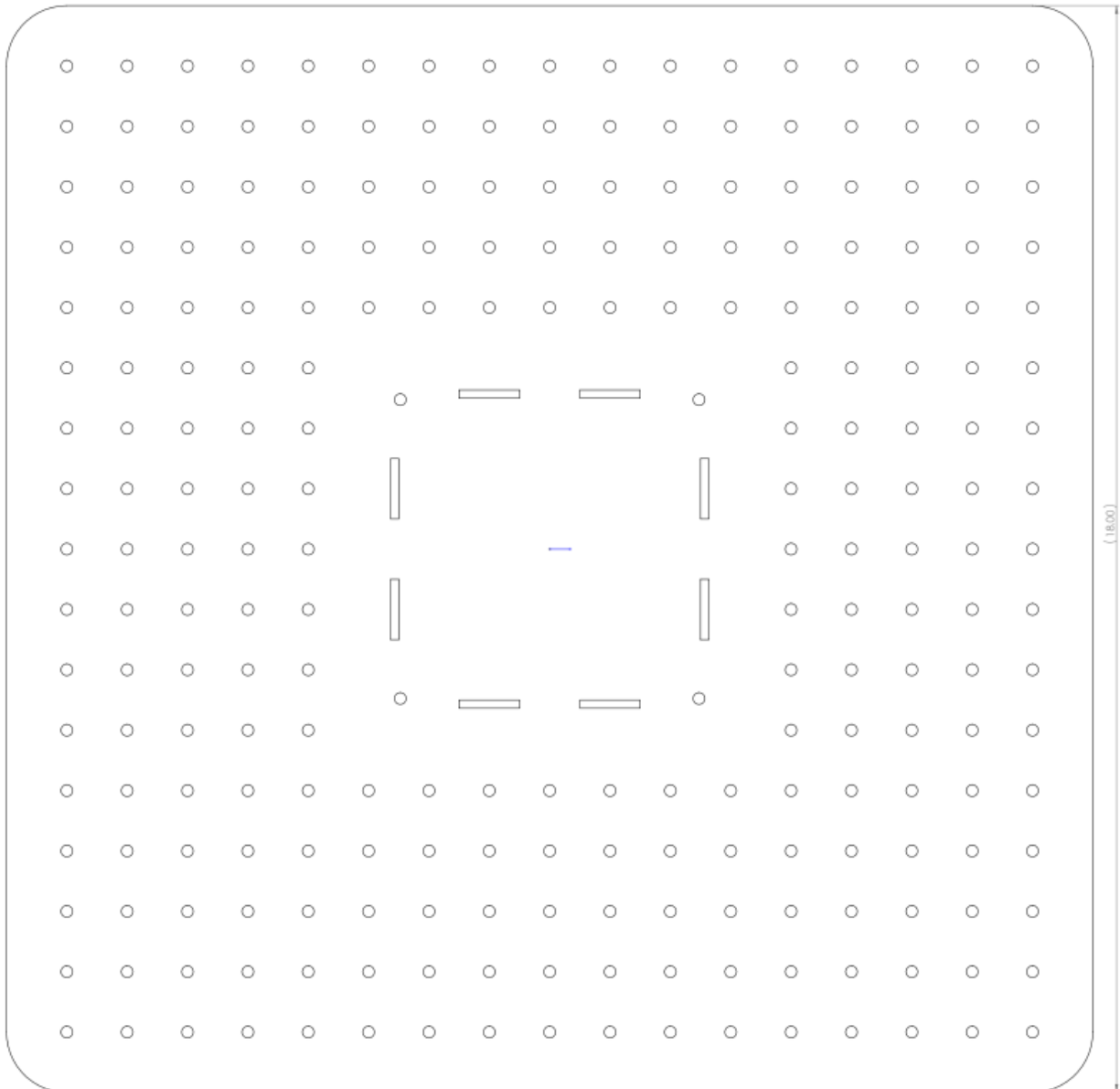
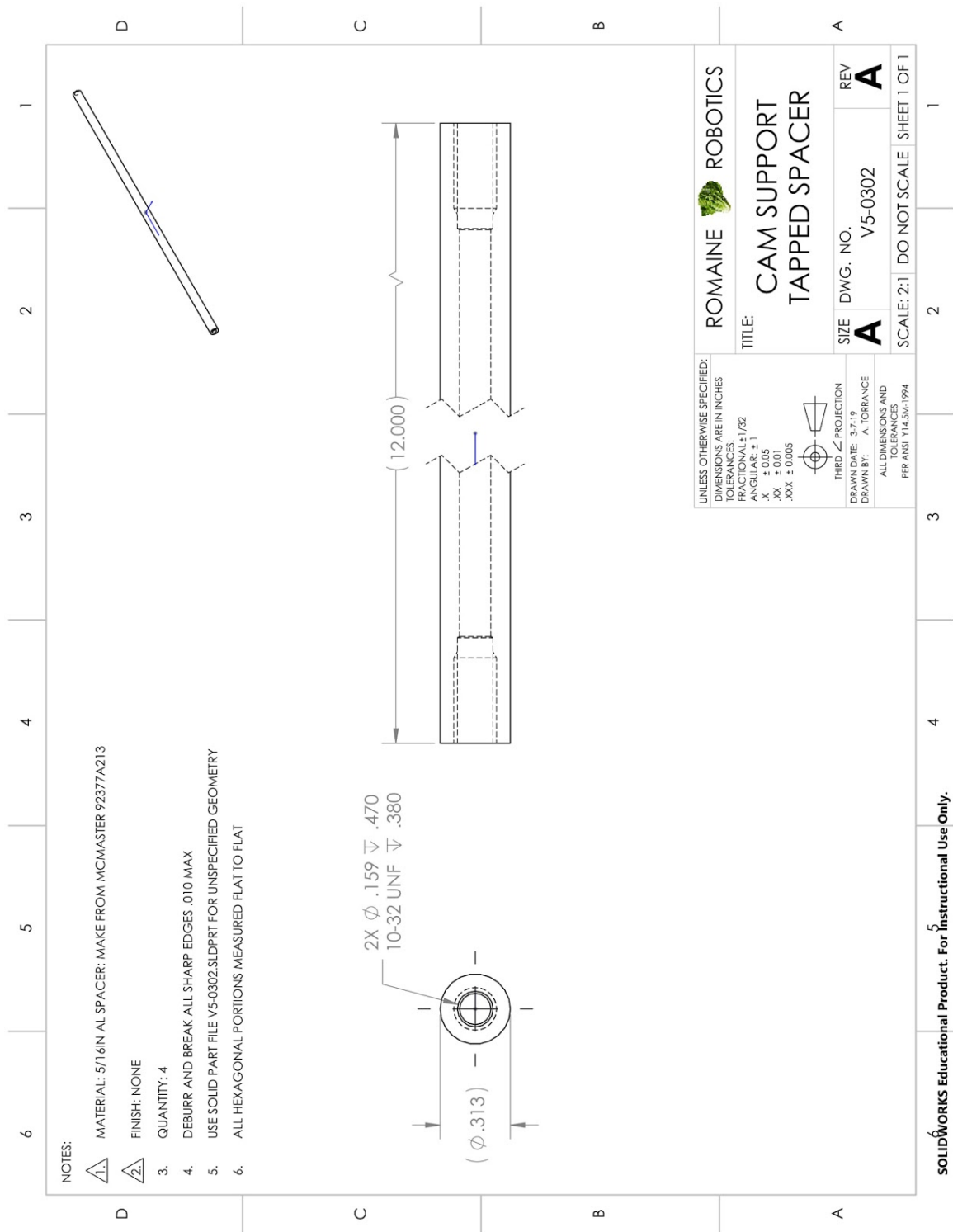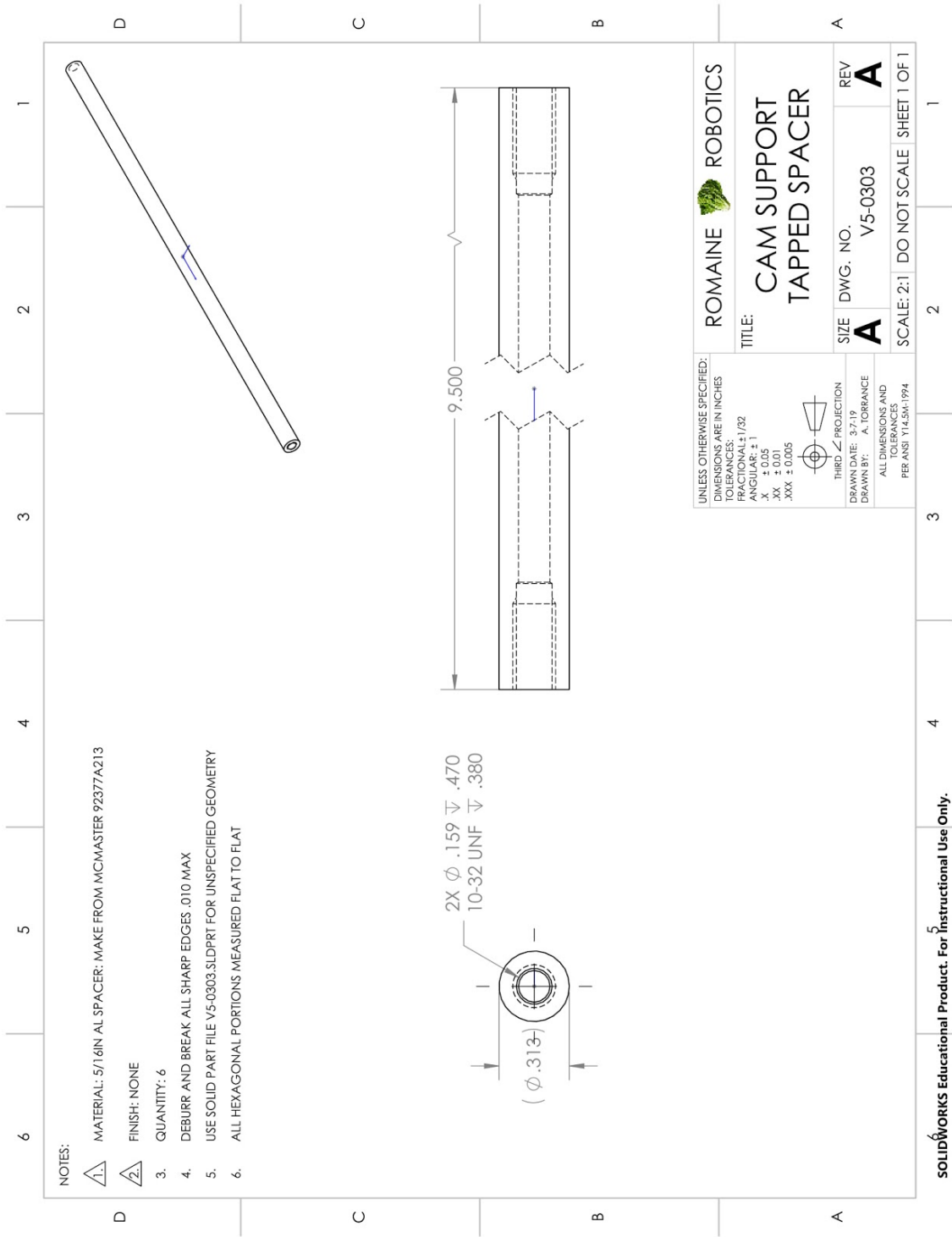DIMENSION INCLUDED FOR REFERENCE [INCHES]

(⌀14.50)
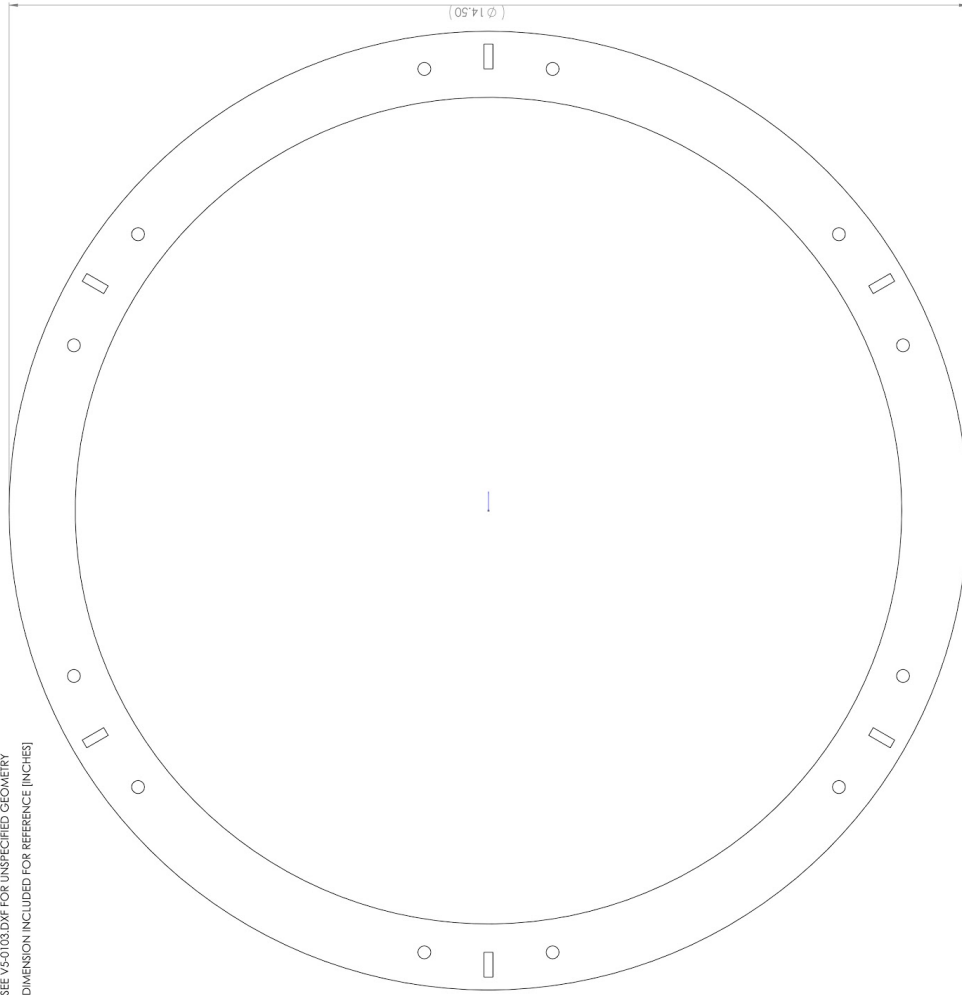
Figure E.7: V5-0103 Bottom Plate
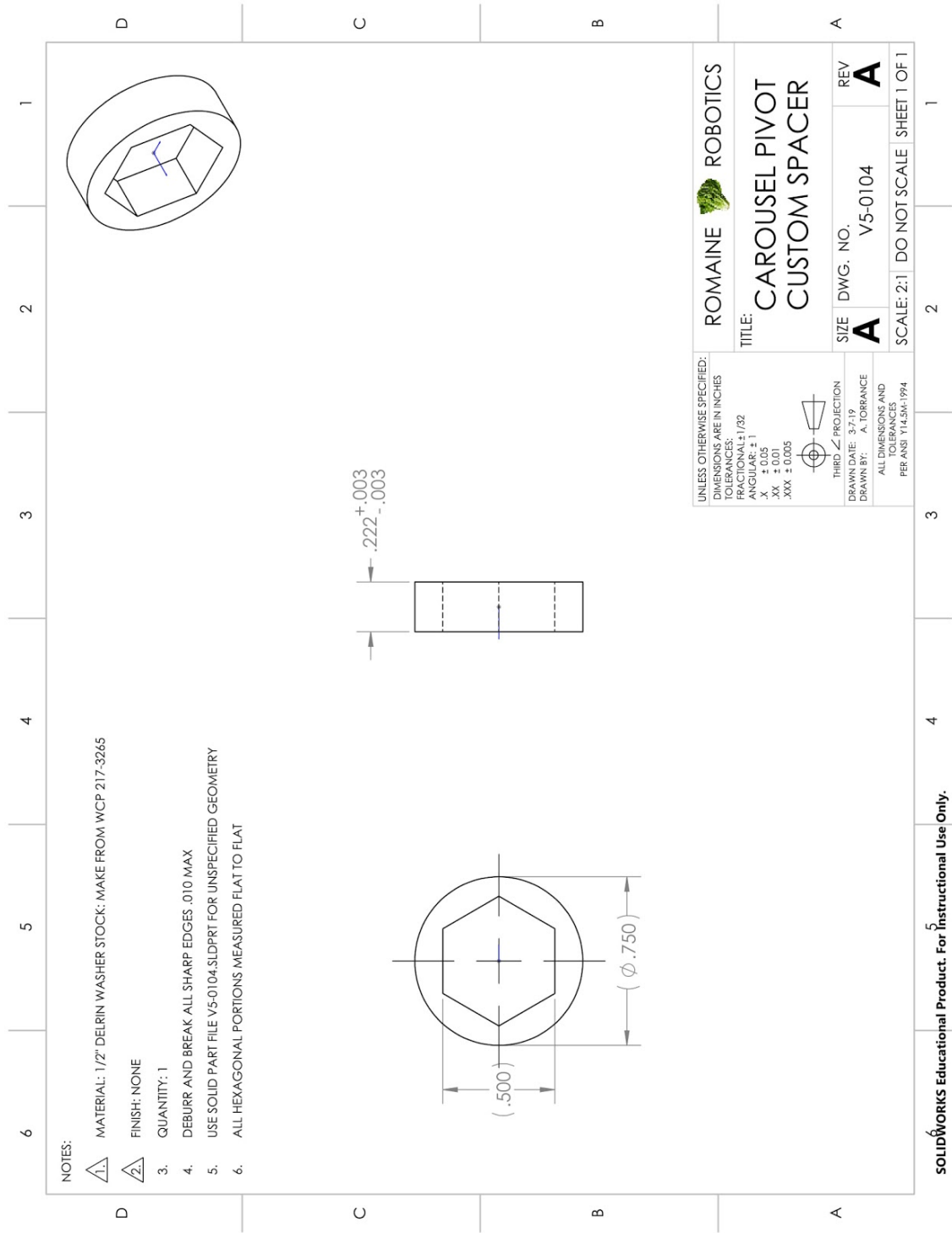
Figure E.8: V5-0104 Carousel Pivot Custom Spacer

NOTES:

1. MATERIAL: 1/2" DELRIN WASHER STOCK: MAKE FROM WCP 217-3265

2. FINISH: NONE

3. QUANTITY: 1

4. DEBURR AND BREAK ALL SHARP EDGES .010 MAX

5. USE SOLID PART FILE V5-0104.SLDPRT FOR UNSPECIFIED GEOMETRY

6. ALL HEXAGONAL PORTIONS MEASURED FLAT TO FLAT

$.222^{+.003}_{-.003}$

(Ø .750)

(.500)

ROMAINE ROBOTICS

TITLE:
CAROUSEL PIVOT
CUSTOM SPACER

SIZE **A** | DWG. NO. V5-0104 | REV **A**

SCALE: 2:1 | DO NOT SCALE | SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL: ±1/32
ANGULAR: ±1
.X   ± 0.05
.XX   ± 0.01
.XXX ± 0.005

THIRD ∠ PROJECTION

DRAWN DATE: 3-7-19
DRAWN BY: A. TORRANCE

ALL DIMENSIONS AND
TOLERANCES
PER ANSI Y14.5M-1994

ROMAINE ROBOTICS

MATERIAL: PLAIN CARBON HR STEEL

THICKNESS: 10 GA SHEET

QUANTITY: 6

NOTES:

SEE V5-0105 SD.DXF FOR UNSPECIFIED GEOMETRY
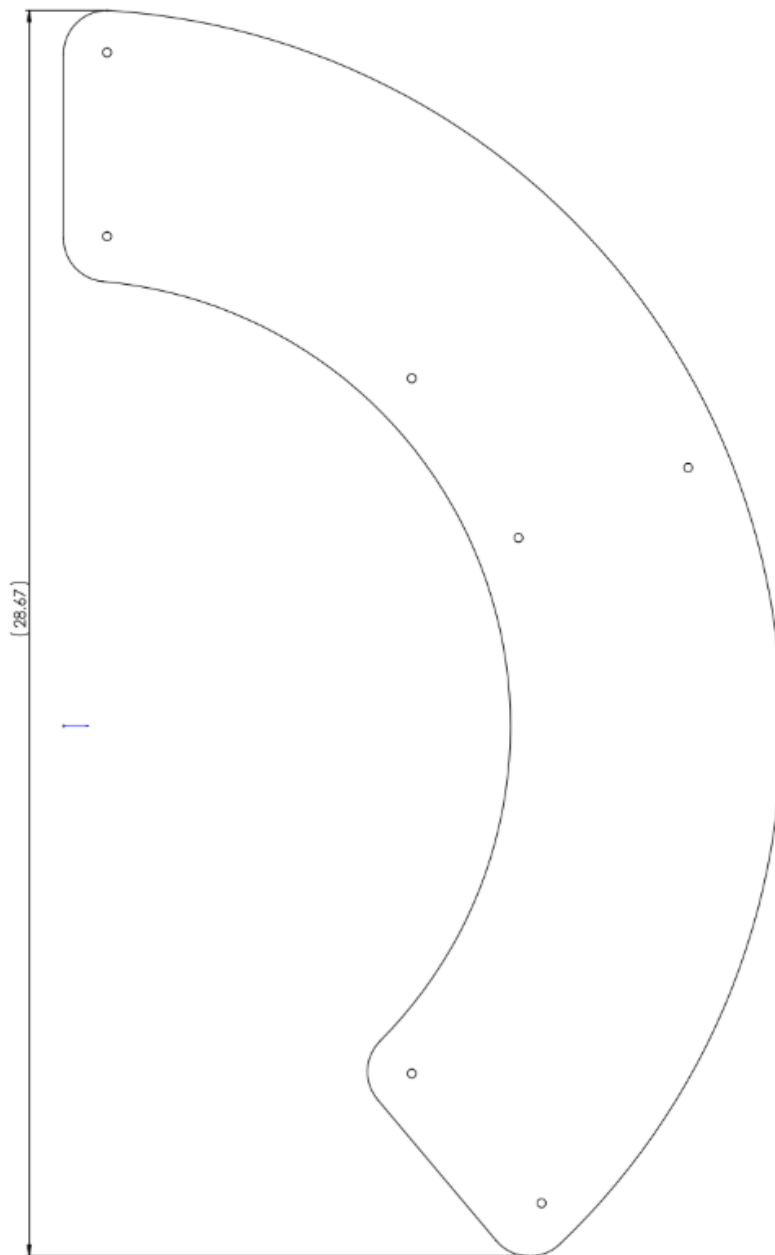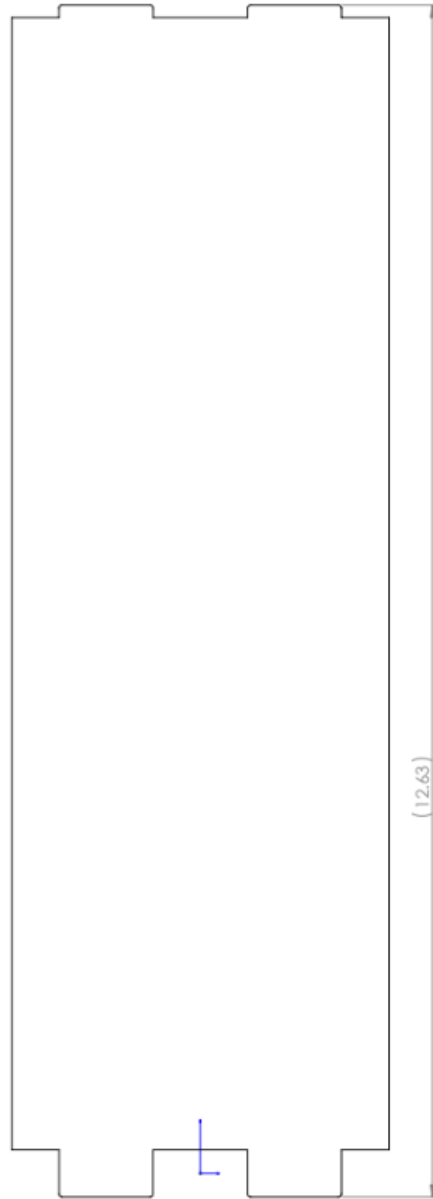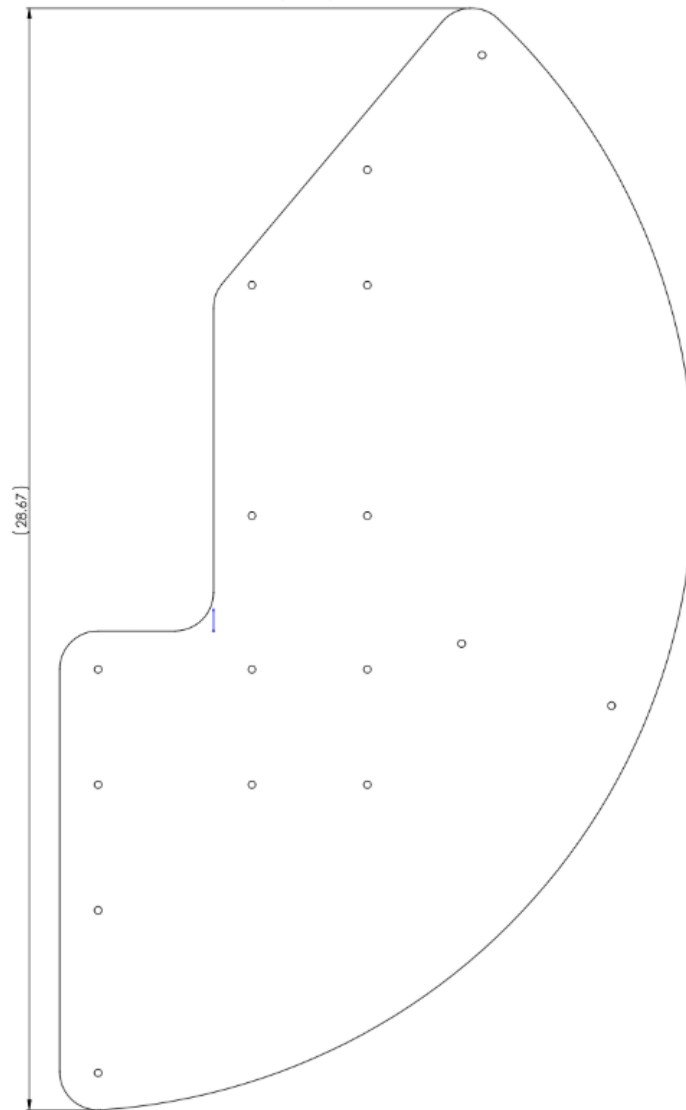
DIMENSION INCLUDED FOR REFERENCE [INCHES]

(2.38)
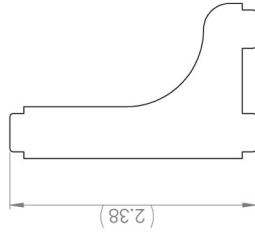
Figure E.9: V5-0105 Standoff
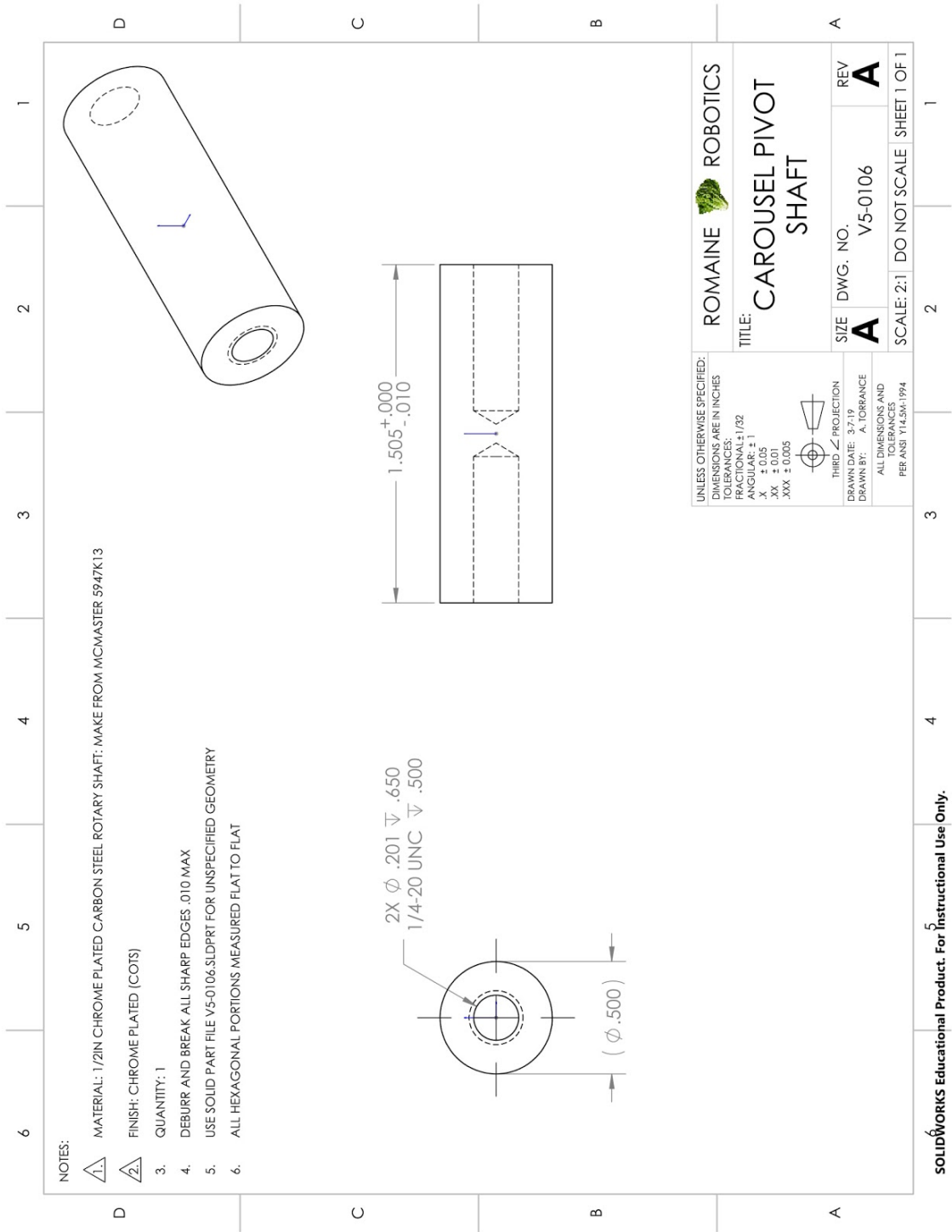
Figure E.10: V5-0106 Carousel Pivot Shaft

NOTES:

1. MATERIAL: 1/2IN CHROME PLATED CARBON STEEL ROTARY SHAFT: MAKE FROM MCMASTER 5947K13
2. FINISH: CHROME PLATED (COTS)
3. QUANTITY: 1
4. DEBURR AND BREAK ALL SHARP EDGES .010 MAX
5. USE SOLID PART FILE V5-0106.SLDPRT FOR UNSPECIFIED GEOMETRY
6. ALL HEXAGONAL PORTIONS MEASURED FLAT TO FLAT

2X ∅ .201 ⩗ .650
1/4-20 UNC ⩗ .500

(∅ .500)

$1.505^{+.000}_{-.010}$

ROMAINE ROBOTICS

TITLE:
CAROUSEL PIVOT SHAFT

SIZE **A** DWG. NO. V5-0106 REV **A**

SCALE: 2:1   DO NOT SCALE   SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL: ± 1/32
ANGULAR: ± 1
X ± 0.05
.XX ± 0.01
.XXX ± 0.005

THIRD ∠ PROJECTION

DRAWN DATE: 3-7-19
DRAWN BY: A. TORRANCE

ALL DIMENSIONS AND TOLERANCES
PER ANSI Y14.5M-1994

SOLIDWORKS Educational Product. For Instructional Use Only.

E10

Figure E.11: V5-0200 Gripper Assembly

ROMAINE ROBOTICS

TITLE: V5 GRIPPER

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±1/32
ANGULAR: ± 1
.X ± 0.05
.XX ± 0.01
.XXX ± 0.005

THIRD ∠ PROJECTION

DRAWN DATE: 3-7-19
DRAWN BY: A. TORRANCE

ALL DIMENSIONS AND
TOLERANCES
PER ANSI Y14.5M-1994

SIZE A | DWG. NO. V5-0200 | REV A

SCALE: 1:2 | DO NOT SCALE | SHEET 1 OF 2

ITEM NO.	PART NUMBER	QTY.
1	V5-0201	1
2	V5-0202	1
3	V5-0203	2
4	V5-0205	2
5	V5-0206	2
6	V5-0208	4
7	6831K42	1
8	91255A028	4
9	90633A411	4
10	6338K411	4
11	90176A152	4
12	90176A159	2
13	90176A161	2
14	90176A163	1
15	91259A544	2
16	97367A111	2
17	94639A445	4
18	90176A158	2
19	98306A116	4
20	98335A031	4

Figure E.12: V5-0200 Exploded Gripper Assembly

ROMAINE ROBOTICS

MATERIAL: PLAIN CARBON HR STEEL

THICKNESS: 10 GA SHEET

QUANTITY: 3

NOTES:

SEE V5-0201.DXF FOR UNSPECIFIED GEOMETRY

DIMENSION INCLUDED FOR REFERENCE [INCHES]

(0.75)
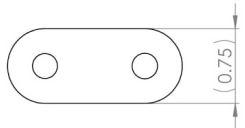
Figure E.13: V5-0201 Gripper Short-link Upper

ROMAINE ROBOTICS

MATERIAL: PLAIN CARBON HR STEEL

THICKNESS: 10 GA SHEET

QUANTITY: 3

NOTES:

SEE V5-0202.DXF FOR UNSPECIFIED GEOMETRY

DIMENSION INCLUDED FOR REFERENCE [INCHES]

(0.75)
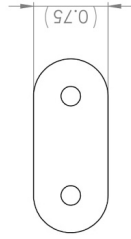
Figure E.14: V5-0202 Gripper Short-link Lower

ROMAINE ROBOTICS

MATERIAL: PLAIN CARBON HR STEEL

THICKNESS: 10 GA SHEET

QUANTITY: 6

NOTES:

SEE V5-0205.DXF FOR UNSPECIFIED GEOMETRY

DIMENSION INCLUDED FOR REFERENCE [INCHES]

(0.75)

Figure E.15: V5-0205 Left Arm

ROMAINE ROBOTICS

MATERIAL: PLAIN CARBON HR STEEL

THICKNESS: 10 GA SHEET

QUANTITY: 6

NOTES:

SEE V5-0203.DXF FOR UNSPECIFIED GEOMETRY

DIMENSION INCLUDED FOR REFERENCE [INCHES]

(0.75)

Figure E.16: V5-0203 Right Arm

E15

ROMAINE ROBOTICS

MATERIAL: PLAIN CARBON HR STEEL

THICKNESS: 10 GA SHEET

QUANTITY: 12

NOTES:

SEE V5-0208.DXF FOR UNSPECIFIED GEOMETRY

DIMENSION INCLUDED FOR REFERENCE [INCHES]

(2.25)

Figure E.17: V5-0208 Arm Standoff
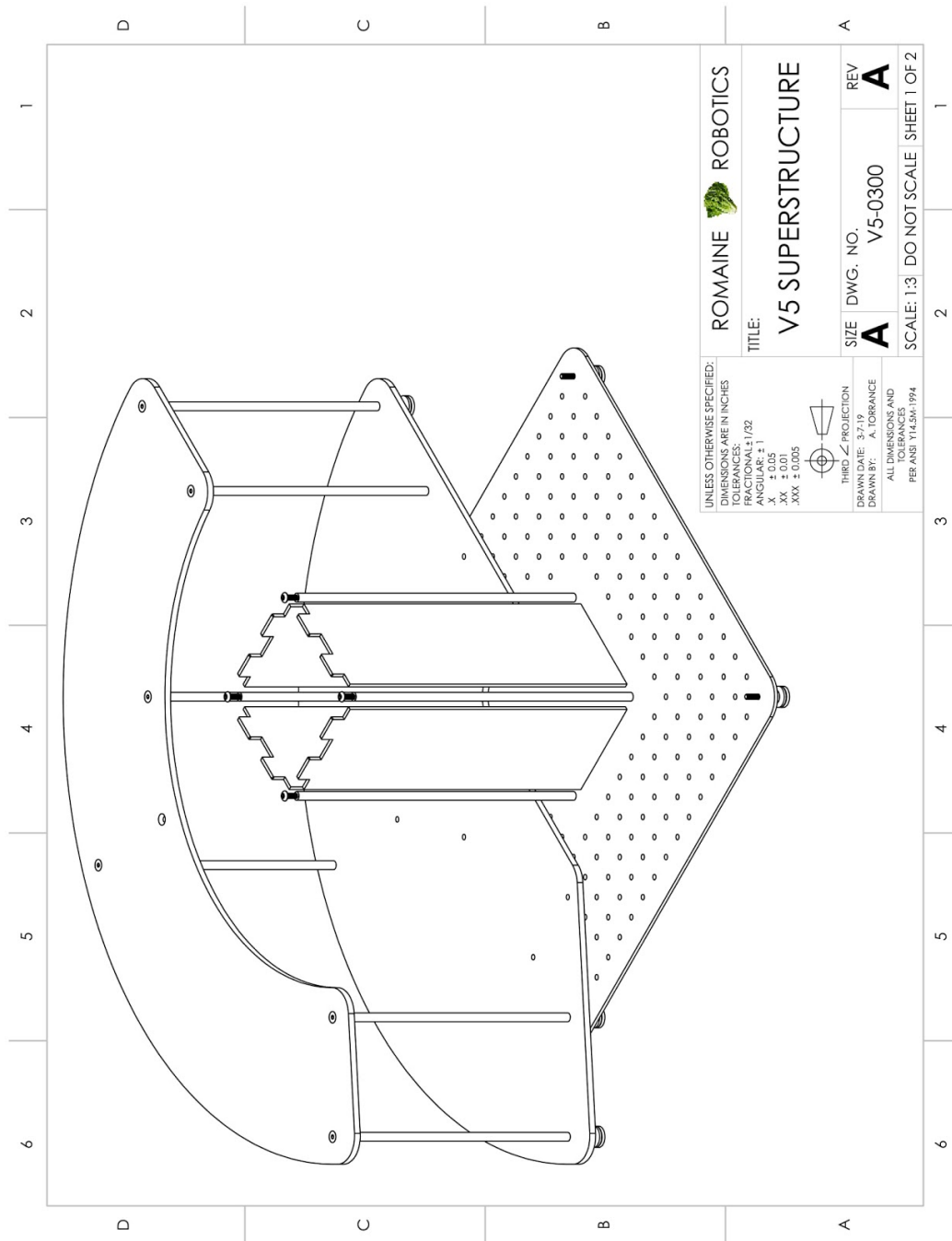
Figure: E.18: V5-0300 Super Structure View

The drawing title block contains:

ROMAINE ROBOTICS

TITLE:
V5 SUPERSTRUCTURE

SIZE **A** DWG. NO. V5-0300 REV **A**

SCALE: 1:3 DO NOT SCALE SHEET 1 OF 2

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL: ±1/32
ANGULAR: ± 1
.X   ± 0.05
.XX   ± 0.01
.XXX ± 0.005

THIRD ∠ PROJECTION

DRAWN DATE: 3-7-19
DRAWN BY: A. TORRANCE

ALL DIMENSIONS AND
TOLERANCES
PER ANSI Y14.5M-1994

ITEM NO.	PART NUMBER	QTY.
1	91255A269	4
2	V5-0302	4
3	V5-0305	4
4	91253A003	4
5	V5-0301	1
6	V5-0303	6
7	V5-0304	1
8	V5-0306	1
9	90480A195	12
10	6111K81	8
11	91253A014	6

Figure: E.19: V5-0300 Super Structure Exploded View

E18

ROMAINE ROBOTICS
MATERIAL: PLAIN CARBON HR STEEL
THICKNESS: 10 GA SHEET
QUANTITY: 1
NOTES:
    SEE V5-0301 .DXF FOR UNSPECIFIED GEOMETRY
    DIMENSION INCLUDED FOR REFERENCE [INCHES]

Figure: E.20: V5-0301 Base Plate

NOTES:

1. MATERIAL: 5/16IN AL SPACER: MAKE FROM MCMASTER 92377A213

2. FINISH: NONE

3. QUANTITY: 4

4. DEBURR AND BREAK ALL SHARP EDGES .010 MAX

5. USE SOLID PART FILE V5-0302.SLDPRT FOR UNSPECIFIED GEOMETRY

6. ALL HEXAGONAL PORTIONS MEASURED FLAT TO FLAT

(12.000)

2X ∅ .159 ▽ .470
10-32 UNF ▽ .380

(∅ .313)

ROMAINE ROBOTICS

TITLE:
CAM SUPPORT
TAPPED SPACER

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/32
ANGULAR: ± 1
.X   ± 0.05
.XX   ± 0.01
.XXX ± 0.005

THIRD ∠ PROJECTION

DRAWN DATE: 3-7-19
DRAWN BY: A. TORRANCE

ALL DIMENSIONS AND
TOLERANCES
PER ANSI Y14.5M-1994

SIZE	DWG. NO.		REV
A	V5-0302		A
SCALE: 2:1	DO NOT SCALE	SHEET 1 OF 1	

Figure: E.21: V5-0302 Cam Support Tapped Spacer

NOTES:

1. MATERIAL: 5/16IN AL SPACER: MAKE FROM MCMASTER 92337A213

2. FINISH: NONE

3. QUANTITY: 6

4. DEBURR AND BREAK ALL SHARP EDGES .010 MAX

5. USE SOLID PART FILE V5-0303.SLDPRT FOR UNSPECIFIED GEOMETRY

6. ALL HEXAGONAL PORTIONS MEASURED FLAT TO FLAT

9.500

2X ⌀ .159 ▽ .470
10-32 UNF ▽ .380

(⌀ .313)

ROMAINE 🥬 ROBOTICS

TITLE:
CAM SUPPORT
TAPPED SPACER

SIZE **A**   DWG. NO.   V5-0303   REV **A**

SCALE: 2:1   DO NOT SCALE   SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL: ±1/32
ANGULAR: ±1
.X   ±0.05
.XX   ±0.01
.XXX ±0.005

THIRD ∠ PROJECTION

DRAWN DATE: 3-7-19
DRAWN BY: A. TORRANCE

ALL DIMENSIONS AND
TOLERANCES
PER ANSI Y14.5M-1994

Figure: E.22: V5-0303 Cam Support Tapped Spacer

ROMAINE ROBOTICS

MATERIAL: PLAIN CARBON HR STEEL

THICKNESS: 10 GA SHEET

QUANTITY: 1

NOTES:

SEE V5-0304.DXF FOR UNSPECIFIED GEOMETRY

DIMENSION INCLUDED FOR REFERENCE [INCHES]

(28.67)

Figure: E.23: V5-0304 Leveling Platform

ROMAINE ROBOTICS

MATERIAL: PLAIN CARBON HR STEEL

THICKNESS: 10 GA SHEET

QUANTITY: 4

NOTES:

    SEE V5-0305.DXF FOR UNSPECIFIED GEOMETRY

    DIMENSION INCLUDED FOR REFERENCE [INCHES]

Figure: E.24: V5-0305 Tower

ROMAINE ROBOTICS
MATERIAL: PLAIN CARBON HR STEEL
THICKNESS: 10 GA SHEET
QUANTITY: 1
NOTES:
    SEE V5-0306.DXF FOR UNSPECIFIED GEOMETRY
    DIMENSION INCLUDED FOR REFERENCE [INCHES]

(28.67)

Figure: E.25: V5-0306 Leveling Platform Base
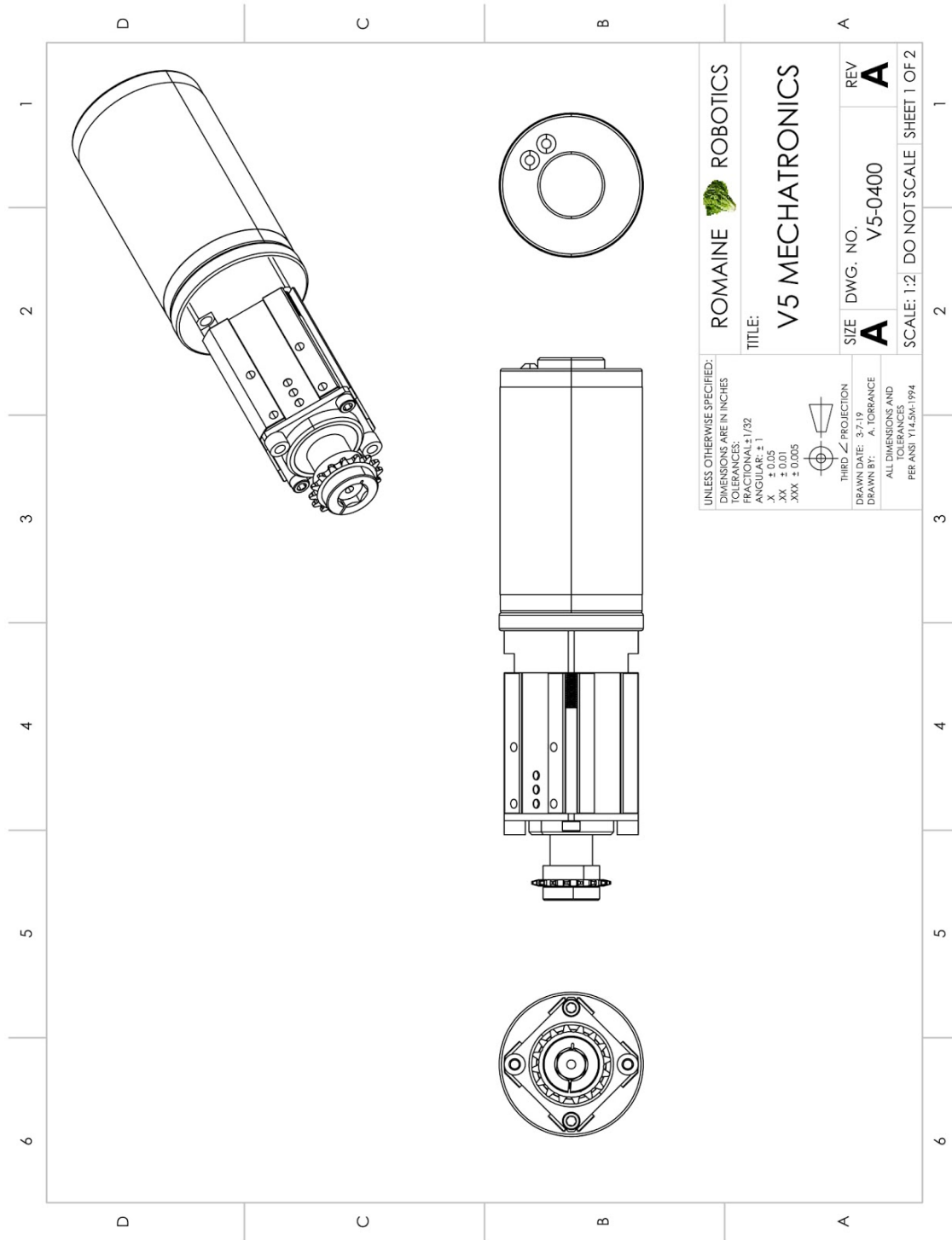
Figure: E.26: V5-0400 Mechatronics

ROMAINE 🥬 ROBOTICS

TITLE:

V5 MECHATRONICS

SIZE	DWG. NO.	REV
A	V5-0400	**A**

SCALE: 1:2 DO NOT SCALE SHEET 1 OF 2

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/32
ANGULAR: ± 1
X ± 0.05
XX ± 0.01
XXX ± 0.005

THIRD ∠ PROJECTION

DRAWN DATE: 3-7-19
DRAWN BY: A. TORRANCE

ALL DIMENSIONS AND
TOLERANCES
PER ANSI Y14.5M-1994

ITEM NO.	PART NUMBER	QTY.
1	CIM_Motor_217-2000	1
2	CIM Sport Gearbox 64-1 AM-3764	1
3	#25 16T 0.500 Hex Bore Hub Sprocket Al (VP 217-2642)	1
4	Clamping Shaft Collar 0.500 Hex (VP 217-2737)	1
5	V5-0401	1
6	V5-0402	2
7	CIMCODER MOTOR ENCODER	1

Figure: E.27: V5-0400 Mechatronics Exploded View

E26

Appendix F: Matlab Code

```
clc
clear
%% Initialization
a=6.46; %% left arm
b=2; % left actuator
c=6.46; % right arm
d=2.561;% right actuator
e=1; %% dogbone Length
s = 1.91; %%length of spring attachment point from pivot to spring
cdAngle = deg2rad(102.5);% angle between c and d
abAngle = deg2rad(80.77); % angle between ab
springUnstretched = 3; %inches
springK = 3.2*2; %lbf/in

%% Set Time and Cam
load('CamCoordsV4'); %load x, y coordinates of CAM
[xp,yp] = pathgen(camx,camy,900); %Converts to better coordinates (thank u chuck)
%plot(xp,yp); %Plot of Cam
camAngle = atan2d(yp,xp) + 360*(yp<0); %Converts each data point to thetas (0->360)
camDisp = sqrt(xp.^2 + yp.^2); %absolute displacement from origin
camDisp = camDisp - 6.538 + .5; %Distance
camDisp = fliplr(camDisp);
camDisp = [camDisp(length(camDisp)/3:length(camDisp)) camDisp(1:length(camDisp)/3)];
RPM = 5;
t = 0:.25:(60/RPM);
sampledDisp = resample(camDisp, length(t), length(camDisp), 0);
%camplot = plot(t,sampledDisp) %Plot of displacement over time
%xlabel('Degrees');
%ylabel('Displaement (in)');
%% Wheel Location Setup (Constant Angular Velocity)
%omega=-.1;
%WheelDisp = 1.24; %distance from followerwheel to horizontal between two pivots (in)
%thetaStart = sin(WheelDisp/2.561); %starting angle of follower wheel to right arm
%thetaR=pi + thetaStart+ omega*t; %Initializes right linkage angles over time from initial location to final
%% Wheel Location Setup (Use Cam)
thetaR=pi + atan(-sampledDisp/2.5)

%% Do Calculation
pR=[5;0]; %% Fixed Right pivot location
pL=[0;0]; %% Fixed Left pivot location

%Calculate locations of Right Linkage
pRact= [5 + d*cos(thetaR);d*sin(thetaR)]; %%right arm actuator location
pRarm= [5 + c*cos(thetaR-cdAngle);c*sin(thetaR-cdAngle)]; %%right arm gripper location
pRSpring= [5 + s*cos(thetaR-cdAngle);s*sin(thetaR-cdAngle)]; %%right arm gripper location

%Do Inverse Kinematics to find angles for dog bone and left pivot
thetaE = -acos((pRact(1,:).^2 + pRact(2,:).^2 - b^2 - e^2)/(2*b*e)); %inverse Kinematics (dog bone)
thetaB = (atan2(pRact(2,:),pRact(1,:))-  atan2(e*sin(thetaE),  b+e*cos(thetaE))); %Inverse Kinematics (left actuator)

%Calculate location of Left Pivot
pLact= [b*cos(thetaB);b*sin(thetaB)];
pLarm= [a*cos(thetaB+abAngle);a*sin(thetaB+abAngle)]; %%left arm gripper
pLSpring= [s*cos(thetaB+abAngle);s*sin(thetaB+abAngle)]; %%left arm Spring

%test = sqrt((pLact(1,:)-pRact(1,:)).^2 + (pLact(2,:)-pRact(2,:)).^2);
%%%measures dogbone length

thetaE = thetaE + thetaB; %Update thetaE to global frame
%pLtemp = [pLact(1,:)+e*cos(thetaE);pLact(2,:)+e*sin(thetaE)];

% Velocity Analyis
openingDistance = (pRarm(1,:)-pLarm(1,:));
```

```
openingDistanceVelocity=diff(openingDistance)./diff(t);
openingDistanceAcceleration=diff(openingDistanceVelocity)./diff(t(:,[1:length(t)-1]));

% Spring Dist Analysis
springDist = (pRSpring(1,:)-pLSpring(1,:));
springDistanceVelocity=diff(springDist)./diff(t);
springDistanceAcceleration=diff(springDistanceVelocity)./diff(t(:,[1:length(t)-1]));
springForce = (springDist-springUnstretched)*springK;
camForce = springForce*((s*cos(thetaR-cdAngle-pi/2))/(d*cos(thetaR-pi))+(s*cos(thetaB+abAngle-pi/2))/(b*cos(thetaR-pi)));
%torque = (sampledDisp+6.538).*camForce.*gradient(sampledDisp); %distance times horizontal (turning) component
torque = (sampledDisp+6.538).*camForce.*gradient(sampledDisp);
mu = 0.2;
torque = torque + (sampledDisp+6.538).*mu.*(camForce./cos(atan(gradient(sampledDisp)))); %%add friction
lettuceForce = springForce.*(s/c);

%%
cup1torque = torque;
cup2torque = circshift(cup1torque, 8);
cup3torque =  circshift(cup2torque, 8);
cup4torque = circshift(cup3torque, 8);
cup5torque = circshift(cup4torque, 8);
cup6torque = circshift(cup5torque, 8);
torquesum = cup1torque+cup2torque+cup3torque+cup4torque+cup5torque+cup6torque;

%%% Make Plots
figure1 =figure('Position', [100,100, 1200, 600] );

plot2=subplot(2,3,4);
plot(plot2,t,sampledDisp,'Color','k');
hold on
axis([0, t(end), -2, max(sampledDisp)+1]);
xlabel('Time (s)');
ylabel('Displacement (in)');

for i=1:length(t)
    %Linkage Plot
    plot1=subplot(2,3, 1);
    hline = refline([0 0]);
    hline.Color = 'k';
    hline.LineStyle = '--';
    axis(plot1,'equal');
    xlim([-5 10]);
    ylim([-5 7]);
    grid on

    circles(1)=viscircles(pR',0.1,'Color','k'); %pR_circle
    circles(2)=viscircles(pRact(:,i)',0.1,'Color','k'); %pRact_circle
    circles(3)=viscircles(pRarm(:,i)',0.1,'Color','r'); %pRarm_circle
    links(1) =line([pR(1) pRact(1,i)],[pR(2) pRact(2,i)]); %link_Ract
    links(2)=line([pR(1) pRarm(1,i)],[pR(2) pRarm(2,i)]); %link_Rarm
    circles(4)=viscircles(pLact(:,i)',0.1,'Color','k'); %pLact_circle
    links(3)=line([pL(1) pLact(1,i)],[pL(2) pLact(2,i)]); % link_Lact
    links(4)=line([pLact(1,i) pRact(1,i)],[pLact(2,i) pRact(2,i)]);%link_dog
    circles(5)=viscircles(pLarm(:,i)',0.1,'Color','r');%pLarm_circle
    links(5)=line([pL(1) pLarm(1,i)],[pL(2) pLarm(2,i)]);%link_Larm
    circles(6)=viscircles(pL',0.1,'Color','k');%pL_circle
    circles(7)=viscircles(pRSpring(:,i)',0.1,'Color','b'); %pRarm_circle
    circles(8)=viscircles(pLSpring(:,i)',0.1,'Color','b'); %pRarm_circle
    % links(7)=line([pLact(1,i) pLtemp(1,i)],[pLact(2,i) pLtemp(2,i)]);%temp

    %text = annotation('textarrow',[0.3 0.5], [0.6 0.5],'String','yar ');

    notation = text(-5, 8, strcat('Wheel Displacement:  ',num2str(pRact(2,i)), ' in'));
    pause(0.0000001); %pause to slow down

%    if(i>40)break; //use this to pause at a moment
```

```matlab
%    end

    % Subplot-2
    if(i<length(t))
        delete(circles)
        delete(links)
        delete(notation);
%        delete(link_Ltemp)

        % Plot Displacement
        %plot2=subplot(2,2,3);
        plot(plot2,t(1:i),openingDistance(1:i),'Color','r');
        grid on
        hold on
        plot(plot2,t(1:i),springDist(1:i),'Color','b');

        %Plot Velocity
        plot3=subplot(2,3,2);
        plot(plot3,t(1:i),openingDistanceVelocity(1:i),'Color','r');
        axis([0 t(end) min(openingDistanceVelocity) max(openingDistanceVelocity)]);
        xlabel('Time (s)');
        ylabel('Tip Velocity (in/s)');
        grid on
        hold on
        plot(plot3,t(1:i),springDistanceVelocity(1:i),'Color','b');

        %Plot Acceleration
        plot4=subplot(2,3,3);
        plot(plot4,t(1:i-1),openingDistanceAcceleration(1:i-1),'Color','r');
        axis([0 t(end) min(openingDistanceAcceleration) max(openingDistanceAcceleration)]);
        xlabel('Time (s)');
        ylabel('Tip Acceleration (in/s^2)');
        grid on
        box on
        hold on
        plot(plot4,t(1:i-1),springDistanceAcceleration(1:i-1),'Color','b');

        % Plot Spring Force
        plot5=subplot(2,3,5);
        plot(plot5,t(1:i),springForce(1:i),'Color','b');
        hold on
        plot(plot5,t(1:i),camForce(1:i),'Color','k');
        plot(plot5,t(1:i),lettuceForce(1:i),'Color','r');
        grid on
        axis([0 t(end) 0 max(camForce)]);
        xlabel('Time (s)');
        ylabel('Forces (lbs)');

        % Plot Cam Torque
        plot6=subplot(2,3,6);
        plot(plot6,t(1:i),cup1torque(1:i),'Color','b');
        hold on
        plot(plot6,t(1:i),cup2torque(1:i),'Color','b');
        plot(plot6,t(1:i),cup3torque(1:i),'Color','b');
        plot(plot6,t(1:i),cup4torque(1:i),'Color','b');
        plot(plot6,t(1:i),cup5torque(1:i),'Color','b');
        plot(plot6,t(1:i),cup6torque(1:i),'Color','b');
        plot(plot6,t(1:i),torquesum(1:i),'Color','k');
        grid on
        axis([0 t(end) -50 300]);
        xlabel('Time (s)');
        ylabel('Torque (in-lbs)');
        grid on;

    end
end
```

Appendix G: Component Data Sheets

G1: CIM Motor

Figure G.1: CIM Motor Curve

Figure G.2: CIM Motor Specification from Manufacturer

G2: CIMCoder Optical Rotary Shaft Encoder
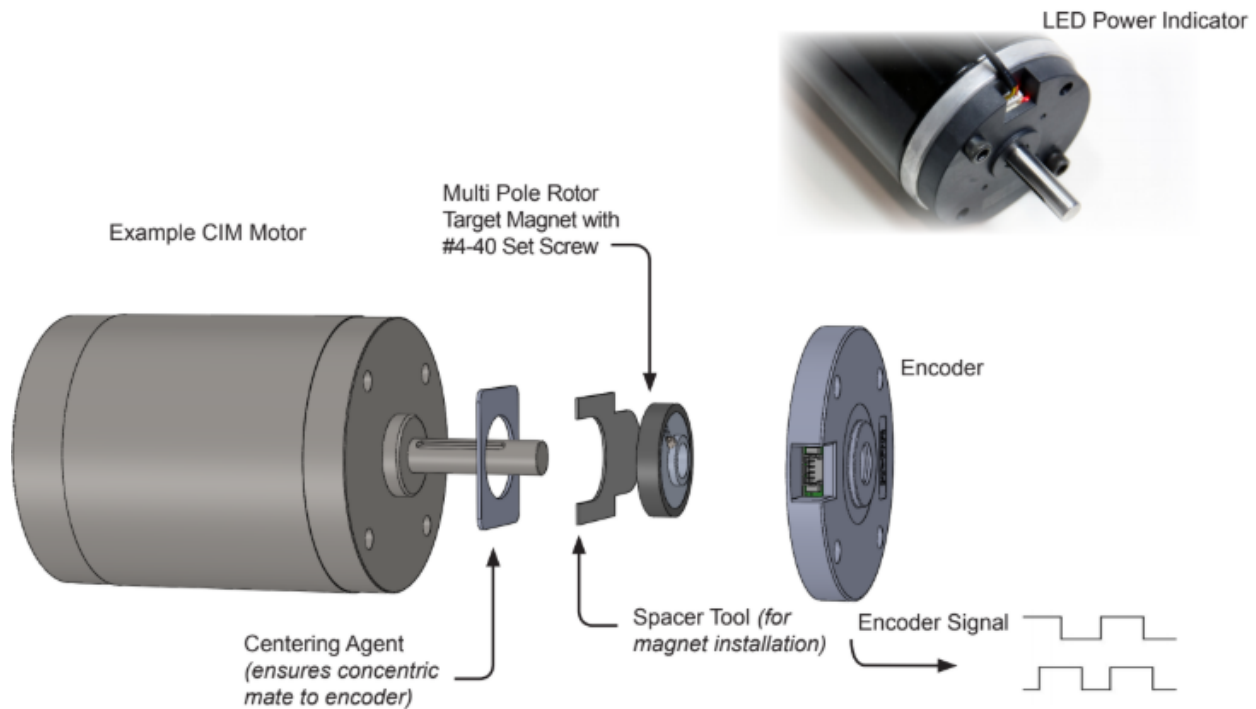
Figure G.3: CIMCoder Assembly and Overview
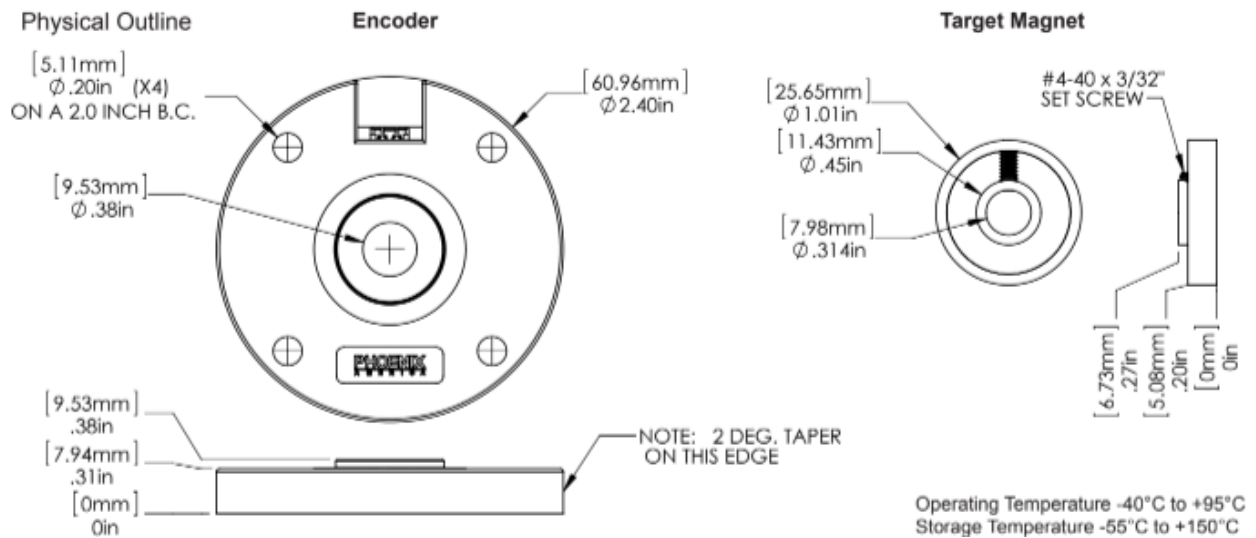
Figure G.4: CIMCoder Dimensions and Specifications

Signal Phasing

Ch A

Ch B
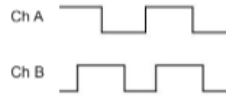
Channel A leads channel B when the CIM motor is running in positive polarity (red wire + and black wire -)

Pull up resistors are necessary to generate an output signal for the desired voltage level and are generally preferred external for encoders.

Pin 1

Vdd

R pull up 10KΩ   R pull up 10KΩ

Signal Out A

Signal Out B

CH A   CH B

Red   V$_{DD}$ **Encoder IC**   Gnd   Black

0.1 µF

Decoupling Capacitor Included inside Encoder

Pull-up Resistance Chart (recommended 1.2 mA sink current)

10KΩ with 12V Supply

Resistance KΩ / Supply Voltage
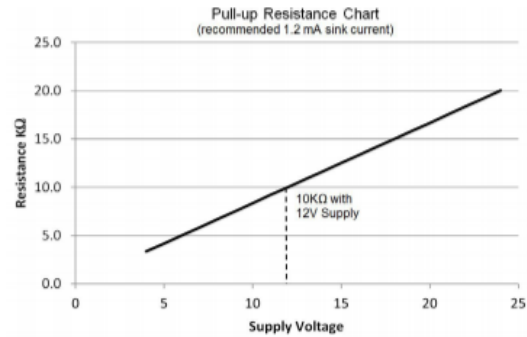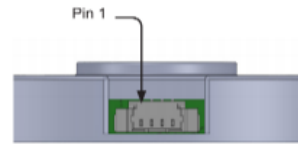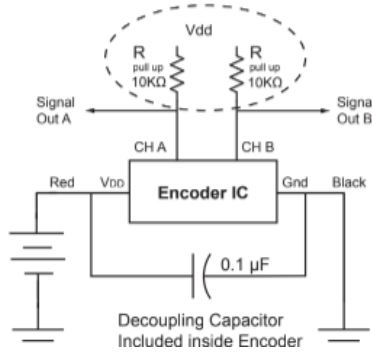
Figure G.5: CIMCoder Electrical Properties

G3: CIMsport Planetary Gearbox

Step 1 : Carefully press the pinion provided with the CIM Sport gearbox onto the CIM Motor. Press the pinion so it is flush with the end of the CIM shaft.
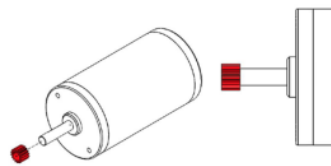
Step 2: Remove the two 10-32 x 1.750 Socket Head Screws from the CIM Sport.
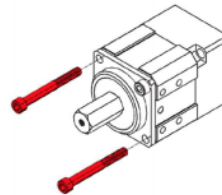
Step 3: Remove the Motor Input Block and the steel Thrust Washer. Set the Thrust Washer aside on a clean shop towel or paper towel.

Motor Input

Thrust Washer
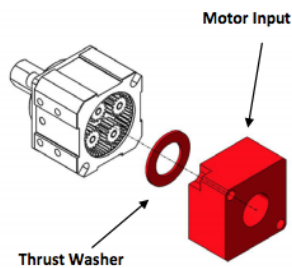
Step 4: Attach the Motor Input Block to the CIM Motor (with previously attached pinion) using the included 10-32x1250 Socket Head Screws. Be sure to install the Motor Input Block with the flat side against the motor.
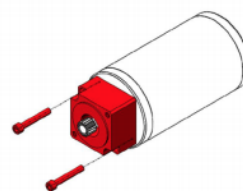
Step 5: Be sure to add a pea-sized amount of included Red Tacky Grease (am-2768) to the gear teeth. If more than one stage is present, add grease to each stage.

Step 6: Reinstall the Thrust Washer into the CIM Sport onto the surface of the gears inside the gearbox. Insert the Motor Assembly into the gearbox, and gently turn the output shaft until the gears mesh.

Figure G.6: CIMsport Gearbox Assembly Instructions

G4: RoboteQ Motor Controller
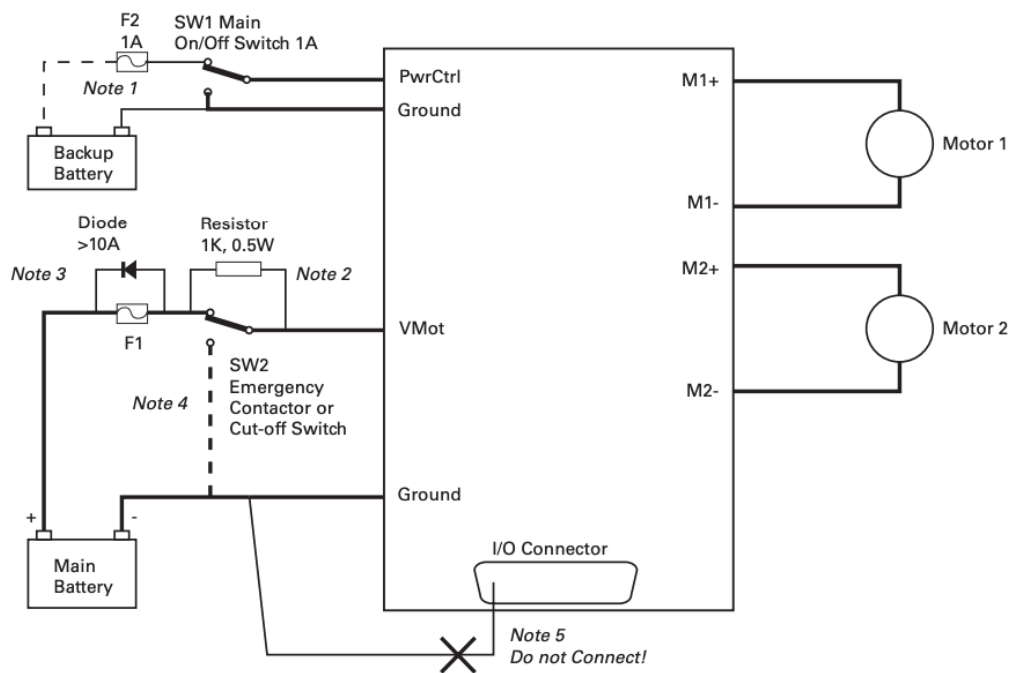
Figure G.7: RoboteQ Overall Wiring Diagram
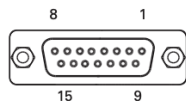
FIGURE 5. Connector Pin Locations

TABLE 2.

Connector Pin	Power	Dout	Com	RC	Ana	Dinput	Enc	Default Config
1		DOUT1						Unused
9		DOUT2						Unused
2			TxOut					RS232Tx Data
10				RC5	ANA5 (1)(2)	DIN5	ENC2A	Unused
3			RxIn					RS232Rx Data
11				RC4	ANA4	DIN4		Unused
4				RC1	ANA1 (1)(2)	DIN1	ENC1A	RCRadio1
12				RC3	ANA3	DIN3		Unused
5	GND							
13	GND							
6			CANL (3)					
14	5VOut							
7			CANH (3)					
15				RC6(1)	ANA6 (2)	DIN6	ENC2B	Unused
8				RC2	ANA2	DIN2	ENC1B	RCRadio2
Note 1: RC6, ANA5 and ANA6 present on hardware version 2.0								
Note 2: On hardware version 1, ANA1 is on Pin 10								
Note 3: On hardware version 1, CAN is only available on SDC21xxN								

Figure G.8: RoboteQ Motor Controller Pinout

Appendix H: Presentation Slides

Slide 7 — Harvesting Process

Harvesting Process

Cut 2 s | Trim 6 s | Package 2 s
Tractor Motion
Current Romaine Harvesting

Cut 2 s | Machine 2 s | Package 2 s
Tractor Motion
Proposed Machine

Slide 8 — Problem Statement

Problem Statement

Romaine Robotics is contracted by a partner farm to redesign their romaine heart trimmer to improve its ability to **handle and control** the lettuce (loading, gripping, and ejection).

Slide 9 — Partner Farm Trimmer Concept

Partner Farm Trimmer Concept

[1] Lettuce
[2] Lettuce Gripper
Untrimmed Lettuce Input
Trimmed Lettuce Output
[7] Conveyor Belt
[6] Motorized Blades
[4] Camera
[3] Lettuce Rotation Control
[5] Blade Position Control
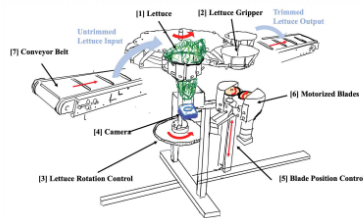
Needs
Does not damage lettuce
Consistent Trimming Height
Match Harvesting Rate
Constant Speed
Holds Lettuce Upright
Rapid Loading
Full Ejection

Slide 10 — Key Needs and Requirements

Key Needs and Requirements

Need	Requirements	Value	Tolerance	Units
Match Harvesting Rate	Throughput Per Head	2	± 0.1	secs
Consistent Stalk Height	Height Variation of Lettuce Stem	0	± 0.13	in
Holds Lettuce Upright	Gripper Gripping Size	3	± 0.5	in
Rapid Loading	Gripper Loading Size	4.25	± 0.5	in
Full Ejection	Gripper Ejection Size	8	± 0.5	in
Does not damage lettuce	Grip Strength	TBD	TBD	lbf
Constant Speed	Rotational Speed	TBD	TBD	RPM

Slide 11 — Grip Strength Determination

Grip Strength Determination

Increasing Force
Load Cell
Microphone
3D Printed Gripper

Load Testing at CSA Moog, Inc.

Increasing Force
Cracking Begins
Substantial Visible Damage

Force Test Data Using Microphone
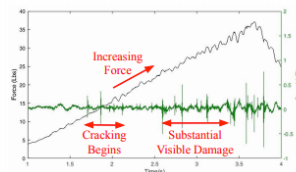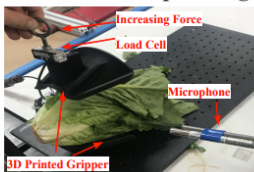
Need	Requirements	Units	Value	Tolerance
Does not damage lettuce	Grip Strength	lbf	6	±1

Slide — Rotational Speed Determination

Rotational Speed Determination

Conveyor Belt
Lettuce Path
Loading Workspace
Human Workspace
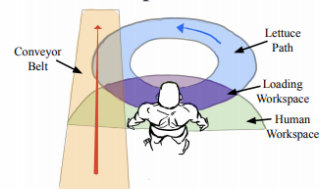
Need	Requirements	Units	Value	Tolerance
Constant Speed	Rotational Speed	rpm	5	± 0.5
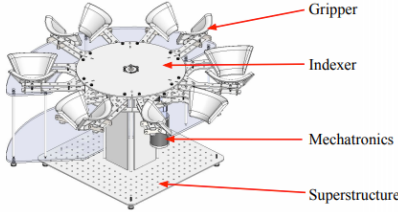
System Overview
- Gripper
- Indexer
- Mechatronics
- Superstructure
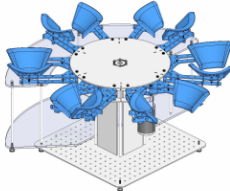
Gripper Subsystem
- Compliant for loading of untrimmed lettuce heads
- Grips tightly during cutting
- Ejects trimmed hearts
- Does not crush/damage lettuce
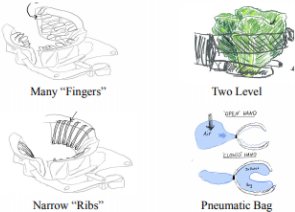
Gripper Cup Concept Selection
- Many "Fingers"
- Two Level
- Narrow "Ribs"
- Pneumatic Bag
- Hard Plastic Cone ✓
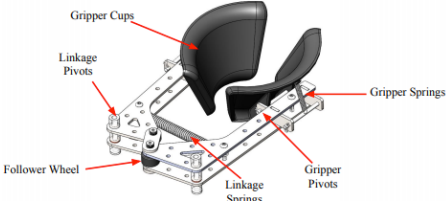
Gripper Design
- Gripper Cups
- Linkage Pivots
- Follower Wheel
- Gripper Springs
- Linkage Springs
- Gripper Pivots
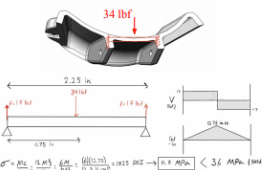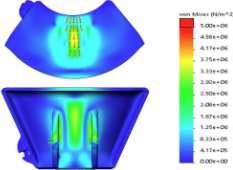
Gripper Cup Load Analysis
34 lbf
Support Beam Hand Calculation
Factor of Safety: 3.1
FEA Simulation Results
Factor of Safety: 7.1
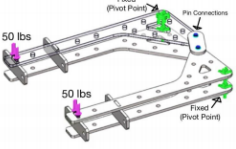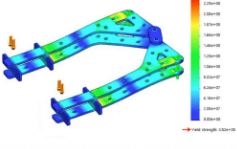
Gripper Linkage Abuse Case
Fixed (Pivot Point)
Pin Connections
50 lbs
50 lbs
Fixed (Pivot Point)
FEA Loading and Fixturing
FEA Simulation Results
Factor of Safety: 1.5

H3

Indexer Subsystem
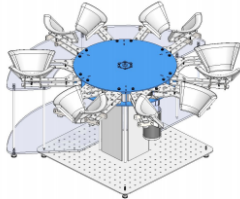
- Holds linkage pivot points
- Moves lettuce through stages
  - Loading
  - Gripping
  - Ejection

Indexer Design

Fixed-Axle Central Pivot
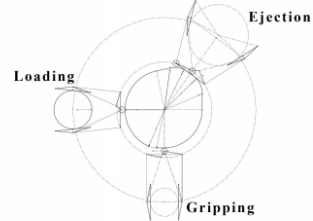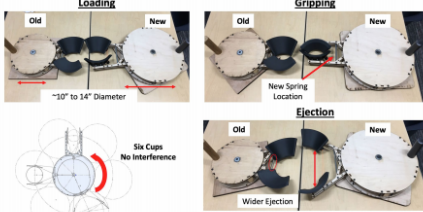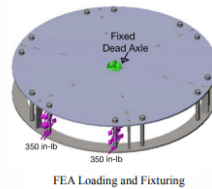Top Plate
Linkage Shoulder Bolt Pivots
Standoff Plates
Cam
Motor Mount
Bottom Plate
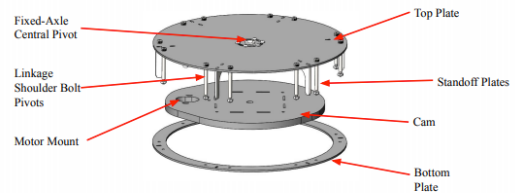
Indexer Torque Transmission

Chain Reduction
Fixed-Axle
Chain Tensioner
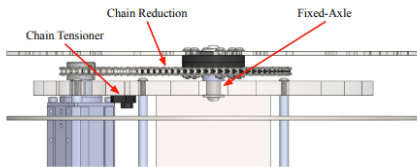
Indexer 3-Stage Cam Design

Ejection
Loading
Gripping

Indexer Wooden Mockups

Loading
Gripping
Ejection
Old / New
New Spring Location
"10" to 14" Diameter
Six Cups No Interference
Wider Ejection

Indexer Abuse Case
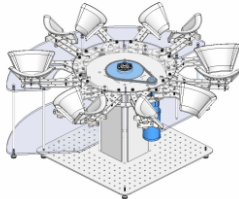
Fixed Dead Axle
350 in-lb   350 in-lb
FEA Loading and Fixturing
FEA Simulation Results
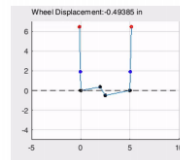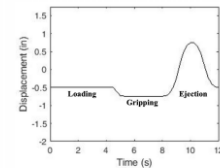Factor of Safety: 1.5

H4
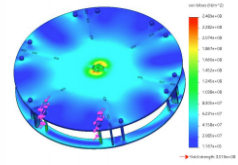
Mechatronics Subsystem

- Drives the system robustly through long-term, continuous, use
- Maintains constant RPM
- Compact, low-cost, lightweight
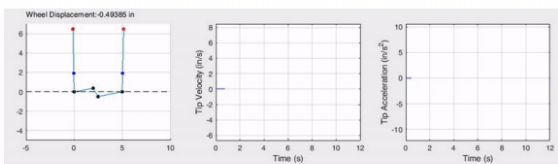
Mechatronics: Kinematic Analysis
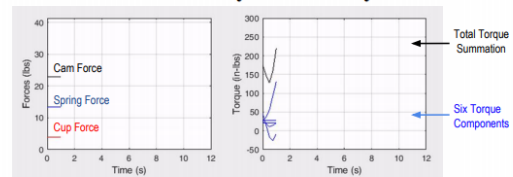
Linkage Kinematics

Cam profile over time

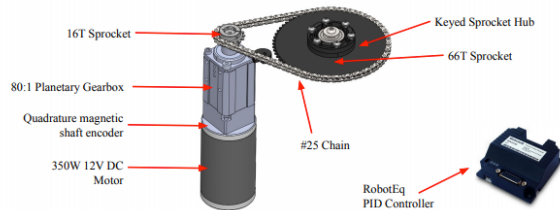**Mechatronics: Kinematic Analysis**

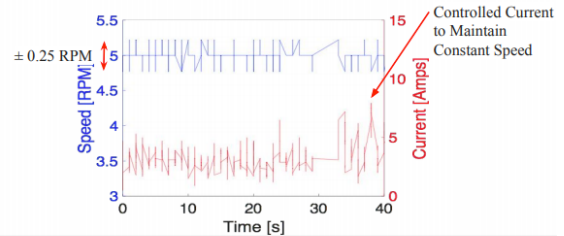Linkage Velocities and Accelerations

Mechatronics: Dynamic Analysis

Linkage Forces and Total Torque

Mechatronics Design

- 16T Sprocket
- Keyed Sprocket Hub
- 66T Sprocket
- 80:1 Planetary Gearbox
- Quadrature magnetic shaft encoder
- #25 Chain
- 350W 12V DC Motor
- RobotEq PID Controller

Mechatronics Verification

± 0.25 RPM

Controlled Current to Maintain Constant Speed
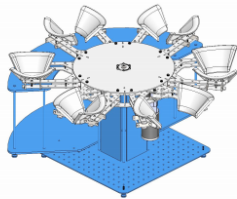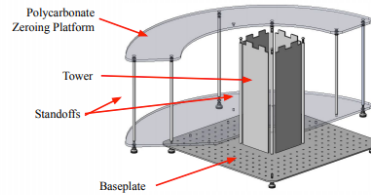
H5

Superstructure Subsystem

- Column holds indexer cam fixed to base
- Horizontal platform zeroes lettuce height for vision
- Base features mounting for vision and cutting systems

Superstructure Design

- Polycarbonate Zeroing Platform
- Tower
- Standoffs
- Baseplate

System Verification

Need	Requirement	Tolerance	Units	Equipment	Trials	Result	Satisfied
Rotational Speed	5	± 0.5	RPM	Hall Effect Encoder	8	5	✓
Consistent Height of Lettuce Stem	0	± 0.13	in	Yardstick, Camera	20	0.13	✓
Gripper Gripping Size	3	± 0.5	in	Calipers	5	2.76	✓
Gripper Loading Size	4.25	± 0.5	in	Calipers	5	4.12	✓
Gripper Ejection Size	8	± 0.5	in	Calipers	5	7.93	✓
Grip Strength	6	± 1	lbf	Force Gauge	10	5.5	✓
Throughput Per Head	2	± 0.1	secs	Stopwatch	8	2	✓

Benefit to Society

- Economic
  - Increasing demand for romaine lettuce
- Political
  - Shrinking agricultural labor supply
- Ethical
  - Alleviate backbreaking labor
- Health and Safety
  - Minimize contact with heart
- Sustainability
  - Higher yields → Less food waste

Conclusion

- Project Goal
  - Redesign lettuce trimmer for improved loading, gripping, and ejection
- Accomplishments
  - Designed and built metal trimmer and delivered to satisfied customer
- Future Work
  - Vision and Cutting Systems

Indexer and Gripper Delivered to Partner Farm → Satisfied Customer!

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- Catherine Borst
- Judy, Rose, Leslie

H6