

## **Project Title: Low-Cost, Reliable Soft Arm for Robotic Tree Fruit Operation Phase II**

**Report Type:** No-cost extension Project Report

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**Cooperators:** Dave Allan, Allan Brothers Fruits  
**Project Duration:** 2-Year

**Total Project Request for Year 1 Funding:** \$ 106,029  
**Total Project Request for Year 2 Funding:** \$ 110,010

**Other related/associated funding sources:** None

**Funding Duration:**

**Amount:**

**Agency Name:**

**Notes:**

**WTFRC Collaborative Costs:** None

**Budget 1**

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**Station manager/supervisor email address:**

| Item            | 2023                | 2024                | 2025          |
|-----------------|---------------------|---------------------|---------------|
| Salaries        | \$51,618.00         | \$53,683.00         |               |
| Benefits        | \$9,718.00          | \$10,106.00         |               |
| Wages           | \$23,314.00         | \$24,246.00         |               |
| Benefits        | \$2,379.00          | \$2,475.00          |               |
| RCA Room Rental |                     |                     |               |
| Shipping        |                     |                     |               |
| Supplies        | \$8,500.00          | \$8,500.00          |               |
| Travel          | \$10,500.00         | \$11,000.00         |               |
| Plot Fees       |                     |                     |               |
| Miscellaneous   |                     |                     |               |
|                 |                     |                     |               |
|                 |                     |                     |               |
|                 |                     |                     |               |
| <b>Total</b>    | <b>\$106,029.00</b> | <b>\$110,010.00</b> | <b>\$0.00</b> |

**Footnotes:**

**Abstract:**

This year, our single soft-growing manipulator successfully achieved single-apple harvesting using an onboard perception system and a soft gripper in a lab environment. We also tested its functionality for multi-apple picking from different depths and planar arrangements, as well as with a moving tree, to prepare for field studies. During the October apple harvesting season, our robot was able to automatically pick several single apples, which is promising since this was our first field trial. We have also identified areas for improvement to further enhance its functionality in future field studies.

**Key Words:**

Soft growing robot; Lab environment; Field trail;

**Objectives:**

*Objective#1:* Design, fabricate, test, and optimize a growing arm/manipulator for orchard operations (Luo – Lead, Karkee – Co Lead;)

The objective was achieved last year. Here is the current performance of our robot.

*Our current achievement:*

- Length: Can extend up to 2.46 ft reliably with a high degree of control.
- Speed: Manipulator displays 1.24 ft/s growing speed and 0.86 ft/s retraction speed at 8 and 3 psi of pressure respectively. We have observed that higher pressures and airflow rates result in dramatically faster extension speeds. Currently, the speed is limited by the airflow rate and the free spin speed of the central motor.
- Targeting Speed: The manipulator can reach and pick a desired apple within approximately 30 seconds, including the time to drop off the apple and reset.
- Payload: 2.39 lbs. payload at 10 psi pressure input while at the max arm length. This payload includes the weight of the tip mount, soft-gripper, and fruit. With the tip mount and gripper being under 1.75 lbs., there is sufficient payload to carry an apple under 0.64 lbs.

- **Workspace:** One RealSense D456 camera is able to detect 3D position in 6 by 3 ft range at a 3 ft depth with a high degree of accuracy. Our robot's optimal workspace has a spherical sector shape with a radius of 2.5 ft and 60 degrees of actuation in the 2D plane, providing a total workspace volume of 22.46 ft<sup>3</sup>.
- **Pressure Reliability:** The maximum input pressure of our fabric material's sealing is above 20 psi, and 5-10 psi is our operation pressure range since it displays adequate payload and control properties. In addition, there is a pressure relief valve to reduce the risk of pressure overloading.
- **System Reliability:** The system can operate for prolonged periods of time, >3 hours, without noticeable changes in control performance or degradation due to the system design in both lab and outdoor environments.
- **R&D cost:** The current prototyping cost (\$) of a single manipulator is five times less than a commercially available rigid manipulator. The estimated cost is approximately \$5,500, which is broken down into \$574 for materials, \$547 for manufacturing, \$3,500 for electronics, and \$879 for other mechanical components. The most expensive part is the central motor, which costs \$1,117. Due to the urgent timeline, we purchased expensive and powerful motors and pressure regulators to verify our system first. We believe we can find alternative items when system verification is done, and the overall cost will be approximately \$3000 at the commercial manufacturing stage.

*Objective#2:* Manipulator integration with a low-cost machine vision system and selected end-effector tools (e.g. for picking, year 1) (Karkee – Lead, Luo – Co Lead).

The objective was achieved last year. Here is the current performance of our robot.

*Our current achievement:*

- **Machine Vision Model:** The current YOLOv8 model trained on the images of apples taken in the Allan Bros Orchards in Prosser, WA with the local and global cameras mounted on the soft robotic manipulator has an apple detection accuracy of 98%.
- **Image Based Visual Servoing (IBVS):** Two cameras are used to estimate the real time positions of the end-effector and detected apples using a QR code mounted onto the end-effector and the machine vision model respectively. The global camera uses eye-on-hand configuration of visual servoing while the local camera uses eye-in-hand configuration to manipulate the end effector on the end goal.
- **Image-Based Localization:** The cross image-based localization used to find the end-effector position utilizes images from both local and global cameras to detect apples, find correlated apples, and determine the displacement between camera frames with some level of distortion between images to determine end-effector location. The vision system is flexible for various requirements in its application.
- **Image-Based Teleoperation:** The two camera vision system is capable of guiding the soft-gripper to desired apples within the system's workspace utilizing a low-complexity controller.
- **Gripper Efficacy:** The soft gripper with a thermoplastic polyurethane (TPU) 3D-printed endoskeleton can grasp apples without causing damage to the fruit. Prior versions of this gripper end-effector have achieved successful pick rates of 87% in a field test during the 2023 harvesting season.
- **Gripper Design:** A secondary motor and gear system allows the entire gripper to twist, simulating the twisting motion of a human worker.
- **Gripper Weight:** The gripper is lightweight at 1.10 lbs. and can be mounted to the soft manipulator arm without exceeding the payload limit.
- **Gripper Cost:** Given the current design that does not require costly sensors, the price of one soft gripper unit stands at approximately \$120.

*Objective#3:* Design and implement a low-level controller to achieve automated operation (Luo – Lead, Whiting – Co-Lead).

*This year we focus on the system integration and verification of the robot with on board-perception and gripper in both simulated lab environment and field environment*

*Our current achievement:*

- Our robot is fully functional for picking apples (including single apples on the same plane, at varying depths, and some apple clusters) in a lab-simulated environment.
- Our robot can pick single apples from V-trellis entry trees and drop them into the collection bin.

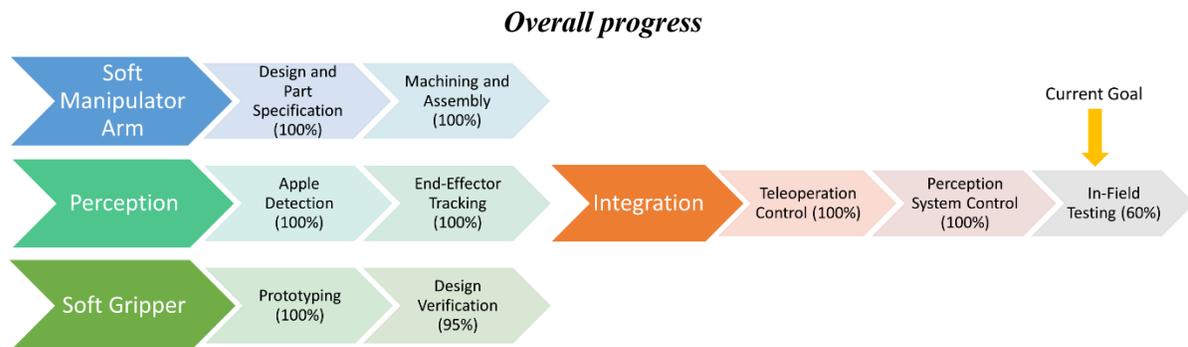


Figure 1. Goals vs. current progress.

### Significant Findings:

*Objective#3:*

- From both lab and field studies, we found that our robot’s motion with payload, perception, and gripper operation did not exhibit any significant errors. This allowed our first year of field testing to successfully grip some apples. We now have a clear plan to further improve our system design to achieve a higher success rate and faster harvesting speed, with enhancements in both hardware and software.

### Methods:

*Objective#3:*

Camera and soft gripper integration: As shown in Figure 2, there are two cameras on the system. One is located at the pressure enclosure and can view all apples in the robot’s workspace. It determines which apples should be harvested first based on their distance from the end effector. The second is a mini camera on the palm, which guides the robot’s end effector toward the desired apples. Our next-generation soft gripper design, which adds an additional servo to achieve twisting motion, making it easier to detach apples from the branch.

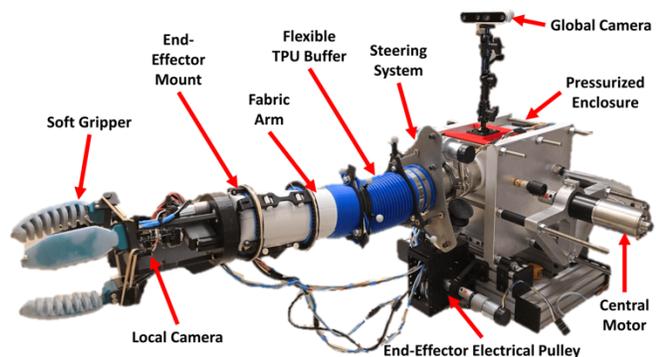


Figure.2 System integration with gripper and cameras.

## Results and Discussion:

### *Objective#3:*

Simulated Lab Environment: Figure 3 shows the experimental setup for lab testing. We used magnets to attach apples to the tree branches.

For single-apple picking, we placed four apples near the corners of the robot's workspace, as shown in the figure.4. The robot was tasked to pick these four apples three times, and all apples were successfully harvested. The average time from starting the pick to dropping the apple into the bin was approximately 24 seconds. These four apples' positions ranged from 2.2 ft to 2.4 ft away from the robot's center.

For multi-apple picking, we set up three case studies, including planar, varying depth, and clusters, as shown in Figure 5. Each test was run three times. In most cases, one apple was dropped due to an unexpected error where the robot's finger pushed the apple away because the perception system could not fully detect the apple's center. The time for picking each apple varied from 20 to 40 seconds, depending on the distance, with apple clusters taking the longest.

We also tested the robot while the tree was moving, simulating a mobile robot carrying the system for apple harvesting. All apples were successfully harvested, with an average harvesting time of 30 seconds per apple.

The harvesting speed is limited by the robot's linear motion and the adjustments made when the gripper closes on the apples. This can be improved through future enhancements in perception and controller design.

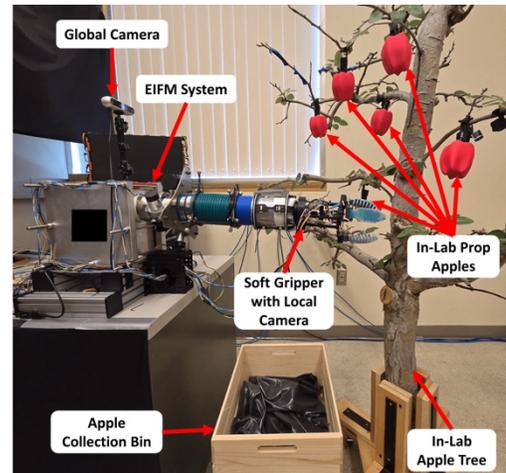


Figure.3 Lab set up

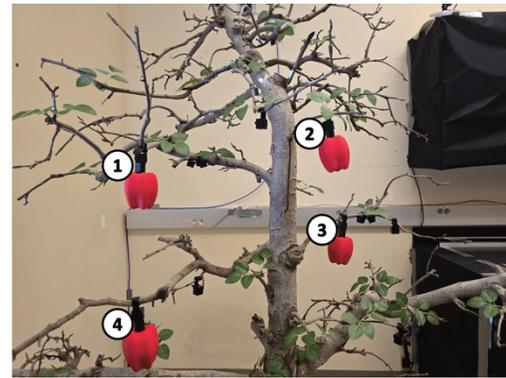


Figure.4 Single apple picking set up

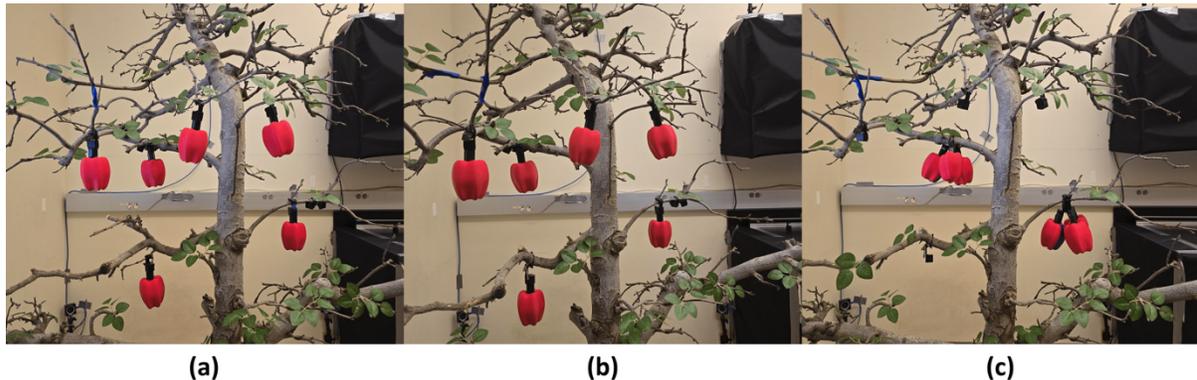


Figure.5 Multi apple picking set up including (a) Planar, (b) Varying Depth, (c) Cluster

In field Study: We deployed our robot system in the Allan Brothers Orchard around mid-October. The trees the system was tested on were the Envy variety vertical V-trellises. We integrated the power

source, pneumatic compressor, and mobile platform. From our observations, the robot is able to position the gripper so that the palm can touch the apple without issues, although the motion is slow, something that can be improved in the future since this was our first demo. The main issue is that the apple easily slides from the palm. We tried adding more twisting motion, which helped significantly. Figure 6 shows one successful picking case. Another concern is that the TPU material used for the exoskeleton may not be stiff enough to securely hold the apple, so we are working on adding more rigid material to the fingers to improve grip.



Figure.6 In the field study, one successful case involved the entire process: initialization, approaching, twisting, detaching, retracting, and dropping.

### Executive Summary:

One of the major challenges facing Washington State tree fruit growers is sourcing adequate labor for critical operations such as harvesting and pruning. To address this issue, many growers and organizations have invested in the development of labor-saving technologies, including robotics. In particular, there has been significant interest in research and implementation of tree fruit harvesting and pruning robots. Our work contributes to this growing field by introducing a novel soft-growing manipulator platform for the orchard environment. Over three years of project development, our soft-growing manipulator has demonstrated the ability to automatically harvest apples in a variety of scenarios using onboard perception in a lab-simulated environment. Furthermore, our first field study has shown the potential to achieve a multi-compact robotic solution capable of picking apples in approximately two seconds each, with low-cost machinery and maintenance that can be adopted by all growers.