Design and Evaluation of a Lightweight Soft Electrical Apple Harvesting Gripper

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***Abstract*— To address apple harvesting labor shortages in Washington State, we are developing an innovative soft growing manipulator that aims to overcome the current limitations associated with conventional robotic solutions, specifically in terms of cost-effectiveness and efficiency. A critical aspect of this technology is the creation of a lightweight apple harvesting end-effector, weighing less than 0.8 kg, to account for the stringent payload restrictions of our custom soft growing manipulator. This paper presents the design of a lightweight cable-driven soft gripper, offers insights into its force characteristics, and provides a case study showcasing its effectiveness in a commercial orchard setting. The gripper's weight is 0.306 kg, and it boasts a successful picking rate of 87.5% without damaging the fruit. In the future, our work will extend to further enhance the soft gripper by incorporating a twisting motion. It will also be seamlessly integrated with the soft growing manipulator and custom machine vision system, which will subsequently undergo evaluation in a commercial orchard.**

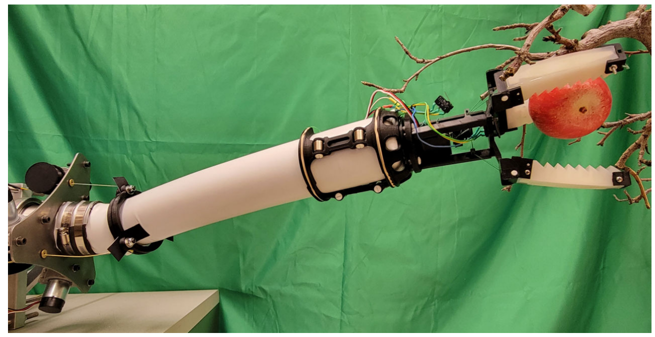

Fig. 1: Soft Apple Gripper. Our soft gripper is light-weight and can be used as the end-effector for a soft, growing manipulator. This manipulator and gripper system can be used for efficient apple picking in orchards.

I. Introduction

In 2022, Washington State led the nation in apple production, contributing over $2 billion to the U.S. GDP [1]. Apple growers throughout the state often employ dozens to hundreds of workers throughout the year for orchard operations such as pruning trees, flower thinning, and fruit harvesting. However, due to an aging worker population and a net decrease in migrant workers, many farmers struggle to find an adequately sized workforce during the harvesting season [2]. The integration of robotics in agriculture can yield numerous benefits, including reducing the necessity for humans to engage in repetitive, labor-intensive tasks [3], [4]. Recent efforts in robotic apple harvesting have focused on traditional rigid manipulators, such as widely available 6-degree of freedom robotic arms [5] and linear robots [6]. These systems can come with high costs and are frequently overly complex for use in orchard operations. In prior research concerning our cost-effective, flexible, growing manipulator arm (Fig. 1), our aim was to tackle the issues associated with increasing costs and labor shortages [7]. Our harvesting system presents several advantages over rigid manipulator harvesters. The soft manipulator arm, constructed from fabric, features a simplified mechanism design that reduces the complexity of inverse kinematics (IK) calculations in a spherical coordinate system. Currently, it achieves a rapid linear extension speed of 0.33 m/s when operating at a pressure of 8 psi (55.1 kpa). Each individual unit costs approximately $4,230, enabling a multi-robot approach to expedite the harvesting process. This approach is particularly crucial when considering the size of an orchard and the brief harvesting season. However, because the arm operates with pressure applied inside the fabric, there exists a specific safety pressure threshold to prevent unexpected arm failure. Currently, this safety pressure is set at 10 psi (68.9 kpa). This constraint limits the overall payload capacity of the arm to less than 1.4 kg. Given that some apple varieties weigh up to, and in some cases exceed, 0.3 kg, it is imperative to ensure that the remaining payload remains under 1.1 kg. To guarantee that the system can effectively harvest apples without causing any harm to the fruit, a lightweight gripper solution is necessary.

Currently, several research teams are developing apple harvesting grippers using flexible material, as it requires much less precision in terms of control and planning. For instance, grippers that solely employ flexible 3D-printable materials like thermoplastic polyurethane (TPU) for their finger components may have the potential to cause surface damage, such as bruising and scratches, to the fruit [8]. Such damage can render apples ineligible for USDA market regulations [9]. Pneumatic grippers that use pressure to inflate fingers have achieved astonishing performance, including a high successful pick rate with a relatively low rate of apple damage. However, they require additional components such as air compressors, regulators, and solenoids, which increase the overall cost [10]. Additionally, soft grippers that utilize

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tactile feedback to determine the necessary force for grasping offer certain advantages, such as detecting obstructions or failed grasps [11]. While these features can be advantageous, they may not always be the optimal, practical solution.

In this paper, we introduce a lightweight, underactuated soft gripper designed for apple harvesting. This gripper not only meets the payload requirements of our soft growing manipulator but also maintains the goal of a simple mechanism design while achieving a highly successful picking rate. The paper is structured as follows: Section I provides the background and motivation. Section II outlines the design and fabrication process of the soft gripper. Section III presents the load analysis for various design settings and the field experimental results in a commercial orchard. Finally, Section IV summarizes the work and discusses future developments and research.

In general, the novelty of this work lies in the design of a lightweight, low-cost, electric, underactuated, soft gripper specifically intended for apple harvesting, serving a highly practical purpose.

II. Design and Fabrication

A. Overall design

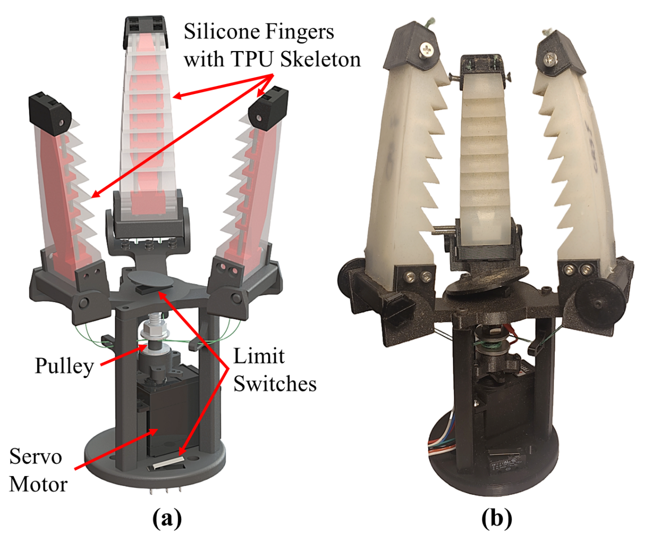

Fig. 2: Soft Gripper Components. The soft gripper contains two limit switches to identify when to close and open the fingers. The fingers are made of silicone with an embedded TPU skeleton. A servo motor and pulley are used to close the fingers. Both the CAD assembly (a) and physical prototype (b) are shown.

Unlike ordinary picking and placing tasks, fruit picking demands a significantly greater holding force to detach the apple from the stem. According to [12], the required force to detach an apple is substantial. This poses a challenge for soft grippers made solely from silicone, as their limited softness can cause apples to slip from their grasp, thereby hindering their ability to achieve a high picking rate [13]. Figure 2 illustrates the overall design components of the soft gripper. To minimize weight, the majority of the parts are 3D-printed using polylactic acid (PLA). This gripper utilizes a cable-driven approach and is equipped with three fingers, for improved grasp stability on the fruit. The gripper's palm size and gap between fingers are based on the average diameter of fruit samples taken during the 2023 harvesting season. The gripper utilizes two limit switches for operation, one on the palm and another at the base. When the apple triggers the limit switch on the palm, indicating that the apple is inside the gripper, the servo will actuate the cables to immediately close the fingers, securely wrapping around the apple. When the limit switch at the base is pushed, the gripper will release the fingers to drop the apple. The gripper weighs 0.306 kg and has a height of 0.219 m.

B. Fabrication

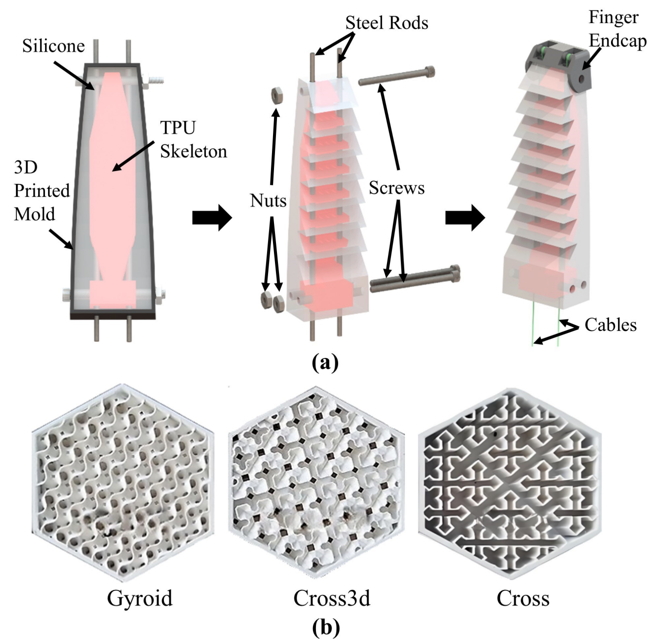

Fig. 3: Soft Finger Components. a) Fabrication process for a single soft finger with a TPU skeleton. Silicone was cast into a mold with a TPU skeleton and steel rods to create a cavity for the cables. The rods are removed and cables are inserted to create bending motions. b) TPU Skeleton Patterns. Three types of TPU patterns (Gyroid, Cross3d, and Cross) were tested for the gripper design.

Figure 3a illustrates the fabrication process of a single finger. First, a negative mold of the finger is printed using PLA. A TPU skeleton is placed into the mold and secured using nuts, bolts, and two steel rods. Dragonskin 30 silicone rubber is then poured into the mold and cured. Once the silicone is fully cured in the mold, the nuts, bolts, and rods are removed from the mold and the finger is then pulled out. With the finger pulled out of the mold, cables are threaded through the cavity left behind by the steel rods and tied to the finger endcaps, firmly securing them in place. The fingers are then fastened to a platform which is in turn secured to the gripper's palm. The cables initially threaded through the fingers, are then passed through the pulley and securely fastened. Through previous designs we observed that the thin layer of silicone on the back of TPU skeleton was susceptible to tearing, leading to the TPU skeleton becoming exposed. The frequent use of these fingers would often cause the skeleton to be ripped out of the silicone. Due to the low bonding strength between TPU and silicone [14], small cuts were made into the horizontal tabs of the TPU skeleton to interlock the two materials.

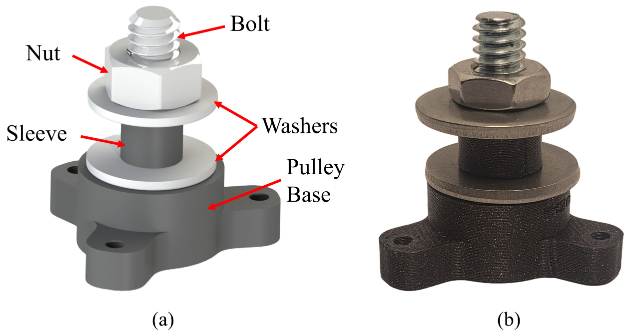

Fig. 4: Pulley Assembly. The pulley was designed to be robust and easy to assemble. This design consisted of using a nut and bolt to securely attach the pulley cables. The pulley base attaches to the servo, and the sleeve spools the pulley cables. Both the CAD assembly (a) and physical prototype (b) are shown.

The silicone surface provides effective protection against damage to the apples, while a 3D-printed TPU skeleton embedded inside the silicone enhances the rigidity of the soft fingers. To choose the optimal stiffness for the TPU skeleton, one that is rigid enough to detach an apple while ensuring the servo possesses sufficient torque to close the finger, we assessed three different printing patterns, as shown in Figure 3(b), along with the TPU skeleton printing settings using an Ultimaker S3 printer. The tendons for the three fingers are driven by a common pulley situated beneath. Given that the servo (FS5115M-FB) has a limited range of 0° to 180°, we optimized the dimensions of the pulley (a diameter of 6.35 mm) to ensure that all three fingers can be fully closed with a 135° rotation of the pulley. We observed over repeated tests that a pulley composed of PLA was not able to endure the forces produced by the tension in the cables. This design needed the cables to be fed through holes in the center of the pulley and would be too complex to re-string and re-tie in the field. To address this, we sought a replacement for the 3D-printed pulley with a design that was more robust and easier to maintain during harvesting operations. Figure 4a shows the pulley with its major components labeled. With this new design, the cables are wrapped around the threads of the bolt and fed through to the bottom of the sleeve. The nut at the top is then tightened down to secure the cables in place. This simpler design would allow farmers to quickly replace worn cables without the need to tie any knots. A limit switch with a large pad positioned in the middle of the palm triggers finger closure when an apple comes into contact with it. The bottom limit switch is used for testing, allowing manual control of the fingers by a human operator. To determine the optimal size for the gripper's palm, we measured the circumferences of 20 apples of the Jazz variety. The apples were randomly selected approximately one week before harvest and their diameters were calculated. The average diameter of these apples was used to determine the size of the inner area of the gripper, this resulted in a palm diameter of 9.8 cm.

III. Experimental Results

A. *Force testing*

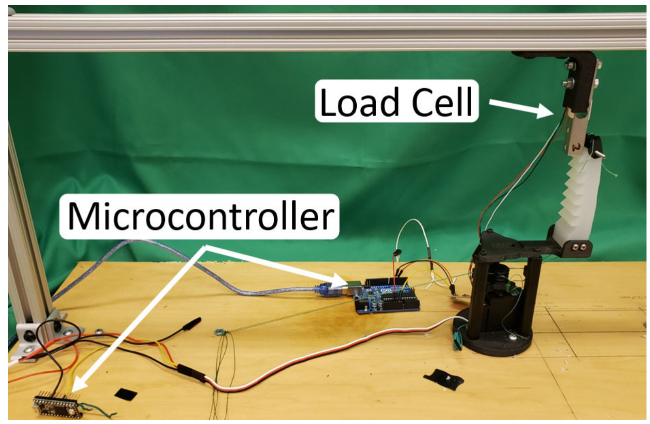

Fig. 5: Force Testing Setup. A single soft finger was pressed against a load cell to measure its force output. This was repeated four times, once for each TPU skeleton infill pattern and once for the control (no infill).

This section introduces the characterization of the force output of an individual finger. An experiment was conducted to measure both the bending angle and the force generated. The experimental setup shown in Figure 5 included a gripper holder with a single finger and a load cell attached to the end of the finger. This force measurement is crucial for apple harvesting, as the tip force holds the apple's surface, preventing it from slipping during harvesting. Three fingers with three different TPU skeleton infill patterns, as shown in Figure 3(b), were tested, along with one finger without a TPU skeleton. Each finger underwent three tests, with its bending angle recorded through protractor measurements.

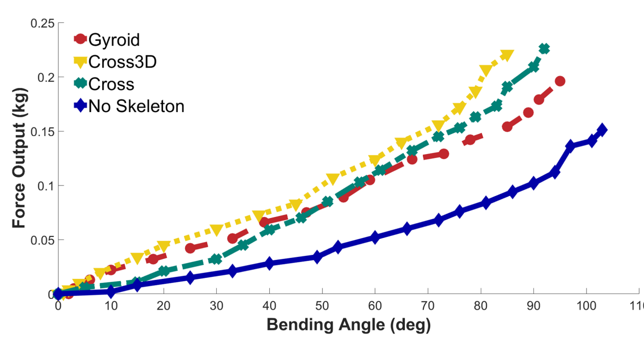

Fig. 6: Force Output and Bending Angle Results. The force output and bending angle are directly related. The TPU-embedded silicone fingers resulted in higher force outputs.

The experimental results, depicted in Figure 6, display the force output of each of the fingers over the entire range in

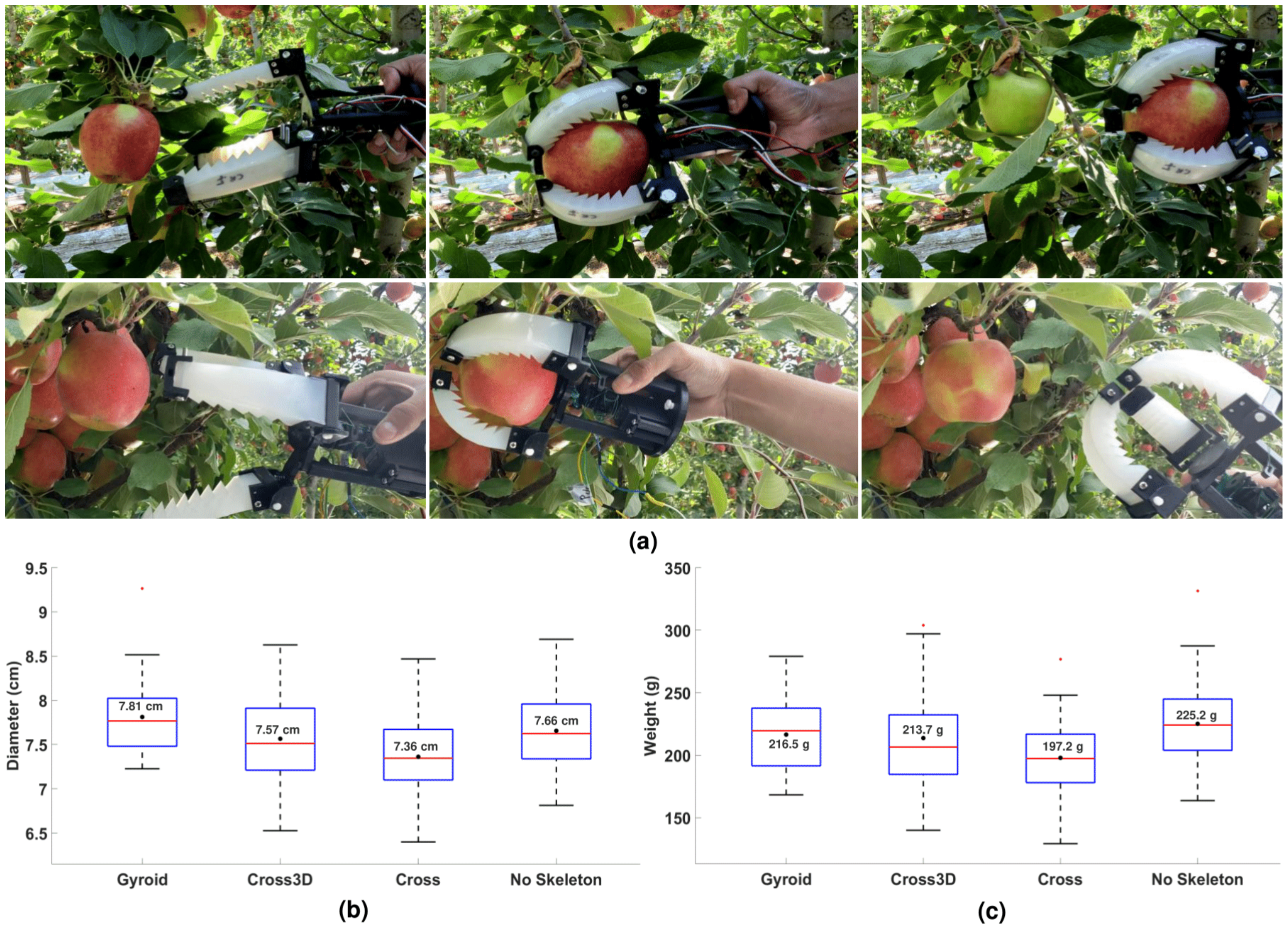

Fig. 7: Orchard Evaluation Results. (a) The three pictures in the top row show a picking sequence during which the soft gripper successfully picked an apple. The three pictures in the bottom row depict snapshots of a trial where the soft gripper failed to pick an apple (the apple escaped grasp). During testing, apples that were not successfully picked by the gripper within 3 attempts were hand-picked and collected for further analysis. (b) Boxplots show the diameters of apples attempted to be harvested by each gripper. The means are indicated by a black dot. (c) Boxplots show the weights of apples attempted to be harvested by each gripper. The means are indicated by a black dot.

which bending occurs. This plot reveals that the soft finger with the cross pattern TPU skeleton generated the highest force, while the soft finger without a TPU skeleton produced significantly less force compared to all other fingers with a TPU skeleton, yet achieved the highest bending angle at 103°. Full gripper prototypes were fabricated using each of the three skeleton patterns and a prototype with fingers that have no embedded skeleton. These grippers were then used in a field evaluation during the apple harvesting season.

B. *Orchard evaluation*

To assess the gripper's performance outside of the lab environment, an in-field evaluation was performed in a commercial apple orchard. As previously mentioned, we developed several gripper prototypes, using the fingers with three TPU skeleton infill patterns, as well as a gripper type with fingers that had no embedded skeletons. The experiment was conducted in Prosser, Washington at the Allan Brothers' orchard during the 2023 harvesting season. The orchard block where the experiment occurred utilized a planar tree architecture. This type of modern tree architecture trains the trees to grow along trellis wires. This ultimately results in the fruit growing in a configuration similar to a wall. In comparison, the traditional tree architecture will grow the fruit in any direction as a globular shape, resulting in increased complexity for a robotic harvesting system [15]. The planar tree architecture offers many benefits such as increased yield, fruit quality, and allows for orchards to be more accessible to mechanized or robotic platforms [16]. We are implementing our apple harvesting platform with this type of tree architecture because it allows the gripper and robotic system to maneuver through the canopy more easily than a traditional tree architecture. Testing was carried out 2 days after the beginning of the harvesting date for the Envy apple variety. Early findings revealed the challenge of harvesting unripe fruits on the trees, prompting the experiments to be scheduled closer to the initial harvest date. Because these conditions are similar to those faced in our targeted, final commercial setting, these experiments would serve to provide data on the efficacy of the system going forward. Many of the apples grew as a single fruit on a branch, but some orchard conditions allowed for multiple fruits to cluster close to one another. The number of fruit in these clusters would vary, commonly being in groups of 2, but during the experiment groups of up to 5 were observed. These bunches of fruit often proved difficult to harvest as their close proximity often interfered with the silicone fingers fully wrapping around the apple or causing other fruit in the bunch to unintentionally fall. The approach to address this issue is beyond the scope of this paper and subject to future work, as it is an edge case.

The harvested apples were chosen at random during the in-field experiment. Due to the planar architecture of the tree, many of the fruit bunches had enough space in between one another for the gripper to easily maneuver within the canopy. The experiment was carried out by having a human hold the gripper and approach the fruit in a way that was perpendicular to the direction of the apple stem. Once the limit switch in the center of the palm was triggered by an apple, the servo motor tensioned the cables and collapsed the fingers. Once the silicone fingers fully wrapped around the apple, the human operator would pull the gripper and apple until it was either detached from the branch or slipped out of the gripper. As shown in Figure 7a, a successful pick would typically have the silicone fingers wrap around the apple and would fully detach the fruit from the branch when pulled. In contrast, a typical failed pick would similarly have the silicone fingers wrapped around the apple, but during the pull, the apple would slip through the tips of the fingers or slip through the gaps between the three fingers. The gripper with fingers that did not use the embedded TPU skeleton was repeatably observed to wrap around the apple, but during the pull the fingers would not be rigid enough and the apple would slip through. Each apple would be attempted to be picked three times before being counted as a failed or successful pick. Fruit that failed to be picked within the three attempts would be carefully removed from the tree by hand and collected for further analysis.

The picked apples were visually inspected in the field for any damage such as bruises, scratches, or cuts. If any damage were to occur as a result of the gripper, it would most likely present itself as one of these types of damage. Fruits that were previously damaged on the branch were avoided to reduce misidentification of damage as a result of the gripper from damage that occurred from natural sources. The most common type of damage caused by natural sources is often presented as spots where holes are formed at the site of an insect entering and eating through the apple and is very distinct from damage that may have been caused by the gripper itself. Although fruit with this type of damage was avoided by the human operator, if apples with the spots were picked, that damage was not recorded as damage caused by the gripper. Apples that were damaged as a result of being dropped to the ground were not recorded and a substitute was retaken. It was observed that no damage occurred to the apple during the harvest caused by the gripper. 40 apples were collected using each of the gripper types totaling 160 apples. Each of the grippers was able to pick the forty apples without needing repairs. The harvested fruits were then measured and weighed. The results from this analysis are plotted in Figure 7(b) and Figure 7(c). From these two plots, it can be seen that the majority of the fruit were of a similar size and weight with only slight variation between each of the means for the different gripper types. However, it's important to note that despite the absence of observable damage to the fruits during the harvesting process, some incidental damage to the branches supporting the apple growth was noted throughout the course of the experiment, though this can be attributed to the operator retracting the gripper too fast during the picking motion.

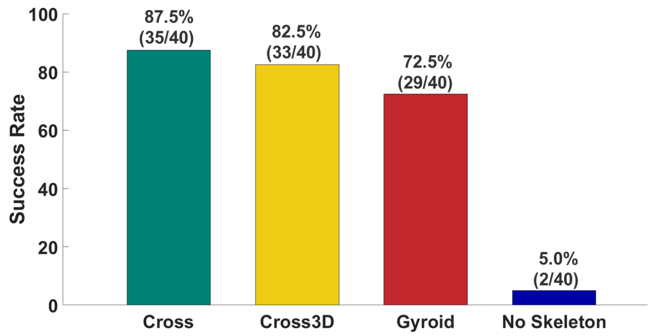

Fig. 8: Successful Grasp Rates. The percentage of successful captures for each gripper type shows that the gripper with the Cross TPU pattern performed best and that no TPU skeleton performs very poorly.

The success rates for each of the gripper types are shown in Figure. 8, with the total number of apples that were successfully captured displayed above the bar. The cross printing pattern for the TPU skeleton performed the highest, with an 87.5% success rate. As stated earlier, the force at the tip of the fingers is crucial for apple harvesting, with the cross infill printing pattern having the highest performance.

IV. Conclusion

In this paper, we present a lightweight (0.306 kg), soft robotic gripper. This gripper will be seamlessly integrated with our soft growing manipulator and machine vision system to enable efficient apple harvesting [17]. In addition to its lightweight construction, our soft gripper exhibits remarkable apple-friendly grasping capabilities, featuring a straightforward mechanism design that easily adapts to various apple sizes and is easy to maintain. Moreover, the overall cost of a single unit is approximately $36, making it a considerably more cost-effective option compared to existing pneumatic grippers. The success rate for picking apples with our gripper in commercial orchards is approximately 87.5%, and its operational lifespan currently extends to 40 cycles without the need for repairs. In contrast, previous designs that used the 3D printed pulley regularly required replacements, sometimes as frequently as every 5 cycles. Future efforts will focus on determining the operational life cycle of the full prototype.

In future developments, we plan to incorporate a twisting motion that mimics the natural human picking motion. This modification is essential as directly pulling the apple can potentially harm the branches. To reduce the probability of apples slipping through the gaps between fingers, we will explore methods aimed at increasing the friction between the fingers and the apples. In addition, future prototypes will use the fingers with the cross infill pattern TPU skeleton. Subsequently, we will proceed with the integration of all system components on a manipulator system, followed by evaluations in commercial orchards that have a diverse range of apple trees and varying weather conditions. The dimensions of the soft gripper will be further optimized based on the results of these evaluations. With respect to the practical aspect of ensuring reliable operation throughout the short harvesting season, it is essential that the soft gripper's thickness and material type are robust enough. Moreover, the repair process for the soft gripper must be streamlined, particularly when it comes to replacing damaged fingers, threads, and pulleys.

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