Project Title: Apple Harvest End Effector and Apple Transport System

Report Type: Final Project Report

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WTFRC Collaborative Costs:

Budget 1
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Item	2022	2023
Salaries	$67,000.00	$40,000.00
Benefits	$23,100.00	$15,000.00
Wages		
Benefits		
Equipment	$55,900.00	$26,000.00
Shipping		
Supplies		
Travel	$9,000.00	$9,000.00
Plot Fees		
Miscellaneous		
Total	$155,000.00	$90,000.00

Original Objectives and Findings:

The primary objectives of the project were to:

1. Design and build a robotic apple harvester system that included an Apple Harvesting end-of-arm tool, arm structure, and an Apple Harvest Transportation subsystem.
    a. System ROI goal for cost to efficiency targeted at 90-120 days.
    b. Preserve fruit, tree, and bud integrity.
    c. Transport module to prevent bruising or puncturing (limit fruit damage).
    d. Harvesting module fits on commercially available platforms (demonstrated on an Amiga machine by Farm_ng).
    e. Arm control system architecture will support common location outputs using a known computer vision system.
2. Performance of each subsystem is economic feasible:
    a. The end-effectuator has appropriate speed, picking an apple every 3-4 seconds.
    b. The system can perform at least 3 million total actuations between maintenance periods.

Original Proposed System Overview

The original proposal included a focus on two subsystems:
1. The apple transportation system, originally proposed as a wall of conveyor belts designed specifically for apple transport to move the apples from the end effectors to a storage bin.
2. The harvest end effector, or end-of-arm, system, which was envisioned as a grasp and twist mechanism to remove the apple from the tree with a telescoping arm.

In our original proposal, we had envisioned a “wall” with conveyors on the inside to transport apples from the robotic picking arms to the storage bin. During our discovery process, discussed in more detail in the findings below, we determined that the points of failure and robustness challenges of this system were potentially over-complicated and that simpler solutions presented themselves. Through the development of the end-effector, we also found that a telescoping arm presented some mobility limitations, particularly given the unstructured nature of the field-wall. We ultimately developed a system built on a five degree-of-freedom (DOF) robotic platform. By moving from the conveyor and telescoping arm system to a 5-DOF platform, we were able to substantially speed up the system without materially increasing the cost.

Findings

During the two-year effort, we were able to complete approximately 90% of the system while making critical discoveries, and enhancing our fundamental understandings of the system requirements, that we believe will lead to a viable commercial solution. Our solution will be easily adaptable for FLC, small growers, and large growers alike. With the understanding that the price of harvesting utilizing an automated system is heavily dependent upon both human interaction and capital investment, our design efforts were weighted towards these two concerns. To be commercially viable, the operational cost of the machine must be approximately cents per apple; to achieve this, it was critical to push the bounds of both physics and cost. Some of the critical findings of our research were that the passive apple transportation system operates consistently without damaging apples, trees, or buds, and a very inexpensive actuation model was viable. The system would be fully functional operating at full speed while using under 2000W while harvesting a simulated 2.2 apples/second. We have found that these simulated scenarios translate into real world actuation and harvest speeds. The in-field testing of the system, which will be conducted at the end of this season and the beginning of the 2024 season, remains to be completed.

<u>General overview of the mechanical design:</u>

1. **Five Degree of Freedom Robot Platform**: The 5-DOF robot is a multi-actuator design in which the suitability for outdoor use and fast actuation is paramount. This general 5-DOF robot design is known for its high speed and precision, which makes it ideal for quickly positioning the end-of-arm tool to pick apples.
2. **End-Of-Arm Tool** Attached to the 5-DOF robot is a end-of-arm tool that has rapid actuation while maintaining gentle interaction with the apple to be harvested. The end-of-arm tool is specifically designed to mimic the action of a human hand gently gripping an apple while manipulating it.
3. **Sensors and Cameras**: The system is equipped with sensors and cameras that help in identifying apples. In our system, the cameras suggest to an operator the apples to pick, and the operator verifies the apple and provides positive feedback to the machine to pick the apple. In future models any vision system may be adapted to the mechanical system to indicate which fruit to harvest.
4. **Transfer system**: After the apple is picked, the apple slides into a transfer tube on the backend of the gripping mechanism. This tube is a soft, flexible chute that safely guides the apple down to the base chassis system. The design of the tube minimizes the potential for bruising or damage during transport.
5. **Apple collection System**: The base of the harvester contains a bin holding system where the apples are collected after being transported through the tube. This system is designed with cushioning to absorb any impact and prevent damage to the fruit during transport off the field.
6. **Mobility and Navigation**: The entire system is enabled to be mounted on a mobile platform equipped with wheels or tracks that can navigate through orchard rows. The platform can use a localization system to enable optimized route finding if wanted by user.

7. **Power and Control Systems**: The harvester is powered by a combination of batteries and electric motors. The control system, with specialized software, coordinates the movements of the robot arms, the end-of-arm tool, and navigation of the chassis.

The system is developed to be "mobile base" or chassis agnostic, with the ability to mount onto any ground-based robotic or other platform, which provides flexibility to the user.

To validate the fundamental understandings, the team is planning to conduct field trials in late 2023 and/or the 2024 pre-season.

Design considerations and discoveries for the end of arm tool and arm include material for: handling of the fruit, manufacturability, cost, and reliability. The requirements above meet the condition that the end effector actuation achieves a total harvest time per apple per arm of 3-4 seconds. The end effector and arm includes a 5 degrees of freedom (DOF) actuation, and a telescoping tube that is attached to a two-axis gimbal mechanism at its base. Once the apple is selected, and the gimbal mechanism orients the arm, the telescoping tube will extend the end effector to the apple. At this point the end effector will grasp and twist to remove the apple. A full-time budget for the system is developed during our study. Initial calculations show the two processes, closing of the end effector and twisting, are estimated to take 300 - 400 ms per apple.

Field Demonstrations:

Objective: To evaluate the efficacy of the apple harvesting robotic system with a focus on the integrity of the harvested apples, the presence of any fruit or tree damage, and the time the picking motion takes.

Test Environment: The test will be conducted outdoors in Washington state late in the harvesting season or in the 2024 pre-season on test plots in the orchard.

Test Material: A minimum of 25 apples for each motion profile will be used for testing.

Results and Discussion:

We developed three R&D workstreams: the gripper mechanism (end of arm), the robotic arm, and the cost and feasibility of the unit.

The gripper mechanism was developed to facilitate the reliable grabbing of apples with the appropriate force within a 3-dimensional, unstructured field-wall environment. The grippers went through multiple iterations to identify the appropriate materials, shape, and approach dynamics to prevent fruit or tree damage. Early versions of the gripper mechanism used a telescoping arm to place the gripper mechanism near the fruit, mounted on a 2-DOF gimbal mechanism. Further discovery on the dynamics of apple picking from our simulated environment indicated that the use of a 5-DOF system with an integrated end-of-arm tool was both faster from apple-to-apple movement and created a greater verity of paths that can be taken for these apples. This 5 DOF and gripper combination created a much more flexible and operationally robust system.

The cost and feasibility of developing a lightweight, robust, and mobility-base agnostic robotic apple harvesting system hinge on balancing advanced technology with practical design considerations to ensure robustness, low bill-of-materials cost, and adaptability. The agnosticism of the mobile base is a particularly strategic feature, allowing the robotic system to be mounted on various platforms—be it wheeled carts for smaller orchards or larger vehicles for extensive agricultural operations, and ranging from fully autonomous to operator driven—making it versatile across different scales and methods of farming. This feature is possible because of the modularity of both the arm and software system in conjunction to the vision system. This universality not only widens the potential market for such systems but also means that upgrades or replacements of the mobile base can be done independently of the harvesting mechanism, potentially reducing lifecycle and maintenance costs.

Currently our system uses lightweight, low-cost materials and deploys "off-the-shelf" components where appropriate to control total materials and manufacturing costs. The system, as intended for testing, is mounted to a farm_ng Amiga mobile base. While we are currently testing quantity one arms on one robot the system is engineered to have up to 6 on each side of the harvesting platform. Through our discovery process, we found that we can service a 9-foot tree with four arms instead of the originally estimated eight. While we will not be testing with all four on each side, scalability is already built into the software. Once we confirm the in-field efficacy of the mechanical design, we will test one complete side at scale.

Our arm design, after over 20 iterations, has been shown to operate without load for over 1.2M actuations without failure. The Gripper design has been tested to operate an order of magnitude less reliably at 10's of thousand. The main challenges with the current gripper design, beyond robustness, include safely handling the fruit without damage and unintentional interaction with the surrounding fruit. Simulations demonstrate that the likely interactions are within the acceptable tolerances, which we expect to verify via field testing.

Looking Forward.

Automated or semi-automated robotic apple harvesting technology represents a significant advancement in agricultural practices, with benefits for farmers and downstream processors if implemented in conjunction with data collection.

The potential for systemic advancement in orchard harvesting operations through automation is substantial – but the technical challenges are non-trivial. While currently we use an operator-in-the-loop system, the leap to full autonomy requires substantial investments in machine learning, perception systems, real-time decision making, navigation and safety. The physics of delicate, soft-touch robotic arm systems are well known and are widely used in manufacturing and packaging operations globally; however, the environments in which they operate are often highly structured and amenable to pre-determined solutions. Unstructured environments, such as the orchard wall, require substantially more sophistication, including physical systems that interact with the fruit in multiple dimensions, including time, and from multiple angles. Further work is required with growers, processors, and cold storage facilities to understand if the implementation of robotic solutions decreases fruit quality or quantity.

Executive Summary

Title: *Apple Harvest End Effector and Apple Transport System*

Keywords: *Automation, Apples, Harvesting, Low-Cost, Reliability*

Abstract: Milano Technical Group was provided funding to research and develop a robotic apple harvesting system, including an end effector and apple transport system, to reduce in-field harvest operations and labor costs. After a substantial discovery process and many iterations, we determined that a potential multi-objective solution system consists of a five-degree of freedom system with a padded gripping mechanism and actuating arm, which allows for freedom of fast movement in multiple dimensions. The system is mobile base agnostic and will be tested using an Amiga from farm_ng. Where feasible, the system was built with off-the-shelf and low-cost parts to minimize build and maintenance costs. We estimate that each arm can retrieve an apple every 3 to 4 seconds and actuate between 1 and 2 million times between major maintenance periods.