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DESIGN OF END-EFFECTORS FOR THINNING APPLE IN THE GREEN FRUIT STAGE

A Thesis in

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by

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ABSTRACT

One essential horticultural process for apple production is thinning, which plays a vital role in determining fruit quality. Robotic technology is an alternative thinning method that reduces labor costs while still being both accurate and precise. This robotic technology successfully works through the end-effector, the only path connecting the robotic system to the environment. Two model end-effectors were designed, each using a different approach to thinning based on the size and shape of standard apples, which is the target fruit of this study. The first end-effector model thins apples one by one, while the second end-effector model preserves the king fruit of the cluster while cutting off unwanted apples. Both models have been designed and simulated using SolidWorks to study the end-effectors' motion. The fabricated end-effector was first tested in the lab, then was tested in the apple orchard during the thinning season. A mechanism design was adopted to singulate apples, which considered the mechanical and physical properties. Model 1 of the end-effector applied an iris dome mechanism to singulate the apple one by one. This mechanism can operate the opening center that can singulate apples appropriately. Model 2 used the idea of a corkscrew to protect the king fruit and remove unwanted apples. The advantage of this design is a time-saving process. Model 2 should be improved for better singulation performance. Both models have their advantages and disadvantages, and this end-effector is a key part of the robotic system.

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ACKNOWLEDGEMENTS

When I look back at this thesis and reflect on my two years of graduate school study, time seems to fly by, and every day feels like it happened yesterday. I recall coming here for the first time after being trapped in my home country for one semester due to COVID-19. We do not grow apples in Thailand. I was both curious and perplexed because I needed to know what apples look like in the green fruit stage. And now, I have gained some knowledge and ideas, which I have combined to complete this end-effectors design.

First and foremost, I would like to express my gratitude to my advisor, Dr. Paul Heinemann, for giving me the opportunity to work at the Smart Ag Laboratory. I could not have had the same graduate experience at another institution because the facility is one-of-a-kind. Furthermore, his advice and guidance have been greatly valued over the past two years. Similarly, I would like to thank Dr. Long He and Dr. Henry Sommer for serving on my thesis committee, Mr. Randall Bock as the thesis special member, and for contributing their ideas and support.

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Chapter 1

Introduction

Agriculture is the backbone of many countries around the world. In the United States, the apple is one of the most produced commercial fruits, with 9.56 billion pounds per year and average of 33,900 pounds per acre, worth $3.03 billion in 2021 (USDA-NASS, 2021). Producing high-quality apples requires the crop thinning process, which is essential. The thinning process increases apple size and prevents apple trees from being overburdened, ensuring the return bloom in the following crop of apples (Dennis, 2000). Nowadays, there are two main types of thinning methods: selective thinning and non-selective thinning. Selective thinning includes hand thinning, while non-selective thinning includes chemical and mechanical thinning. Hand thinning is very labor intensive, so chemical thinning and mechanical thinning have been developed as non-selective thinning methods that are less labor intensive. However, these methods have drawbacks; for instance, chemical thinning relies on the weather, and mechanical thinning can cause tree damage. Usually, hand thinning is required to follow up for both non-selective methods. Automated thinning has been proposed as an alternative to hand and chemical thinning to reduce labor costs while still thinning precisely. This robotic technology successfully works through the end-effector, the only path mechanism connecting the automated system to the environment.

Currently, the end-effectors used in horticulture applications are designed for different processes and suit specific type of fruit, based on the fruit's shapes and clearance position, which determine the end-effector's design. Horticulture applications strive to make end-effectors that are easy to clean, maintain, have low power consumption, have a low cost, and are highly efficient (Blanes et al., 2011). End-effectors that harvest fruit will not damage the fruit in the process. However, different fruits require different end-effectors that ensure there is minimal damage. For instance, strawberries in the greenhouse environment, separating mature fruit from unmatured berries is challenging. Xiong et al. (2019) designed a harvesting system with a cable-driven gripper that uses the fingers to push the stem to the cut, enabling separation surrounding strawberries away from the target. For the cherries cluster, the pneumatic system is used to help suck the target fruit from the tree or bush, increasing location accuracy and preventing damage (Tanigaki et al., 2008). Silwal et al. (2017) designed end-effector for apple harvesting, the end-effector is designed to learn human behavior to find the best pattern to remove the target apple. In contrast to the harvesting process, the end-effector for the thinning process does not need to be designed to minimize damage since the target fruit only needs to be removed without damaging the king fruit; to ensure the biggest fruit in the cluster will continue to grow.

Despite the availability of mechanical thinning procedures for some fruits, such as peach, techniques are not as common for apples because of the fruit's thinning challenges. Thinning during the blossoming mechanical thinning technique is efficient and effective for peaches. Mechanical thinning becomes more challenging for the cluster fruits, especially apples in the green fruit stage. This challenge originates from thinning occurring for apples 10-30 days after bloom. The fruit's stem is quite lengthy for a Golden Delicious apple, and its stem ends are close together at the state of this process. Manual thinning is efficient since it is simple and quick to cut off unwanted fruit. Due to obstacles, including position, orientation, and leaves, automatic thinning is challenging. As a result, the end-effector must be appropriately designed with a proper gripper.

This study focused on developing the end-effector for apple thinning. The steps include:

1) finding parameters for design; 2) determining design feasibility through simulation; 3) fabricating prototypes; 4) testing in the lab; 5) testing in the orchard; 6) evaluating the pros and cons of the end-effector.

Chapter 2

Literature Review

Growers began applying thinning to apples 200 years ago after observing the plant's tendency to overcrop and considered cutting off half of the green fruit on the overloaded apple tree (Byers, 2003). Before the introduction of chemical thinner, hand-thinning was performed with scissors in the early 1920s (Byers, 2003).

The previous crop year will significantly impact the following yield. Effective crop thinning will avoid the biennial-bearing phenomena, which happens when there are many blossoms one year and fewer return flowers the following year (Byers, 2003). To further clarify this phenomenon, an "on-year" is a year with high flowering and requires thinning in order to ensure the fruit's proper size and quality. On the other hand, the "off-year" is the year with the least blossoming; if thinning takes place during an off-year, the fruit production will not have desired quantity and quality and will sell for a low price. Four years of data collection have shown that annual crop thinning increases average yields and prevent inconsistent yields. In the case of 4-6-year-old apple trees, avoiding fruit development will have a more significant impact on the young tree and a long-term effect on the growth and structure of the tree, resulting in reduced yields later.

Thinning Method

Hand Thinning

The technique of hand thinning was first used when people realized that the thinning procedure might manage apple quality and maintain bloom. The green apples are thinned by hand after they fully blossom, which takes place after 30-40 days and is known as the "June drop" (Dennis, 2000). The weight and yield of an apple depend on the number of apple present. Kon & Schupp (2013) funded a single fruit that was placed every 7 to 8 inches along the length of the branch using the conventional hand thinning technique. This method made individual fruits larger, but the overall yield was lower than when using a hand-thinning gauge, which thins to a six fruit per cm branch cross-section area (BCSA). That maintains individual fruit weight and has a higher total yield than the conventional hand-thinning method.

Understanding the required time for each thinning technique is crucial, in addition to considering the fruit yield of each approach. Depending on the number of fruits present on the tree, hand-thinning takes time. The degree of fruit abscission after fertilization depends on the environment and cultivars. Time spent hand-thinning relies on the number of fruits on the tree. After fertilization, the fruit's abscission and degree depends on the environmental conditions and cultivars (Iwanami et al., 2015). That means the time it takes for hand thinning also depends on cultivars. The time required for hand-thinning organic apples was estimated to be 532 h.ha^{-1} in Japan (Iwanami et al., 2015) and 100-300 h.ha-1 in other countries (Weibel & Häseli, 2003). In contrast, hand-thinning with chemicals takes only 83 h.ha^{-1} in the USA (Glover et al., 2002), which costs $1000 to $2000 per acre. As labor costs in the agricultural sector increase, chemical and mechanical thinning are becoming practical approaches to maintaining productivity and quality.

Chemical Thinning

Chemical thinning has long been used in apple orchards to reduce hand thinning costs and work more land in the same amount of time as hand thinning (Williams & Edgerton, 1981). The chemical sprays for thinning apples were developed before the 1940s and are modeled after "lime-sulfur" (calcium polysulfide), a chemical used to control pests. Chemical spray can increase immature fruit drops from the apple tree. After the 1940s, numerous investigators experimented with creating many different chemical thinners. It is important to note that performance of chemical thinning depends on the carbohydrate level in each tree; when the carbohydrate level is too high, it is hard to thin.

On the tree, multitudes of blossoms and developing fruitlets compete for resources to grow. Resources refer to food, specifically carbohydrate-based food. These carbohydrates are produced from the tree's storage sources, particularly the leaves, which use photosynthetic processes to convert light energy into carbohydrates. There is a shortage of carbohydrates at this time of year because there is not enough leaf area for photosynthesis (Robinson & Lakso, 2011). Fruitlets compete for carbohydrates because there is a supply shortage compared to demand, and only the strong survive. This is referred to as fruit drop or June drop because the weak flowers or fruitlets lose out and fall off. This shortage is increased by the common thinners, which causes even more fruitlets to fall off. Some, such as NAA, inhibit photosynthesis, decreasing the number of carbohydrates. Others, such as Sevin, reduce the supply of carbohydrates by slowing their passage from leaves to fruitlets. The Maxell-type thinners raise respiration, which burns more carbohydrates and reduces the energy for growing fruitlets. Thinners enhance the lack of carbohydrates in these three ways, increasing fruit decline. Growers can forecast the response to thinners from year to year by considering this. As an illustration, cloudy weather immediately after bloom reduces light for photosynthesis, reduces carbohydrates, and increases fruit drop. In that case, producers might reduce their thinning rates. When the temperature is warmer outside, thinners function better. The ideal temperature is around 70 °F, and below 60 °F, most thinners will not work properly. At 80 °F or higher, thinners can have very significant effects or over-thinning (Hirst, 2022).

Many chemical thinners are used for post-bloom apple thinning, depending on stage that growers want the chemical to be applied. For example, the cytokinin called 6BA increases cell division, which means this chemical can thin the apple tree and increase the size of the fruit. The thinner that is active for the most extended period is called Naphthalene acetamide (NAD); it is recommended for those looking to thin early. Ethephon (Ethephon 2, Motivate, Verve) is used to thin the apple when the fruit is larger than 17 mm in diameter and is very useful when the temperature is warm (Krawczyk et al., 2022a). Of note, chemical thinners are not efficient when the fruit diameter reaches about 22 mm. In warm weather, apples can grow about 1 mm per day; farmers have only 4-6 days to use chemical thinner when the fruit is 18 mm in diameter (Krawczyk et al., 2022a). Moreover, the weather conditions that occur two days before thinning time affect the carbohydrate levels in the tree (Krawczyk et al., 2022a). The main problems involved in chemical thinning are related to various environmental factors such as temperature, light, and humidity (Greene, 2002).

Mechanical Thinning

Mechanical thinning is an alternative way of thinning a variety of fruit in the bloom state, especially peaches, since chemical thinning is unpredictable. This section will discuss mechanical thinning in the bloom state for both apples and peaches. String thinning is one such mechanical thinning approach.

Mechanical thinning efficiency depends on vehicle velocity, centripetal force, velocity, and the structure of string thinners. Though researchers agree that these factors are essential, there is some discrepancy concerning the specifics of how these factors should be executed. For instance, Beber et al. (2016) conducted a study that measured the rate of string thinners' effect on thinning efficiency by using the thinning device "Darwin 200 " and maintaining a constant speed of 6 km/h to thin Jonagold apples. This study found that a more than 270 rpm rotation speed damages the tree and leaves, while a rotation speed below 200 rpm leaves more than 250 flower clusters intact per tree, thus not achieving the desired thinning result. In contrast, Solomakhin et al. (2010) used a faster motor velocity (between 420-480 rpm) while lowering the vehicle speed to 5 km/h, which caused damage to apple leaves, buds, and shoots. This damage resulted in a decrease in the average yield of up to 30% and 40% with Golden Delicious and Gala Mondial apples, respectively.

As these studies show, the appropriate speed of the vehicle and the motor speed of string-thinner devices is essential to the thinning process. The device developed does not replace hand thinning but can reduce human work (Miller et al., 2011). A spiked-drum shaker has been used to thin the peach tree at 52-55 days after full bloom, which can reduce the crop load up to 58% and reduce the time spent on hand thinning up to 50%, in addition to increasing peach size by 9%. Miller et al. (2011) compared the motor speed between 260 rpm and 180 rpm; the difference does not affect fruit size but reduces hand thinning by 54% and 81%, respectively. In addition to investigating motor speed, the net economic impact between mechanical thinning and hand thinning was discussed; it ranged from $175/ha to $1966/ha in 2007 (Miller et al., 2011).

The mechanical thinning discussed so far is called non-selective thinning. One drawback of non-selective thinning is that the mechanical speed can damage the leaves and trees. As such, the concept of selective thinning was created to reduce this damage. Selective thinning has resulted in the development of a robotic arm, end-effector, and vision system. For instance, stereo vision can map the 3D blossom to identify the unwanted blooms in peaches (Nielsen et al., 2012). A selective thinning system for peach blossom was developed consisting of a robotic arm, an end-effector, and heuristic and kinematics algorithms (Lyons et al., 2015). In this design, the end-effector makes a tangent force of 5.6 N to remove unwanted blooms along the branch.

End-effector in Horticultural Application

An end-effector is a functional component of a robotic system that helps it interact with its surroundings or a specific object. It is named that because it is placed at the distal end when attached to a serial manipulator and directly affects the workspace. The end-effector is the only path that connects the robotic arm and the target. The end-effector design has many essential factors: velocity and acceleration, force action during grasp target, mass, properties, etc. These factors are helpfully selected by Monkman et al. (2006) in their explanation of the design parameters. In agricultural applications, pick and place end-effectors are very useful and vary according to their specific application. Blanes et al. (2011) specified the unique requirements for fresh fruit and vegetables. For example, the end-effector for fruits and vegetables must include easy and fast pick and place production, be easy to clean and maintain, be of low weight and energy consumption, and be able to adapt to various shapes. Various manipulations of end-effector design are based on these factors (Blanes et al., 2011).

In robotic agriculture applications, the end-effector used for harvesting has been dramatically improved. Many studies worked on different end-effector designs depending on the fruit's shape and motion control. As such, many studies compared the applications of pneumatic and electric end-effectors. Both applications show high accuracy, easy maintenance, small size, and repeatability compared to hydraulic end-effectors. After determining the manipulation strategies, design parameters, and factors involved, the function of the end-effector will be determined.

Before the manufacturing process, CAD software was often used to analyze the performance under conditional control. Different software programs have been used to aid the development of various end-effectors. For example, Edan et al. (1992) used finite element analysis to determine the critical static stress in their study investigating melon harvesting. The stress result from finite element analysis ensured the gripper was strong enough under the weight of a melon. Similarly, the kinematic and dynamic performance analysis program in Solidworks was used to determine the parameters needed to design the end-effector for sweet harvest peppers in a greenhouse setting (Bachche & Oka, 2013). This software showed that the end-effector for the sweet harvest peppers consists of the parallel mounted jaws on gears driven by a servo motor.

The unstructured environment inherent in agriculture is one of the significant problems of robotic agriculture. For instance, crops such as sweet peppers present an obstacle crop environment. When designing an end-effector, it is necessary to understand the difference between constrained-azimuth and fully-azimuth end-effector movement. Constrained-azimuth movement means the robot manipulator can rotate between 0 and 60 degrees to find the target (Bac et al., 2016). In contrast, fully-azimuth movement allows the end-effector to rotate 360 degrees to find the target fruit. Both methods can see the target 63% and 64% of the time, respectively. However, it is essential to note that the constrained azimuth method could avoid risky paths during the movement (Bac et al., 2016).

The challenges of end-effector design, especially in the harvesting process, include the following:

1. Not damaging the target fruit.
2. Separating fruits in the singular cluster.
3. Achieving the high positional error.

4. High-speed performance.

Though there are many challenges, a few end-effector designs have adequately addressed these challenges. For instance, Xiong et al. (2019) helped develop a cable-drive gripper for strawberries that addressed all of the above challenges. In this design, three active fingers push the surrounding berry, and passive fingers and cutting fingers help move the target strawberry to the correct position and cut the strawberry. The design of the end effector also depends on the vision system and tree structure. Xiong et al. (2019) used the vision system to detect the fruit instead of the stem. The strawberry's nature necessitates that the end-effector be designed to pick a target on the bottom of the fruit when the robot initially detects the target fruit. After choosing this target, a gripper closed-loop control with three internal infrared (IR) sensors helps the gripper move to the optimal location for cutting. In addition, this model has an inner container that makes the gripper work continuously, avoiding back and front moving every work cycle.

Another end-effector that adequately addresses the four challenges were designed to harvest cherries (Tanigaki et al., 2008). In cluster fruit harvesting like cherry, the pneumatic system helps to locate the target fruit. The cherry-harvesting robot study shows that the strength between the fruit and stem was about 1 N. The force between the stem and branch was about 2.5 N. Acknowledging these different levels of force is essential because this end-effector was designed to use a cutting process instead of a pulling process. After all, the cherry should be harvested with its stem still attached. The system consists of the vacuum sucker, back and front device, a pair of fingers, and an open-close mechanism. This study demonstrated that the vacuum sucks the target fruit and the obstacle around the clustered fruit. Moreover, the finger can damage the fruit during the grasping time .

Though vacuum end-effectors can be beneficial in certain harvesting processes, the unstructured environment can also create a problem when using a vacuum end-effector to harvest other fruit. As a result, mimic hand-picking motion for end-effector design was developed to avoid the problem between the sucker and unwanted obstacles. Silwal et al. (2017) studied the hand-picking process in apple harvesting; hand-picking was used to consider the steps of the pattern movement humans use when picking apples:1) horizontal pull, 2) horizontal pull and twist, 3) inclined pull and incline pull and twist. The Silwal et al. study helped generate an end-effector design for apple harvesting, where the finger is attached to a force sensor to measure the force when the apple departs from the branch. The force was measured by sensors applied to the control system. Before this design, no end-effector had a sensor attached to measure force for the control system.

Chapter 3

Goals, Objective, and Research Question

Given the lack of an existing end-effector for green fruit thinning, this study focuses on the end-effector for thinning apples in the green fruit stage. The end-effector should result in gripping the target fruit and accessing the target quickly, and removing unwanted fruit without damaging the king fruit.

Research Goal

The goal of this study is to identify parameters for fabrication and compare the efficiency of different end-effector models.

Research Objectives

The specific research objectives are:

1. Identify the essential factors for end-effector design criteria.
2. Create designs and simulate in the CAD program.
3. Prototype the two designs and test in the laboratory environment.
4. Compare and contrast the two different models and assess each model in terms of strength and weaknesses in the orchard.

Research Questions

These objectives attempt to answer the following research questions:

1. How should the end-effector be designed to thin apples at the green fruit stage?
2. What are the strengths and weaknesses of the end-effector in the laboratory environment?
3. What are the strengths and weaknesses of the end-effector in the orchard?

Chapter 4

Understanding the Physical and Mechanical Properties of Apple in the Green Fruit Stage for End-effector Design

An essential step in designing an end-effector for thinning apples in the green fruit stage is understanding the level of crop variability. The variation plays a profound role in selecting the green fruit removal method for the end-effector depending on mechanical and physical properties of the fruit. Determining the mechanical properties of how apples respond to pulling and bending force are essential for the end-effector design. End-effector performance is thus not only measured by successful mechanical removal of the unwanted fruit in the apple clusters but also by ensuring that the plant and the king fruit remain undamaged.

Materials and Methods

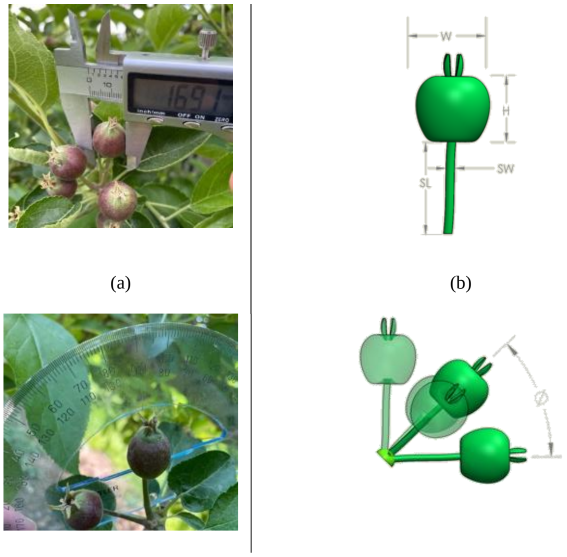
Parameter Measurement of Fruit Appearance

The physical parameters of the apple at the green fruit stage affect the end-effector design. In the green fruit stages, the apple has unique physical properties, including fruit appearance, arrangement, stem length, and fruit size, which must be considered in all aspects. Different geographical areas in which the apples grow have different weather, soil, and nutrient conditions that affect growth. Apples were collected during the thinning season or "June drop," 30 days after full booming between May and June 2022, at the fruit research center, Russell E. Larson Agricultural Research Center, in Rock Springs, PA.

The number of fruits were counted, and five different shape measurements were taken. For each apple in a cluster (Fig. 4-1) the shape parameters measured were:

- H- largest diameter parallel to the stem
- W-largest diameter perpendicular to stem
- SL- the length of the stem
- SW- the diameter of the stem
- ϕ - the angle between the fruit and the king fruit

The angle between the king fruit and surrounding apple was measured with the protractor. A digital caliper took all other size measurements.



(a) (b)

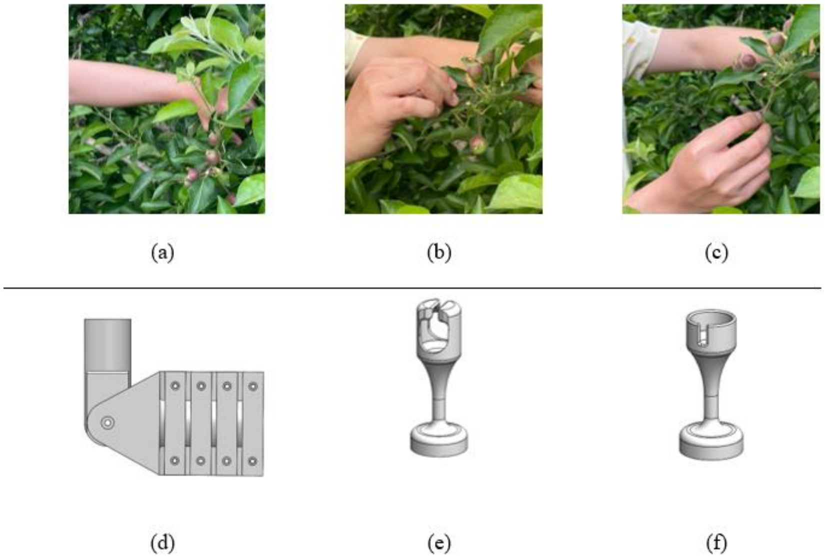
(c) (d)

Figure **4-1**: Physical parameter measurement (a) digital caliper measured the largest diameter perpendicular to stem (b) W as largest diameter perpendicular to stem, H as largest diameter parallel to the stem, SL as the length of the stem, SW as the length of the stem (c) protractor measured the angle between the king fruit and surrounding apples (d) ϕ as the angle between the fruit and the king fruit

Mechanical Test and Experiment

Tension and Bending Grips Design

Humans remove unwanted apples in the green fruit stage, one of the methods is bending and pulling. The challenging problem in the robotic end-effector design was to remove the unwanted fruit, especially the second biggest one in the cluster, without damaging the king fruit. The tensile strength experiment was used to understand the apple cluster under load, including tension (pulling) and bending. The grips for this test were developed based on humans holding the branch before pulling and bending in order to remove the unwanted apple. A tensile strength tester, the 3400 series Instron machine, measured the properties of the apple cluster with the grip designed for a suitable apple shape. The apple branch was attached to the clamp to prevent movement, and the distance between the cluster and clamp was 5 cm during the bending and tension test. Due to the unique shape of the apple, the shape of the gripper was designed to hold the apple properly (Fig. 4-2).


(a) (b) (c)

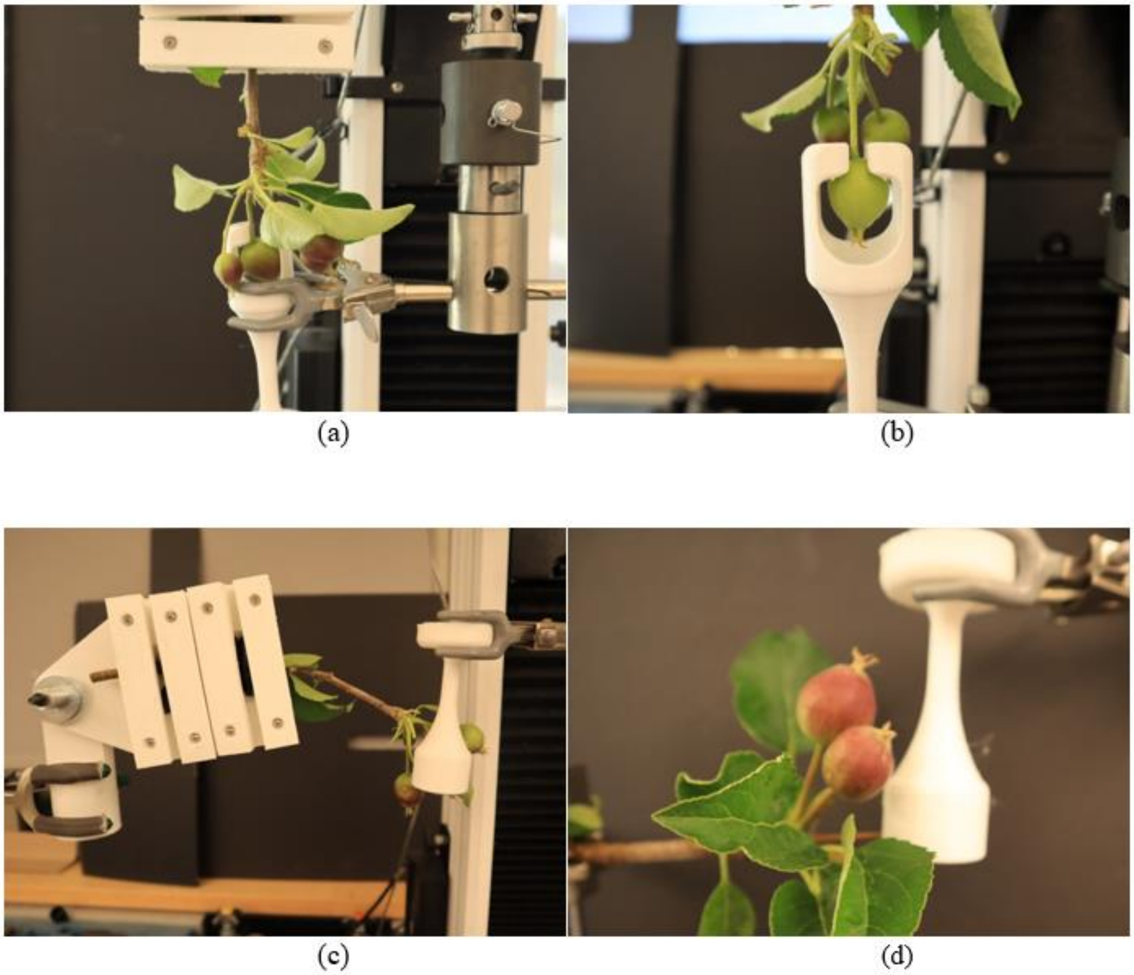
(d) (e) (f)

Figure **4-2**: Grips for tension and bending test (a) hand grabbing (b) hand pulling (c) hand bending (d) clamp for fix the branch (e) gripper for tension test (f) gripper for bending test

Tension and Bending Test

“Golden Delicious” apples used in this test were at the green fruit stage 30 days after full bloom. To prevent the product from losing its initial properties, the apple clusters were cut and put in the fertilizer to maintain plant vigor after cutting. The samples were transferred from the orchard to the laboratory one hour before the experiment.

To measure the mechanical properties of the 60 apple clusters which 30 clusters were used in tension test and the rest of the apple clusters used in beading test, a 3400 series Instron machine was used, and the loading rate was set as 5 mm per minute during the test as shown in Fig. 4-3.



(a) (b) (c) (d)

Figure **4-3**: Mechanical properties test: (a) tension test (b) tension grip pulls the apple (c) bending test (d) bending grip bends the apple

Cutting Stem Experiment

A cutting mechanism is one of the methods used to thin apples, so measuring the required torque is essential to determine the energy consumption, as well as the motor size, for cutting the stem of the target fruit. The cutting torque of the stem target fruit was measured using a force sensor attached to a small scissor that was used for the hand thinning. Since the data collection with this sensor does not directly measure the force, a Phidget Interface Ki program (Products for

USB Sensing and Control, Canada) was used to collect voltage data from the force sensor. After that, the voltage was converted to force based on an equation from the previous work by Zahid et al. (2020).

$$F = 14.6 - 13.95 \times \cos(S \times 0.002958) + 20.31 \times \sin(S \times 0.002958) \quad (1)$$

$$\tau = F \times r \quad (2)$$

Where

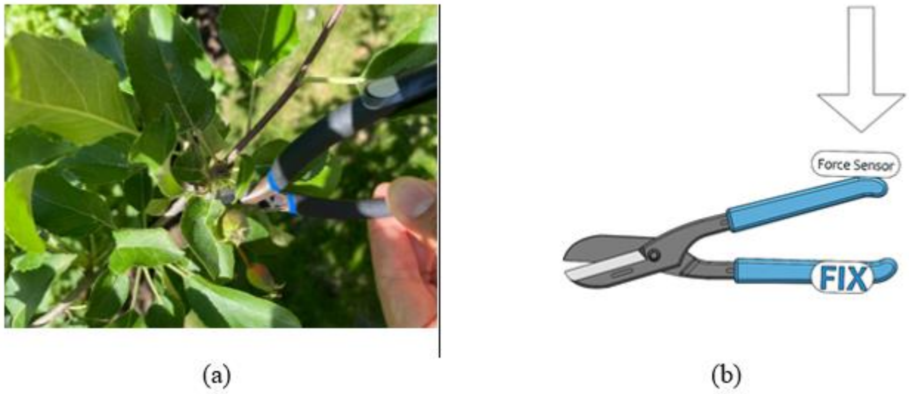
F is the force in Newton

S is the sensor output (voltage)

τ is the torque in Newton-meter

r is the moment arm in meter

Finally, the force was converted to the torque required to cut the stem.



(a)

(b)

Figure **4-4**: Cutting stem experiment (a) field experiment (b) schematic of the cutting device

Results and Discussion

Physical Properties of Apple Stems in the Green Fruit Stage

The 60 clusters of Golden Delicious apples were measured for their physical properties after a chemical thinner consisting of Carbaryl 4L at 1 qt / ac plus MaxCel 2 qt / ac was applied. This study focused on a cluster that had more than three apples. The angle of the apple was measured between the king fruit stem and the measured fruit. The fruit number was labeled based on the size of the fruit.

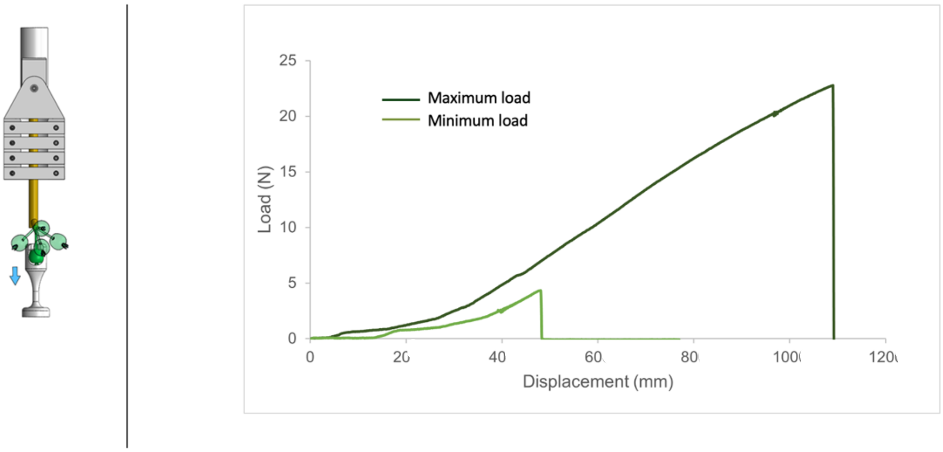
Table 4-1 provides essential information about the apple's physical properties. The end-effector dimension and condition were based on the target appearance. The second largest apple in the cluster was selected to be removed for this test. Krawczyk et al., (2022) found that after chemical thinning, the second largest apple had not responded to the chemical thinner. Hand removal of the second biggest apple in the cluster is typical. The following section will discuss the experiment investigating the apple cluster after the second biggest one is removed.

Table **4-1**: The physical parameters of the 60 clusters "Golden Delicious" apple at the green fruit stage

Fruit number	Physical parameter														
	Fruit Diameter(mm)						Stem (mm)						Angle		
	H			W			SW			SL					
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
1	15.46	20.26	24.75	18.85	22.79	26.50	1.60	2.09	2.65	20.75	28.07	38.11	-	-	-
2	9.36	18.38	23.80	16.31	21.09	26.50	1.60	2.08	2.75	19.00	28.69	48.39	15	44.3	70
3	9.23	15.50	19.92	12.25	18.52	24.00	1.00	1.93	2.71	18.52	29.07	39.67	15	50	80
4	6.59	13.13	16.50	11.50	16.25	19.91	1.19	1.75	2.12	10.50	27.06	38.35	15	52.13	90
5	12.23	12.80	13.99	13.00	15.12	15.88	1.50	2.00	2.25	25.50	29.58	36.25	45	45	45

Mechanical Properties

The behavior of the second biggest apple in the cluster to an applied tension is shown in Fig. 4-5. The result shows the random load and extension of the apple before departing from the cluster; the maximum load is up to 20 N to remove the apple, whereas the minimum is only 5 N. It is interesting to note that when the load is more than 10 N the apple clusters have different damage. This damage includes clusters removed from the branch and the king fruit removed from the cluster along with the second biggest fruit. In this situation, the force for pulling the apple from the cluster cannot be identified, but the apple under the tension force had a soft and brittle behavior.

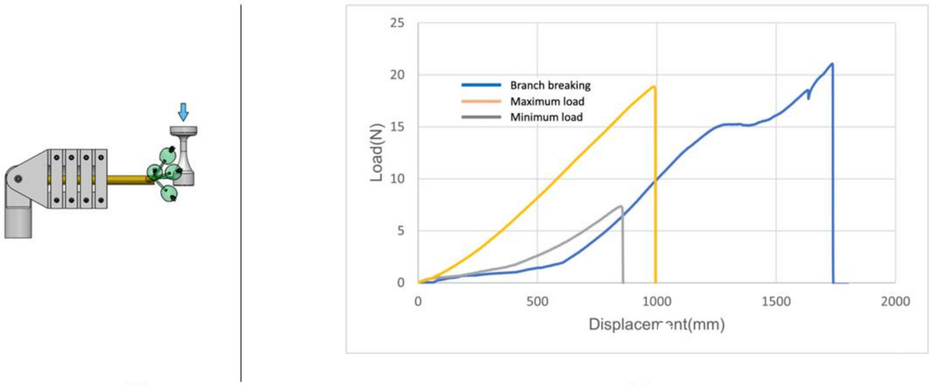


(a) (b)

Figure **4-5**: The result of tension test: (a) direction of load (b) load-displacement (light green and dark green currve represent the maximum and minimum respectively)

Bending Test

The behavior of the second biggest apple in the cluster to an applied bending load is shown in Fig. 4-6. The result shows the random load and extension of the apple before departing from the cluster; the maximum load is up to 20 N to remove the apple, whereas the minimum is only 5 N. Similar to the tension or pulling test, when the load is more than 15 N the apple clusters have different damage. However, the bending test shows one more results regarding this damage than the tension test. The typical scenario for the bending test when the load is more than 15 N is that the branch has damage before the apple departs. In this situation, the force for bending the apple from the cluster cannot be specified, but the apple under the bending force has a soft and brittle behavior. Moreover, only the normal force can be measured while the bending gripper moves down the cluster of apples. While the apple will still be pulled by a lateral force, this, unlike normal force, cannot be measured. The cluster was damaged from this test due to the combination of the normal force that can be measured and lateral force that cannot be investigated in this experiment.



(a)

(b)

Figure **4-6**: The result of bending test (a) direction of the load (b) load-displacement curve (gray and orange curve represent the maximum and minimun respectively, blue curve show the branch breaking senario)

The Damage Under Tension and Bending Force

Fig. 4-7 shows the observation of three typical scenarios of a damaged cluster of apples under the bending and pulling test. The first depiction shows the whole cluster departing from the branch after applying the force. This means the second biggest fruit attached in the cluster is stronger than the cluster with branches. If the cluster and fruit have a strong bond, the expected damage happens at the branch close to the fixed support, as shown in Fig. 4-7b. This scenario commonly occurs during the bending test. Fig. 4-7c depicts the king fruit departing from the cluster along with the second biggest fruit after applying the load. These damages should be avoided during apple thinning at the green fruit stage. Based on the observation, the unwanted fruit can bend 8 cm from the initial position without damage. This information is essential to designing a green fruit thinning end-effector.

(a) (b) (c)

Figure **4-7**: Different types of damage (a) cluster breaking (b) branch breaking (c) king fruit breaking

Cutting Torque

In the stem apple cutting procedure, the biggest torque should have the function of cutting the stem apple from the apple cluster. In general, a cutting torque should range between 2.50 and 3.88 Nm. The magnitude of the cutting torque depends on the shape of the cutter. Furthermore, the cutting method should avoid cluster damage. These results show that an end-effector should be developed that could cut the stem without causing any damage to the king fruit and surrounding branches.

Conclusion

The grip system has been developed in this research to understand the "Golden Delicious" apple cluster's behavior under load. Cutting the stem of an apple is the best way to remove the unwanted fruit in a cluster to avoid damage; however, based on the tension and bending test, the apple can bend before breakdown. This study is useful for the engineering design and development of effective end-effectors for thinning apples in the green fruit stage. Henceforth, the cutting stem method has been determined as the proper approach to remove the apple, but the challenge lies in how to single out apple before this cutting process. The importance of examining physical and mechanical properties for removing green fruit in the cluster was determined. These properties are considered the fundamental data for removing unwanted fruit and the design of the end-effector.

Chapter 5

End-effector Prototype Design and Fabrication

An end-effector is a device at the end of the robot arm designed to interact with the environment. The exact nature of this device depends on the application of the robot. The objective of the end-effector design was to develop prototypes that could remove unwanted apples while protect the king fruit. The end-effector has been designed to meet the specific design criteria shown in Table 5-1.

Table **5-1**: End-effector for Thinning apple in the Green Fruit Stage Design Criteria

MUST
- Be able to remove the unwanted apples from the apple cluster.

SHOULD
- Be designed with fingers that can adapt to the apple shape

COULD
- Be cleaned and maintained easily

WILL NOT
- Damage the king fruit in the cluster

The knowledge acquired from physical and mechanical properties is critical for the design process. The first step in the conceptual design process was the ideation phase. There are typically three to five fruits simultaneously in the apple cluster in the green fruit stage. The most prominent fruit in one apple cluster is the king fruit, surrounded by small or unshapely fruits or the fruit has a size as the king fruit. The idea of the design is to remove surrounding unwanted fruits without damaging the king fruit. Two end-effectors that use different approaches to thin green apple fruits were designed.

- The first end-effector cuts off surrounding unwanted fruits one by one in each cluster, leaving the king fruit intact.
- The second end-effector holds and protects the king fruit and removes the other unwanted fruits at once in each cluster.

Model 1 Conceptual Design

A cluster is a group of tiny apple fruits in the green fruit stage. Traditionally, growers manually remove unwanted apples in each cluster one by one. The same idea is used for model 1 design; the end-effector aims to remove the target unwanted apple one by one. The goal of thinning the apple is to remove the unwanted apple while the king fruit is protected. Based on the mechanical properties test, the results show that apples can be bent at least 5 cm before breaking. The 5 cm is referred to as the critical number to cause damages to apples. Therefore, a hollow sphere cup was designed with a 100 mm outer diameter and 90 mm inner diameter to singulate individual unwanted apples. From the schematic design shown in Fig. 5-1, the shape with these dimensions is able to grab the target apple, however, there are chances that the outside surface of the cap will touch other apples including the king fruit. Previous test has shown that when the king fruit is bent less than 5 cm which is the critical number, no damage will be caused.

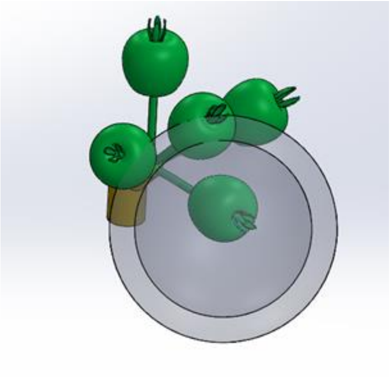


Figure **5-1**: Schematic of the 100 mm diameter sphere grabbing one apple in the cluster

This idea was tested in the orchard during the thinning season. For the preliminary study, the cup was designed as half of a sphere with a handholding bar for convenience. As mentioned, the testing cups have the same sphere shape with the same dimensions. All of the testing cups had holes at the bottom with different diameters, including 15 mm, 30 mm, and 45 mm, to deal with the different size of the target apples. The test showed that this hollow sphere did not cause damage to the king fruit, which means that the king fruit stem can bend during singulation.

Fig. 5-2 shows several example scenarios during the test. From the results, the 15 mm cup can singulate the target apple with a diameter of less than 15 mm and cannot singulate the apple with a diameter of more than 15 mm. The 20 mm cup can singulate the target apple but cannot fit into a hole that smaller than its diameter. Moreover, a problem noticed with this cap design is that when the apples are close to each other, the cup has the potential to break the surrounding apples during singulation. The target apples tested in this experiment had between 10 mm and 25 mm diameters. The biggest cup used in this experiment had a diameter of 30 mm that could grab an apple with a diameter of less than 30 mm. However, in some cases, this cup held two apples at a time, which is more than the goal singulate one by one. This test shows that the fixed-size cup had some problems when dealing with clustered fruits, because apples are unpredictable in size in each cluster. Thus, the end-effector should have a mechanism that can be flexible for adjusting the hole size based on the target size.

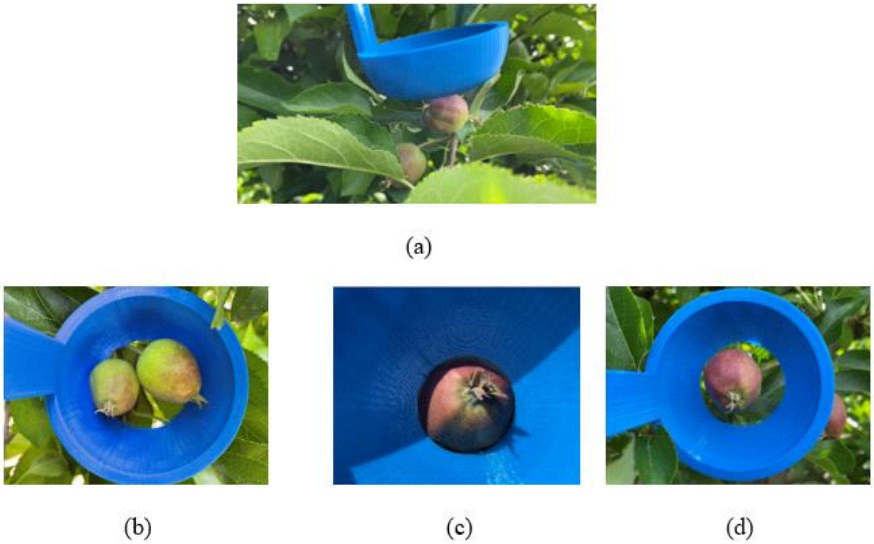


Figure **5-2**: The fixed-size cups experiment (a) 30 mm cup in the orchard (b) 30 mm cup grabbing two apples (c) 15 mm cup cannot singulate an apple when the diameter of the hole is smaller than the apple diameter (d) 20 mm cup succeeds in singulating the apple

Iris Mechanism

The iris is a small, annular structure in the eye found in most mammals and birds, including humans. It controls the size and diameter of pupils, regulating the amount of light reaching the retina. In the mechanical field, the mechanism that mimics this organ is called the iris mechanism (Iris Calculator, 2022). Like human eyes, the iris mechanism center is designed to be able to gradually open and close in order to control the size. A common application of the iris mechanism is controlling the light exposure in digital cameras. There are several ways to design and construct an iris mechanism. The planar iris mechanism is a typical design (Fig. 5-3). It is recorded that this mechanism was invented in 1858 (Iris Calculator, 2022).

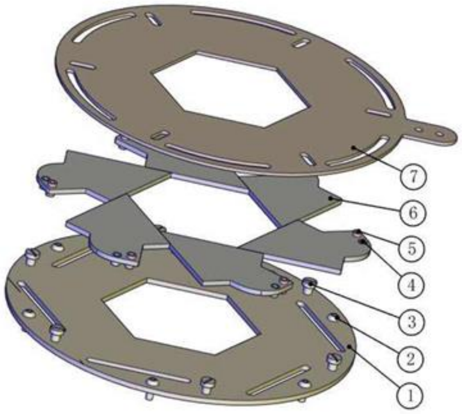
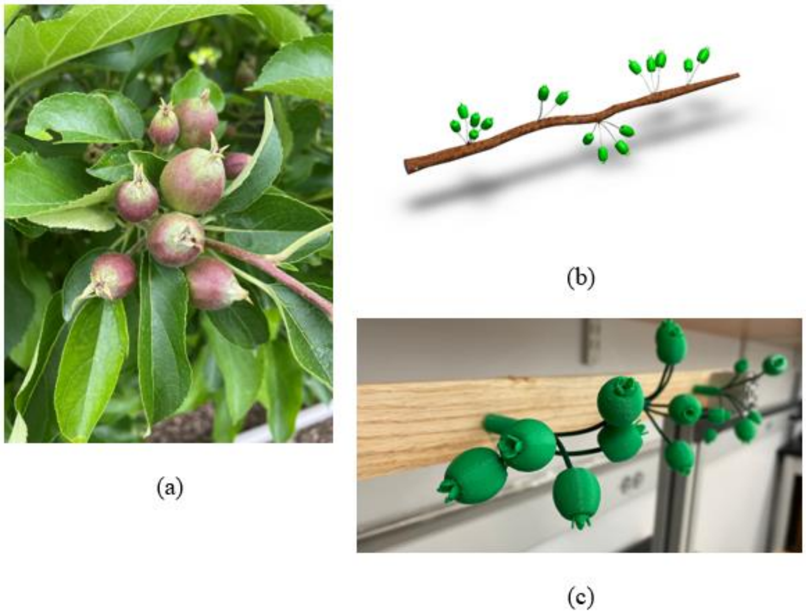


Figure **5-3**: Iris mechanism 1. Fixed Plate, 2. Bolt, 3. Shoulder Bolt, 4. Short Shaft, 5. Long Shaft, 6. Blade, 7. Driving Plate (Tanerxun, 2022)

Fig. 5-3 shows the vital components of this mechanism include fixed plate, blade, and driving plate, each of which is designed to make the size adjusting mechanism function properly. These three components are critical for every iris mechanism design. The movement of planar iris mechanism is on a 2D plane. In this study, however, the movement should be within a sphere as tested for the fixed-size cup. For end-effector model 1, the iris mechanism was applied to the sphere, so that the end-effector can adjust hole sizes based on apple sizes, therefore achieving the goal to singulate unwanted apples one by one.

Model 1 Component and Concept of the Driving Part

The “iris dome” or “iris box” is referred to as the spherical iris mechanism. During the design process, apples in the green fruit stage were fabricated using 3D printing base on the physical properties of real apples to test the end-effector mechanism under the laboratory settings (Fig. 5-4).



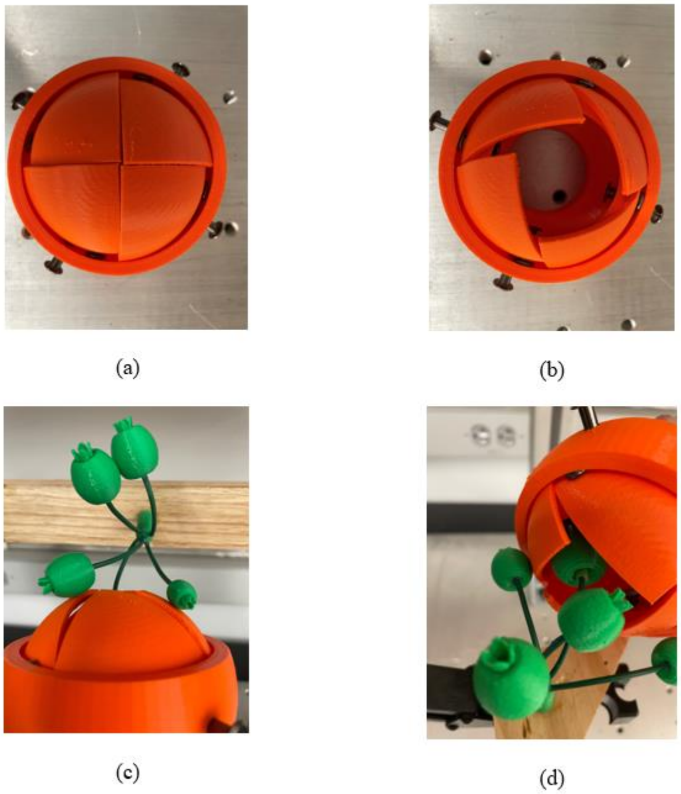
(a)

(b)

(c)

Figure **5-4**: Apples in the green fruit stage (a) real apples in the green fruit stage (b) schematic for apples in the green fruit stage (c) fabricated apples in the green fruit stage in laboratory

The iris mechanism components were designed from three concentric hollow spheres for the sphere movement. A simple iris mechanism to generate spaces at the center of the hole uses a four-blade structure. Therefore, initially, a four-blade iris dome was designed and fabricated as shown in Fig. 5-5.



(a) (b) (c) (d)

Figure **5-5**: Four-blade dome iris mechanism (a) close center space (b) open center space (c) iris mechanism singulates the green fruit (d) open center space during singulation of the green fruit

Fig. 5-5 shows that fabricated prototype properly singulates green fruit apples in the laboratory using a manual approach. The underlying idea of using the iris mechanism is to control the size of the hole to an appropriate diameter for a specific green fruit apple. As seen from Fig. 5-5b, the space generated by the four-blade iris mechanism has a rectangle shape with more corner areas. However, considering the geometry of the green fruit, the opening of the end-effector should not have space at the corners. To minimize the spaces at the corner, another prototypes with octagon holes in the center of the end-effectors were designed (Fig. 5-6).

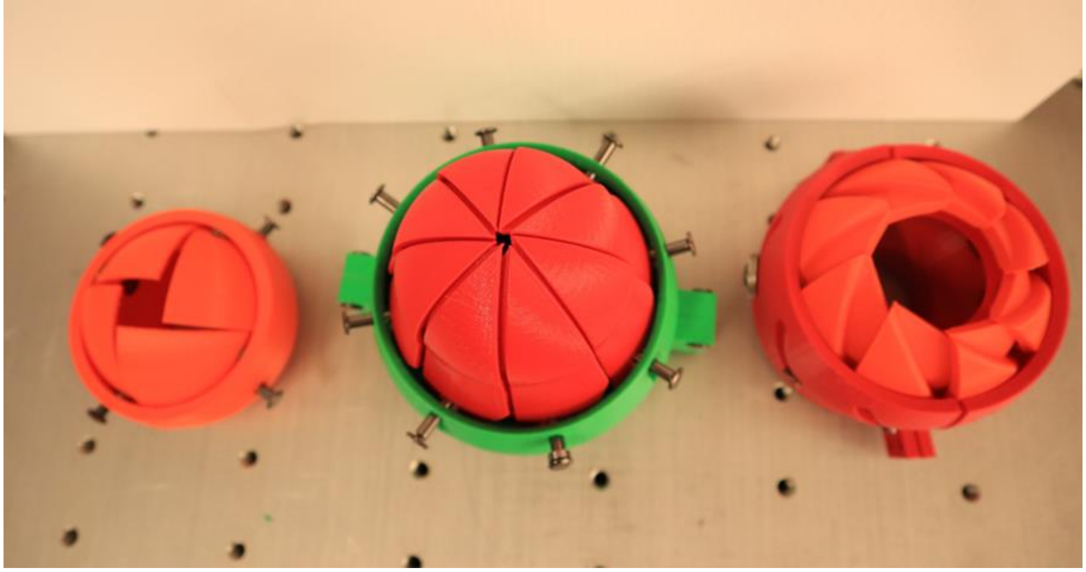


Figure **5-6**: Designed iris mechanism prototypes (from left to right: 4-blade, 8-blade oval, and 8-blade)

Model 1 Prototype

The 8-blade iris dome mechanism was chosen as the Model 1 end-effector for thinning apples in the green fruit stage. The major advantage of this iris dome mechanism is that it can gradually open and close the center of the end-effector with control of the movement. Moreover, an 8-blade mechanism can generate an octagon shape that does not have spaces at the corner, which makes the shape fit with the apple shape.

Three hollow spheres are shown in Fig. 5-7 to explain why the three key components of the iris dome mechanism have to be concentric. The dimension design of the three key components is illustrated from Fig. 5-7b to Fig. 5-7d. This iris dome mechanism has three key components: 1) the internal sphere which can either work as the fixed or driving component has a diameter of 50 mm with 5 mm thickness, with the diameter chosen to accommodate an average target apples size of target less than 30 mm; 2) the middle sphere which works as the blade has a diameter of 72.5 mm with 10 mm thickness, the 10 mm thickness is the sum of the thickness of lower and upper blades that will be further explained in the later sections; and 3) the external sphere that can either work as the fixed or driving component has a diameter of 100 mm with a 5 mm thickness; the diameter size is equivalent to the cup previously designed and tested to singulate apples in the green fruit stage. It is vital for this dome to work properly that all three spheres must have the same center or to be concentric.

The three components are named to refer to the geometry of the end-effector. The component that has the same function as the driving plate of the planer iris diagram the driving sphere, and the fixed plate is named the fixed sphere. The blade is called the same name as for the planer iris mechanism but was designed in a different geometric, in this case is a sphere.

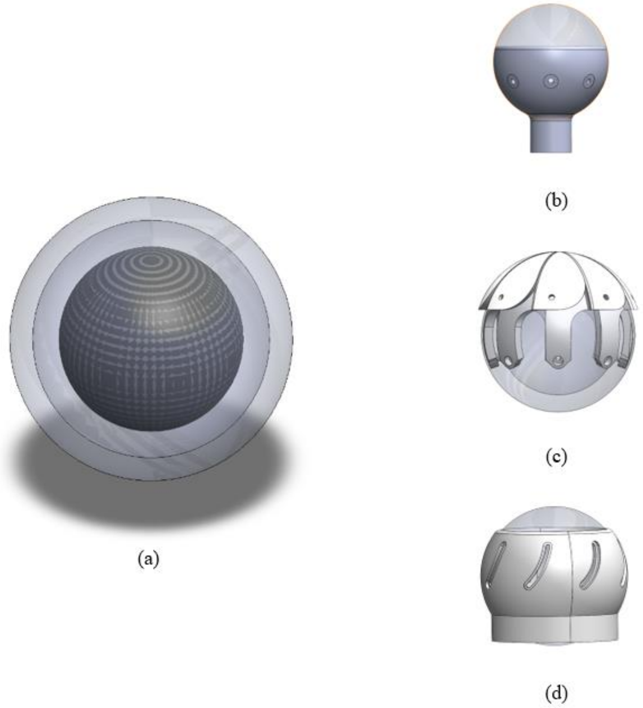


Figure **5-7**: Three key components of the iris dome mechanism (a) concentric sphere concept (b) internal sphere concept (c) middle sphere concept (d) external sphere concept

The Model 1 mechanism was fabricated, and the prototype was initially operated manually. While manually moving the prototype, it was found that the movement was not as smooth as expected. This is a potential problem because when attached to a robotic arm system it will require extra energy to control the actuator. There are two possible reasons that caused this problem: 1) the friction among components was too high, and 2) the torque generated from the driving sphere was not enough to drive the blades.

To find out if friction was the main reason that caused this problem, the materials and pins along the movement were changed, for example, bearings were added at the link, shoulder bolts were utilized. It was then confirmed that the friction was negligible and was not the major cause.

Thus, it was assumed that the torque generated is not enough to drive the blades. As shown in Fig. 5-6, the iris mechanism controls the opening of the dome through the blade that has one pin attached to the internal sphere and another pin attached to the external sphere. From Equation 1, if the adequate torque (τ) used to drive the blade is a certain number, then the force (F) applied to the movement is inversely proportional to the position (r) which means the perpendicular distance between the two pins. The blade design for the manually tested prototype is shown in Fig. 5-8. The two pin holes designed to hold the blade between the internal and external spheres have a perpendicular distance of 5 mm, which is quite small that makes the force required to be big.

$$\tau = r \times F$$

Where;

τ is the torque vector (Nm)

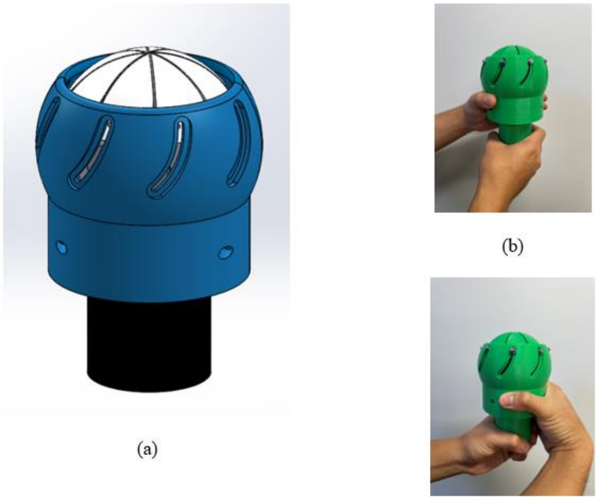
r is the position vector (a vector from the point about which the torque is being measured to the point where the force is applied)

F is the force vector

(a) (b)

Figure **5-8**: Blade design (a) first design (b) second design

To address this problem, the design of the blade was re-considered. A straightforward way would be to increase the distance, this way the required force would be smaller. Therefore, as shown in Fig. 5-8b, the new blade version was designed to have a vertical distance between the two holes up to 25 mm. The new design was fabricated, and the prototype is shown in Fig. 5-9. When tested manually, this design was able to move smoothly.



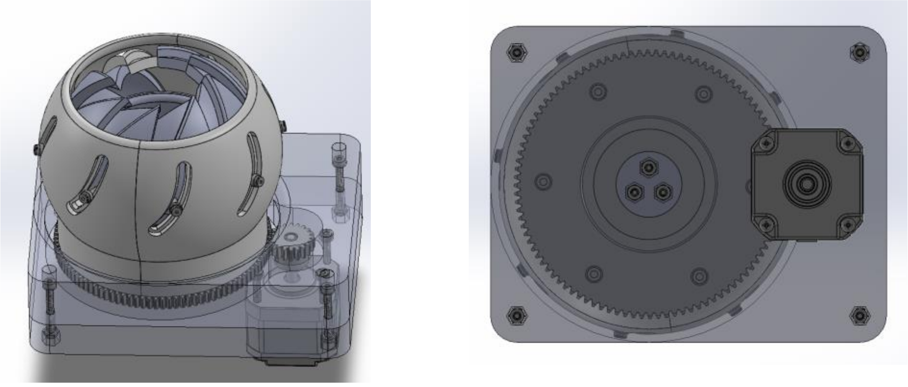
(a) (b) (c)

Figure **5-9**: Model 1 end-effector (a) schematic design with handheld bar (black column) (b) internal sphere fixed and external sphere driving (c) internal sphere driving, and external sphere fixed

As mentioned at the beginning of this section, the iris dome mechanism has three key spheres. The middle sphere was designed to be the Blade. The fixed and diving spheres should be from the internal or external spheres. Fig. 5-9b shows right hand holding the column to fix the internal sphere and left hand moving the external sphere to be the driving part. In contrast, Fig. 5-9c shows right hand holding the outside surface to fix external sphere and left hand moving the internal sphere to be the driving part. The iris dome mechanism can work properly under both scenarios, which part does the driving will depend on the application.

The overarching goal of this project is to develop an autonomous system for thinning apples in the green fruit stage. The actuator is the one essential part of automating the system. The control system is an essential part in achieving automation. Although this study focuses on the design of the end-effector, the location where the actuator is mounted on the end-effector should also be taken into consideration.

For the first motorized design, the internal sphere was designed to be the fixed part and the external to be the diving sphere. The external sphere acting as the driving sphere was achieved by attaching a ring gear to the bottom and then controlling it using a stepper motor (Fig. 5-10). This driving system required a gearbox attached to the bottom of the end-effector. It also required some spaces between the external driving sphere and the gearbox allowing the external sphere to move. However, this end-effector was developed to be used in apple orchards. During the operation, small pieces from the tree can be made that are typically dusty and messy. There are chances that dust and small pieces from the environment will drop inside the space in between the gear box and the external end-effector.

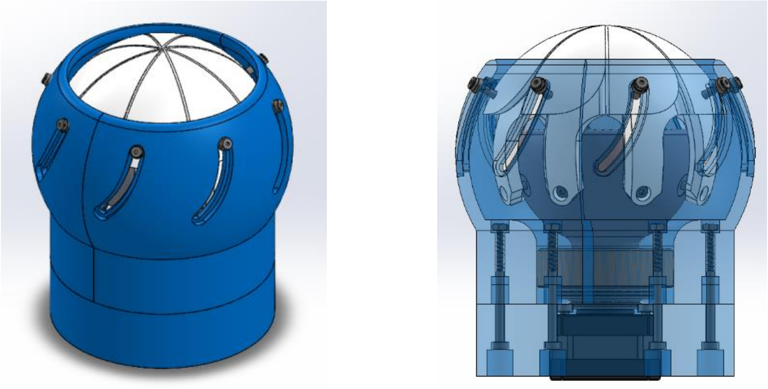


(a)

(b)

Figure **5-10**: Model 1 gear driving (a) first design with fixed internal end-effector (b) bottom side of end-effector

To avoid the problem for the first motorized design, a second design with the end-effector fixed externally was proposed (Fig. 5-11). Instead of being driven from the ring gear, this end-effector was designed to be directly driven by a stepper motor. This design does not require a gearbox, which makes the size of the end-effector smaller than the first design. Moreover, the internal driver does not require space between the driving mechanism, which can avoid problems caused by a dusty working environment.



(a)

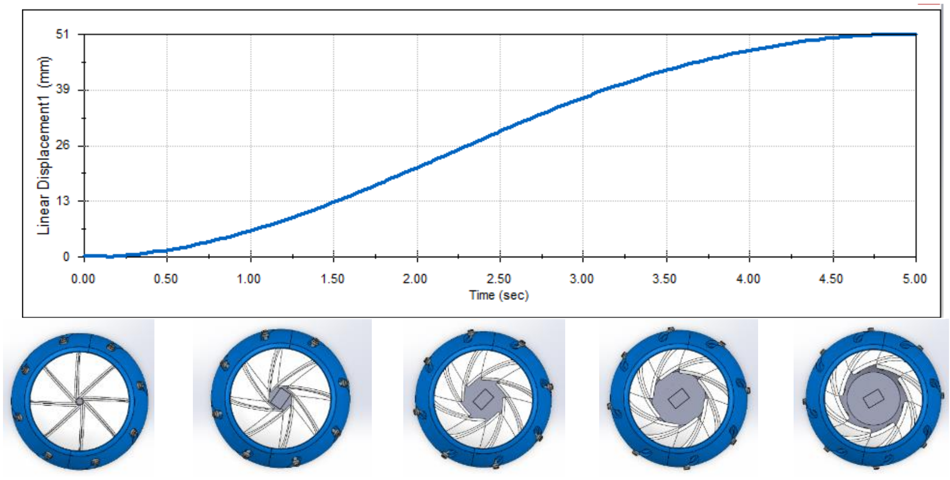
(b)

Figure 5-11: Model 1 stepper motor driving (a) schematic end-effector at the initial position (b) (a) schematic inside end-effector

Comparing the two designs with a different driving part, the second design was chosen based on the advantages discussed above. Because the opening area of the second design is controlled by a stepper motor, a kinematic analysis is required to analyze the angular displacement of the stepper motor and the diameter of the opening of the end-effector, which is presented in the following section.

Model 1 Kinematic Analysis

The key point of Model 1 is that the diameter of the opening is controlled by driving the internal mechanism with a stepper motor. The motion analysis conducted in Solidworks shows that the end-effector can be driven to operate holes with diameters between 0 and 50 mm when the stepper motor was rotated between 0 and 30 degrees. During this simulation, the stepper motor was rotated with a constant speed to reach the angular displacement 30 degrees from the initial position in 5 seconds. Fig. 5-12 shows the magnitude of linear displacement of the opposite point in the end-effector blade (or iris blade). The magnitude displacement represents the diameter of the opening hole of the end-effector. This opening hole is used to singulate the apple from the cluster. The graph shows the relationships between time and the magnitude of linear displacement of the end-effector blade.



(a) (b) (c) (d) (e)

Figure **5-12**: Model 1 kinematic analysis show magnitude displacement represents the diameter of the opening hole of the end-effector (a) 1s (b) 2s (c) 3s (d) 4s (e) 5s

Model 2 Conceptual Design

Ideally, one apple per cluster is enough for high quality yield. From the horticultural perspective, the largest fruit preserves the best nutrient and size when the surrounding apples are removed in the green fruit stage. The idea of Model 2 came with the intent that the end-effector could protect the king fruit and remove all unwanted surrounding fruits (Fig. 5-13).

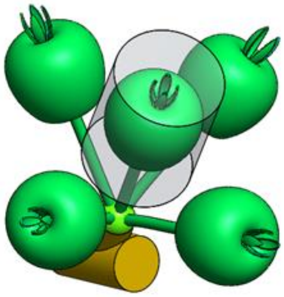


Figure **5-13**: Schematic showing the idea to protect the king fruit

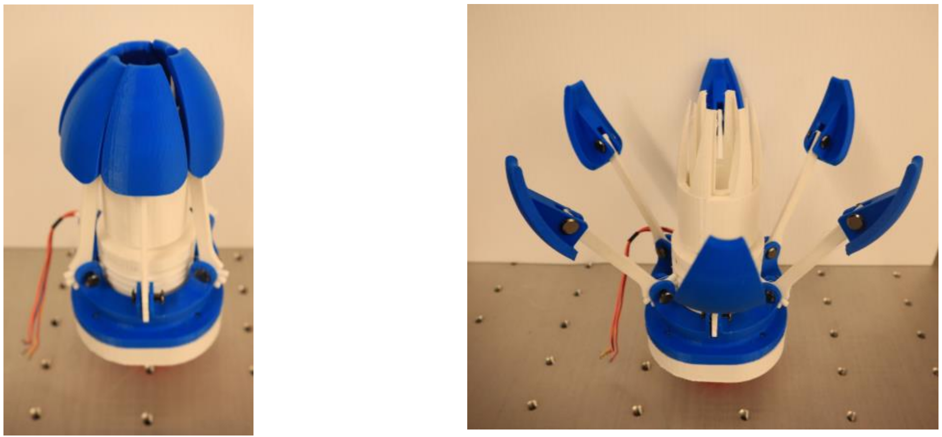
Model 2 Prototype

There are two steps for Model 2 to remove unwanted apples from the cluster: first, the mechanism protects the king fruit while at the same time pushes the stems of unwanted apples to the cutting mechanism, second, the cutting mechanism cuts unwanted apples. The idea of Model 2 is inspired by the corkscrew design (Fig. 5-14). When the corkscrew is working, the screw can move forward while the fingers on both sides rotate simultaneously. To better illustrate this concept, the corkscrew is separated into three key components: driving part, screw, and fingers. Similarly, Model 2 has the driving component, the cutting mechanism, and the fingers, respectively.

(a) (b)

Figure **5-14**: Schematic design of the corkscrew (a) corkscrew at the initial position (b) corkscrew moving forward by 40 mm

The driving component for Model 2 is designed to move the cutting mechanism forward 40 mm. This number is chosen because the average diameter of apples is 20 mm and the average length of stems is 20 mm; the cutting mechanism has the function of grabbing the king fruit from the bottom. So, the moving distance is designed to be 40 mm. Fig. 5-15 shows the prototype of Model 2 using a gear to drive the cutting mechanism. This design has six fingers to push surrounding unwanted apples away from the center. There are usually up to seven fruits in total in one apple cluster. If the king fruit is protected, there should be up to six unwanted apples. Considering the design should be symmetric, a six-finger structure was therefore developed.

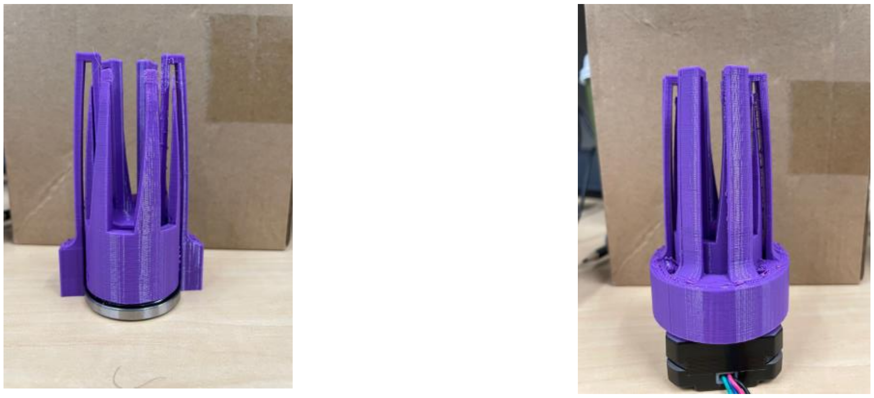


(a)

(b)

Figure **5-15**: Model 2 prototype (a) end-effector at the initial position (b) end-effector moving forward by 40 mm

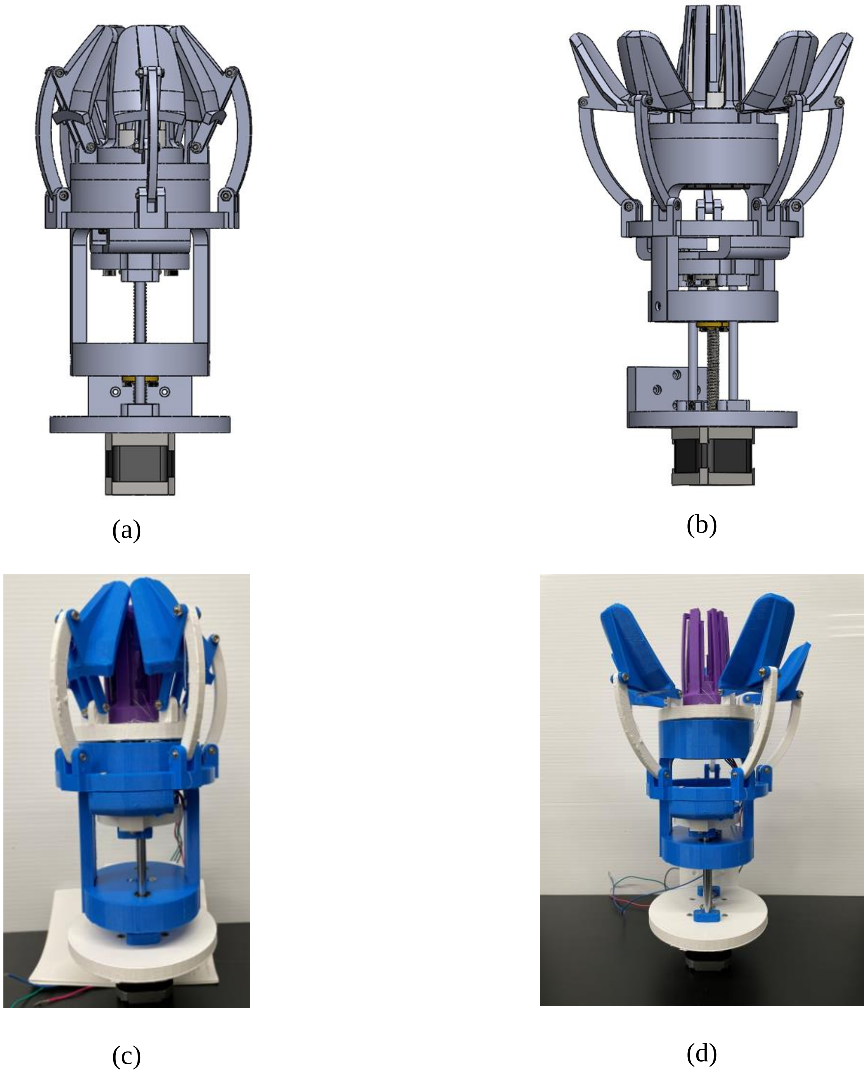
The cutting mechanism is the critical component of Model 2, which has two functions. One is to protect the king fruit, and the other is to cut the stem of the unwanted fruit. To achieve these two functions, a two-column structure was designed. Fig. 5-16 shows the space between the two columns designed to grab stems of unwanted apples. When stems are inside the space, the rotation movement will complete the cutting process. The external column is designed to be fixed, and the internal part will be rotated. The internal column has a diameter of 30 mm, corresponding to the diameter of the king fruit. This way, it can hold and protect the king fruit. The actuator is designed to drive the internal column directly.



(a) (b)

Figure **5-16**: Cutting mechanism model 2 (a) inside prototype cutting mechanism (b) motorized cutting mechanism

However, the initial design of the driving component was found to have a problem when moved manually. The gear driving idea initially came from the design of a corkscrew. The gear is scaled to have a diameter of 40 mm to make the end-effector fit the size of apples. After the prototype assembly, it was found that the gear movement was not smooth. Moreover, the gear column design was hard to fabricate. The gear structure should move the cutting mechanism forward and rotate the fingers. These functions can be achieved using a t-type screw and a stepper motor. Therefore, a second version of the driving component was proposed (Fig. 5-17).



(a) (b)

(c) (d)

Figure **5-17**: Model 2 screw driving (a) schematic end-effector at the initial position (b) schematic end-effector 40 mm move (c) fabricated end-effector at the initial position (d) fabricated end-effector moving forward by 40 mm

Chapter 6

Singulating Experiment in the Orchard

This chapter focuses on field experiments using the two different types of end-effectors for thinning apples in the green fruit stage. Due to the demanding working conditions, erratic environment, and complex activities, developing robotic solutions for selective thinning of apple production is difficult. In contrast to a laboratory setting, the designed end-effectors with the structural concept described in Chapter 5 were used to deal with the uncontrolled in-field conditions in an apple orchard.

This chapter aims to evaluate the end-effector's performance by quantifying its fruit singulating rate during the thinning season. According to the mechanical test results in Chapter 4, developing an end-effector should be based on cutting techniques that minimize cluster damage. For the cluster fruits, separating the individual fruit before cutting is a challenge. This separating process is referred to as “singulate” in this study.

Design of Experiment for Singulating Apples

The end-effector should be able to singulate the target fruit in the cluster effectively. The experiment was designed when the end-effector was in the proper position. The term “proper position" has been used to refer to situations in which the end-effector and the target fruit are in the same line or colinear.

Based on the experimental design, there are two possible outcomes for each trial. The term “binomial experiment” is used here to refer to the experiment that contains a fixed number of trials and each trial results in only one of the two outcomes: success or failure. This experimental design follows the following four properties of Binomial Experiments.

1. The experiment consists of n repeated trials. In this case, there are 100 trials. The Model 1 end-effector was tested to singulate 100 target fruits from a set of clusters, and the Model 2 end-effector was tested to singulate king fruits from another set of 100 clusters.
2. Each trial has only two possible outcomes. The singulation process of the tested end-effector either succeeded or failed.
3. Each trial is independent. The outcome of one trial does not affect the outcome of any other trials.
4. The probability of success is the same for each trial. For an experiment to be a true binomial, the probability of "success" must be the same for each test. In this case, the success rate is a dependent variable that this experiment tries to determine.

Data Collection

The research variable chosen for the design experiment shown in Table 6-1. The simple random sampling method was used to collect data in this experiment. Random sampling is a straightforward and widely used data collection technique in the experimental field. It provides the collection of unbiased data allowing studies to reach an unbiased conclusion. Simple random sampling is the process of randomly choosing a small group of members from a larger population. It gives every individual in a population an equal and fair probability of being selected.

The experiment was conducted during the thinning season or the so-called "June Drop," which is about 30 days after full bloom, between May and June 2022. The study site was located at the Russell E. Larson Agricultural Research Center, Rock Springs, PA. The apple clusters chosen to encompass the top, middle, and bottom canopies of the apple tree, taking into account the varying density distributions in these three places (Fig. 6-1).

Table **6-1**: Research Variables

Research Question	Independent Variable	Dependent Variable
Compare and contrast the two different models and assess each model in terms of their strengths and weaknesses in the orchard	The end-effectors access the apple clusters.	The number of apples singulated from the cluster.

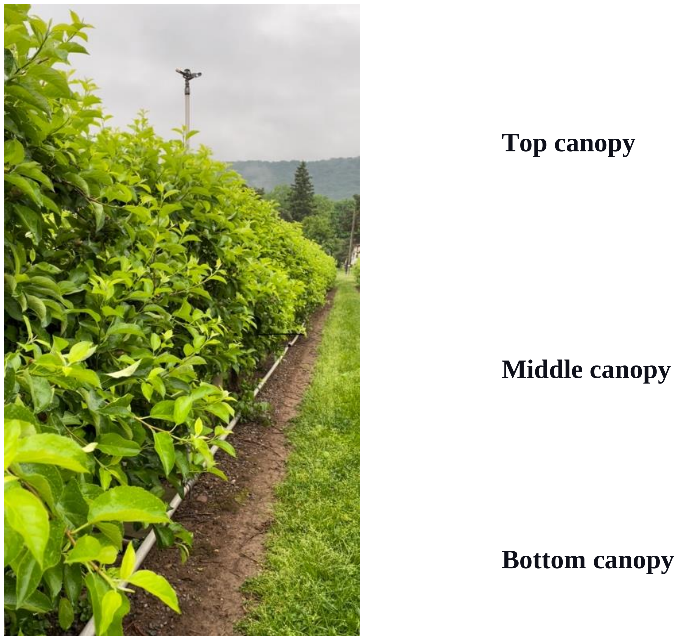


Figure **6-1**: Illustration of apple canopy sections

Model 1 Field Experiment

A robotic end effector can be delivered to a target in three dimensions, and a six DoF robotic arm can present the end-effector utilizing three rotations (θ, ϕ, and ψ, along Z-axis, Y-axis, and X-axis, respectively) and three positions (x, y, and z). The estimated pose of a target apple was controlled manually. The end-effector was moved to the position colinear with the target apple. After that, the end-effector moved along the colinear line to singulate the target apple from a cluster (Fig. 6-2).

Figure **6-2**: Model 1 colinear to the target apple before singulation

Model 1 Results and Discussion

The target for Model 1 is the individual unwanted fruit that is expected to be singulated from the cluster. The results shown in Table 6-2 indicates that the trials were successful. The 100 percent successful rate shows that Model 1 can effectively achieve the desired goal. The end-effector is the last action part for a robotic system. A common misfunction of end-effector is that the designated positions are not properly targeted which makes the whole system not work successfully. Furthermore, when a robotic system works in the 3D world, one challenging problem is to accurately reach every position with six degrees of freedom. The end-effector was not attached to a real robotic system, instead, human decisions and actions were applied, where targeting to the appropriate position is not a problem. This partially explains the complete success rate of the process. It can be assumed that the end-effector can reach the proper location with an accurate robotic system. The next challenge affecting the effectiveness of end-effector would be addressing the various sizes of targets and adjusting to them. As previously illustrated in Chapter 3, apples in the green fruit stage used in this study have diameters ranging from 6.59 mm to 26.50 mm. From the observations, there are one to five small sized fruits in a cluster and the sizes of the fruits are typically different. To solve this problem, the iris mechanism was applied to the Model 1 end-effector. Therefore, the robotic system can control the size of the mechanism to grab the unwanted apple in the real world. In every experiment conducted, the end-effector was able to singulate unwanted apples with different sizes. The next step for testing Model 1 would be to attach it to a robotic system and check if the iris mechanism would work smoothly adjusting to the desired sizes with the control system.

Table **6-2**: Results for Model 1 sigulation field experiment

Unwanted Apple (trial)	**Successful**	**Failed**	**Success Rate**
100	**100**	**0**	**100%**

Model 2 Field Experiment

Ideally, only the king fruit in the cluster will be kept after the thinning process. This model has two actions to singulate the king fruit from other unwanted fruits. The same technique from Model 1 was used, that is the end-effector was moved to the position colinear with the target which, in this case, is the king fruit.

The Model 2 singulating process includes three steps as follows:

1. The end-effector was moved to be colinear with the king fruit.
2. The driving part of the end-effector was moved 4 cm to drive the finger mechanism pushing unwanted apples away from the king fruit.
3. The cutting mechanism inside the model grabbed the king fruit simultaneously with the fingers in step 2 separating surrounding apples. (Fig. 6-3)

Figure **6-3**: Model 2 targeted to the king fruit (a) end-effector colinear with the king fruit (b) end-effector moving to the cluster (c) cutting mechanism grabbing the king fruit inside

Model 2 Results and Discussion

The concept that protects the king fruit in each cluster was applied to model 2. The end-effector was manually moved to be colinear with the king fruit in the apple cluster before the cutting mechanism was moved to grab the king fruit and allow the gripper fingers to push away the surrounding apples. Table 6-3 shows that the success rate for Model 2 was 75%, which means that within 100 apple cluster trials, the end-effector can properly singulate 75 king apples. It is interesting to find that in this experiment there are a large number of failures when the end-effector was manually moved to the proper positions before the last action of the mechanism. When the pose estimation is not the problem during the manual movement, the result of 25 clusters shows that this mechanism should be improved for better singulation performance.

When designing Model 2, it was assumed that the king fruit is located in the middle of each cluster. However, the king fruit is not always in the middle in the real unstructured environment, which may have caused the cutting mechanism to grab leaves or branches. This is a critical issue of Model 2 because it may damage the apple tree. If the design is based on an ideal situation, in this case the symmetric structure of the cluster, it may cause failures in the real application. However, it was appropriate to simplify the problem for the preliminary design and make further improvements or changes in the future.

Table **6-3** : Results for Model 2 singluation field experiment

Apple Cluster (trial)	**Successful**	**Failed**	**Success Rate**
100	**75**	**25**	**75%**

Chapter 7

Conclusions and Future work

Conclusion

Two prototype end-effectors were designed and fabricated for the robotic thinning apple in the green fruit stage. First, understanding apples' physical and mechanical properties were essential to end-effector design. The suitable method to remove unwanted fruit from a cluster of apples without causing damage is to cut the stem; nevertheless, according to the tension and bending test, an apple stem can bend before breaking. The engineering design and development of efficient end-effectors for thinning apples in the green fruit stage would benefit from the outcomes of this study. Cutting the stem has been a successful method for removing the apple, but the challenge lies in how to singulate the apple before this cutting process.

A mechanism design was adopted to singulate apple, which considered the mechanical and physical properties of apple stem. Model 1 of the end-effector applied an iris mechanism dome to singulate the apple one by one. This mechanism can operate the opening center that can singulate apples appropriately. However, singulating the apple one by one is a highly time-consuming process. Model 2 used the idea of a corkscrew to protect the king fruit and remove unwanted apples. The advantage of this idea is a time-saving process. For example, if the apple cluster has seven small apples, model 1 takes seven times to remove apple one by one, while Model 2 operates only once to achieve these tasks. However, Model 2 should be improved for better singulation performance. Both models have different advantages and disadvantages, and this end-effector is a key part of the robotic system. This part must be combined with other components to make the system work in the apple orchard to achieve the larger goal of automated thinning apples in the green fruit stage.

Future work

Due to time constraints, several tasks, such as in-field tests, automation, and further improvements, have been left for future work. In this study, the king fruits in apple clusters are assumed to be in the middle; however, variations in king fruit locations are observed in the real orchard. To achieve system automation, a more comprehensive understanding of the properties of apples in the green fruit stage is required. Therefore, a pose estimation algorithm for apple cluster structures is proposed as the next step. This pose estimation will be performed prior to the singulation and cutting processes. When automation is complete, it will be necessary to compare the thinning methods used by the two designs, assessing their effectiveness and the ability to increase apple yields. Concerning the design, efforts will be made to simplify the mechanism and identify potential manufacturers. Before the next thinning season, cutting mechanisms will be added to both end-effectors.

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