**FINAL PROJECT REPORT**
**WTFRC Project Number:** TR-07-704

**Project Title:** Automated picking hand development


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| **PI:** | Tony Koselka | **Co-PI:** | Derek Morikawa |
| **Organization:** | Vision Robotics Corp | **Organization:** | Vision Robotics Corp |
| **Telephone/email:** | 858-523-0857 | **Telephone/email:** | 619-200-4865 |
| | tkoselka@visionrobotics.com | | dmorikawa@visionrobotics.com |
| **Address:** | 11722 Sorrento Valley Rd | **Address:** | 11722 Sorrento Valley Rd |
| **Address 2:** | Suite H | **Address 2:** | Suite H |
| **City:** | San Diego | **City:** | San Diego |
| **State/Province/Zip** | CA 92121 | **State/Province/Zip:** | CA 92121 |

**Cooperators:** Dr. David Barrett at Olin College of Engineering


**Other funding Sources**

**Agency Name:** California Citrus Research Board
**Amount requested or awarded:** $27,500
**Notes:** The project is being worked on as part of the SCOPE program at Olin College

**Total Project Funding:**

**Budget History:**

| **Item** | **Year 1:** |
|---|---|
| **Salaries** | |
| **Benefits** | |
| **Wages** | |
| **Benefits** | |
| **Equipment** | |
| **Supplies** | |
| **Travel** | 2500 |
| | |
| | |
| | |
| **Miscellaneous** | 25,000 |
| **Total** | **27,500** |

## OBJECTIVES

The Washington Tree Fruit Research Commission, VRC, and individual growers all recognize that the development of the picking hand remains a significant risk factor in the development of the robotic fruit harvester. This picking hand, or end effector, must individually remove every apple from a tree and deposit it a conveyor system. It must be so gentle that it does not damage the apple it is picking, shaped such that it does not bruise any apple it pushes past, and either snap or cut the stem as appropriate. It must operate very fast, about half a second on average, to pick each apple once the hand is positioned near it and perform millions of picks per year. Ideally, it can pick apples ranging in size from Ø2" – Ø4" whether the fruit hangs straight down or rests against a branch or another apple. The capability of these hands is essential to a viable Automated Robotic Harvester. In 2007-2008, the Washington Tree Fruit Research Commission, Vision Robotics, the California Citrus Research Board and Olin College collaborated on this essential task.

The Olin Team worked to create a versatile end effector for harvesting oranges and apples. Their goal was to consider:

- fast operation,
- gentle holding of the fruit,
- snapping and cutting the orange stem as appropriate, and
- easy transfer to the fruit handling system.

The final objective was a conceptual prototype demonstrating the harvesting of apples and oranges in realistic conditions.

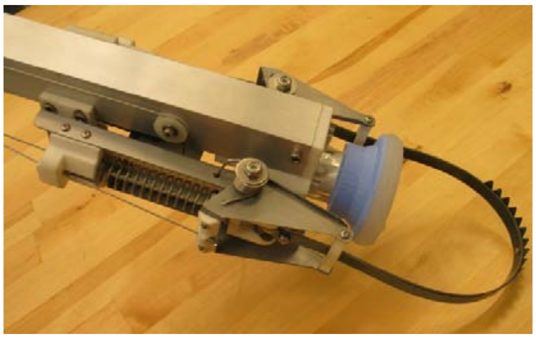
## SIGNIFICANT FINDINGS

Being a school project, it picking hand project was completed at the end of the school year in May. The Olin team prepared a final report and video of the prototype, which have been forwarded to the Commission. In addition, a provisional patent application has been filed for the key technical ideas including the concept of a suction cup holding mechanism coupled with a moving hoop (cutter) to sever the stem. VRC anticipates completing a full patent application by the end of the calendar year.

The team followed a design process that began with extensive research on current technologies and prior art that is relevant to fruit harvesting. This background research provided insight for several levels of ideation, which carried ideas from crude sketches into three-dimensional sketch models. A series of field tests enabled the team to collect data about the forces involved in harvesting fruit, the orientation and location of the fruit, and to define the major difficulties associated with harvesting. The field tests also enabled an iterative process of testing, debugging and refining the picking hand.

During the second half of the project, the team developed a series of functional prototypes and a test environment that simulates conditions in both apple orchards and orange groves. The significant findings include:

- There is a significant body of prior work applicable to picking hands that can be separated into two broad categories: mechanical aids for fruit harvesting and handling, and non-fruit picking robot end effectors.
- The end effector for mechanically picking tree fruit can be broken into two distinct functional tasks, holding the fruit and removing the fruit from the tree.
- The team identified five plausible ways to hold the apples:
    1. Tube
    2. Pouch
    3. Suction
    4. Flex-fingers
    5. Jointed fingers



- The team identified four plausible methods to reliably remove fruit from the tree:
    6. Lifting (snapping)

7. Noose
8. Jaws
9. Single jaw

- Using a selection matrix, the team selected a design direction incorporating high flow suction with a single jaw (hoop) for the picking hand.
- Unit tests confirmed that the approach can hold apples without bruising and that the single jaw can both snap and cut the stems.
- Preliminary tests suggest that this design will work for most fruit including a variety of sizes and those in clusters.
- Suction for grasping
  - High flow suction system allows for gripping of any size fruit even in the presence of obstructions
  - Suction gripping systems does not bruise fruit even in the presence of small obstructions
- Hoop pivots around fruit to sever stem from tree
  - Sizing mechanism allows for various fruit sizes
  - Can snap stem or cut for removal
- End effector can assume a low profile for effective tree penetration
- Through a series of tests, the prototypes demonstrated the capability of picking apples in the lab.

- The single jaw implementation probably needs refinement.
- The prototype was not tested in orchards to confirm that the system can pick all apples regardless of the position on the tree and the orientation of the stem relative to the ground and the approach vector of the arm.
- Preliminary tests indicate that the concept does not bruise apples.
- The Olin team provided a detailed final report and video that has been forwarded the commission.

## RESULTS AND DISCUSSION

The Washington Tree Fruit Research Commission (WTFRC) has been working with Vision Robotics (VRC) on robotic mechanization for various labor-intensive operations on fresh fruit trees. This project includes two types of robots, the Scout and the Picker/Pruner. The work is based on a similar project for the California Citrus Research Board (CRB), which has enabled significant progress on the conceptual design, vision system and software algorithms.

The feasibility of the Picker robot is predicated on the development of a viable end effecter (picking hand) for removing the fruit from the trees, which growers and other interested parties have long recognized this as a critical subsystem that does not have a current solution. In order to pick tree fruit, the robot's picking hand must quickly, but gently grasp the fruit and remove it from the tree using the appropriate techniques for apples, citrus and other tree fruit. The hand must also facilitate easy transfer to the fruit handling system that conveys the individual pieces to the bin. A successful design must operate in all appropriate environmental conditions, be robust, have a manufacturing cost of $250 or less in production quantities, and be serviceable by typical farming techniques.

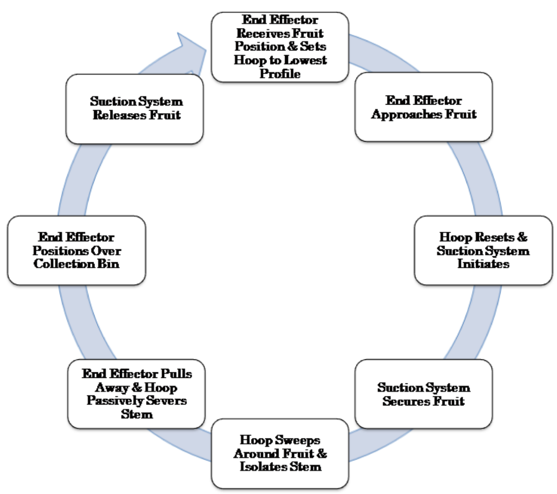
Franklin W. Olin College of Engineering is a new engineering college that is dedicated to producing technological leaders for the future. From day one, the students learn by tackling open-ended engineering projects that demand technical excellence, creativity, risk-taking, communication skills, teamwork and personal initiative. The Senior Consulting Program for Engineering (SCOPE) is the culmination of Olin's project-based curriculum. In SCOPE, students undertake an authentic engineering challenge for an actual corporate sponsor, funded through an educational grant from the sponsoring company. Each project fields a team of five students who spend one-fourth of their senior year working on the project over the course of two semesters.

The Vision Robotics SCOPE Team is an interdisciplinary group consisting of five students, Conor Frackleton, Maria Firstenberg, Simone Sequeira, Eugene Kozlenko and Joe Roskowski, and Benjamin Linder, the team's faculty advisor.

The team  was tasked with developing a strategy for the removal of tree fruit and demonstrate a prototype that shows potential to be economically viable for harvesting fresh oranges and fresh apples. The final prototype end effector was mounted on an arm that will be manipulated by a human operator, but all motions of the end effector are automatic. The team create a test environment that consists of an artificial tree that approximates conditions found in the field. The demonstration and prototype design will pick both apples and oranges in conditions relevant to each.

The team performed extensive research on current technologies and prior art and experiments and calculations to determine the forces required for harvesting apples, the orientation and location of the fruit, and the major difficulties with mechanical harvesting. Several levels of ideation carried ideas from crude sketches into three-dimensional sketch models. The team analyzed the various ideas to determine the most promising design for minimizing fruit damage, picking at a wide variety of orientations, dealing with small obstructions, and picking a variety of sizes and selected the combination of a suction mechanism for holding the fruit and a single jaw for severing the fruit stems. In short, the project yielded a prototype picking hand that is a very good starting point.

The background research, brainstorming and early tests were chronicled in the December progress report. Based on this information, the team created a flow diagram for the mechanical harvesting picking hand requirements.




The team used a selection matrix approach to identify the best approach keeping I mind that the single most critical factor for apples the delicateness of the fruit.

**Removal Mechanisms**

| **Criteria** | **Weight** | **Lifting** | **Noose** | **Jaws** | **Single Jaw** |
|---|---|---|---|---|---|
| Minimal Fruit Damage | 5 | 0 | 0 | -1 | 1 |
| Implementation Feasibility | 3 | 0 | -1 | 0 | 0 |
| Effective for Range of Fruit Orientation | 3 | 0 | -1 | 0 | 0 |
| Ability to Reach Fruit | 4 | 0 | 1 | 0 | 1 |
| Severs Stem from Branch | 5 | 0 | 1 | 1 | 0 |
| Retains Fruit | 5 | 0 | 0 | 0 | 0 |
| Minimal Fruit Damage to Neighboring Fruit | 2 | 0 | 0 | 0 | 0 |
| Variable Fruit Size | 3 | 0 | 0 | -1 | 0 |
| | **Total** | 0 | 3 | -3 | **10** |

**Holding/Grasping Mechanisms**

| **Criteria** | **Weight** | **Tube** | **Pouch** | **Suction** | **Flex Fingers** | **Joint Fingers** |
|---|---|---|---|---|---|---|
| Minimal Fruit Damage | 5 | 0 | 1 | 0 | -1 | -1 |
| Implementation Feasibility | 3 | 0 | 0 | 1 | 0 | 0 |
| Effective for Range of Fruit Orientation | 3 | 0 | 1 | 1 | 1 | 1 |
| Ability to Reach Fruit | 4 | -1 | -1 | 0 | 0 | 1 |
| Severs Stem from Branch | 5 | 0 | 0 | 0 | 0 | 0 |
| Retains Fruit | 5 | 0 | 0 | 1 | 1 | 1 |
| Minimal Fruit Damage to Neighboring Fruit | 2 | -1 | 1 | 1 | 0 | 0 |
| Variable Fruit Size | 3 | -1 | 1 | 0 | 1 | 0 |
| | **Total** | **-9** | **9** | 13 | 6 | **7** |

The proposed harvesting method consists of a suction system that grips the fruit and a single baling hoop (jaw) that passes around the fruit to break the stem. Although suction is commonly used to manipulate fruit in packing houses, it has been implemented only minimally in harvesting applications. Additionally, suction has not been implemented in conjunction with a single baling hoop. One strength of this design is that the baling hoop is can locate and break/sever the stem in a wide variety of orientations of the fruit relative to the end effector. Additionally, the hoop with suction implementation is able to move into a low profile configuration for penetrating the tree canopy.

Harvesting fresh fruit using the team's current end effector requires several stages of motion. Initially, the end effector is moved into position by a robotic arm while being collapsed into the low-profile penetration mode. This mode consists of retracting the baling hoop to its smallest configuration and positioning it directly in front of the suction cup. When the end effector is within an inch of the fruit, the hoop drops to the bottom of its configuration. With the hoop out of the way, the arm moves toward the fruit until the suction cup secures it. At this point, the hoop traces the contour of the fruit by approximating the fruit shape as a sphere. As the hoop passes around the fruit, it locates the stem of the fruit regardless of the fruit's orientation relative to the end effector. After completing its path around the fruit, the hoop tightens down to a small configuration above the fruit and the arm pulls the end effector out of the tree. As the fruit is pulled away from its branch, the stem is bent around the hoop and breaks or is severed. After successfully removing the fruit from the tree, it can be deposited into a receptacle by turning off the suction.

The current picking method requires that the end effector is approaching the fruit such that the stem is located on the top hemisphere of the fruit. If the approach has the hoop come into contact with the stem on the lower hemisphere of the fruit, the hoop could push the fruit out of the suction cup. To prevent this scenario, the end effector can rotate 180˚, positioning the stem in the appropriate hemisphere. This implementation requires some amount of sensing.

The team also identified a number of possible enhancements. The suction system could be set to blowing air rather than sucking during the end effector's approach to the fruit. The intent of blowing air over the fruit would be to remove any dust that may be coating the fruit and to push small obstructions out of the way. Two hoops could be implemented rather than one. In this case, a hoop could move around the fruit starting at the bottom while another hoop starts at the top. This could facilitate a stem cutting mechanism that operates when the two hoops come together rather than depending on the motion of the arm to break or sever the stem. The remainder of this report details the features of the current design and specific design.

**Scalable Baling Hoop**

During the orchard visits, the team attempted to determine how much force was necessary to remove apples by pulling a force meter across the stems until they broke from the shear stress. This method simulated the technique used by pickers. These values determine the range of forces that the end effector will need to generate to separate fruit from a branch and are helpful for calculating the pressure that will be applied to an apple's skin by the end effector. Apples require forces ranging from 5 N to 40 N to remove from the tree. In addition, the team's preliminary testing indicated that the preferred design could be implemented without bruising the apples.

The team found a number of harvester designs using a single fixed diameter jaw that sweeps around a fruit in order to sever the stem. The team's design is different from these fixed jaw designs in that the hoop can be scaled to any number of sizes, which enables the hoop to contour to the shape of a wide range of fruit sizes. The benefit of this design is that it is far more versatile. The hoop's ability to closely follow the surface of fruit also enables the end effector to pick fruit from clusters by passing the hoop between fruit. An added benefit of a scalable hoop is that it permits the end effector to maintain a low profile while approaching fruit as described in the previous sections.

In its present configuration, the hoop is constructed of five layers of spring steel. Each layer of spring steel is ten thousandths of an inch thick and three eighths of an inch wide. The layered approach was taken because the hoop needed to be flexible in one direction while rigid in the other. The bands are secured to one another at three points - at each end and at the center. Each end of the hoop is secured to a slider that controls the arc length of the hoop and a slot that controls the width of the hoop. The sweeping motion of the hoop is controlled by a third degree of freedom that moves both arms simultaneously. In order to cut a stem, one of the layers has a series of sharpened notches which facilitate severing the stem.

During tests, the team found that while the specific implementation moved the hoop in an arc around the apple, the sharp surface did not always remain perpendicular to the stem, which made it difficult to cut or snap the stem depending on the apple orientation. Potential enhancements include:

- Active cutting could be implemented in the hoop to ensure more reliable results.
- Using a range of different end effectors, each with a different sized fixed diameter hoop could also be effective in harvesting for the required size range. In this scenario, the harvesting robot would use a specific end effector depending on the size fruit it is picking. Changing the end effectors could occur in the field if a variety of sizes were stored on the harvesting robot.

**Padded High-Flow Suction System**

Suction has been used in many different food related handling applications, including fruit handling in packing houses. However, the use of high flow suction in harvesting has not been seen. A high flow system allows for the fruit to be gripped during manipulation while still on the tree without risk of suffering pressure damage. Additionally, the high flow system is able to retain a fruit even if the seal is imperfect – allowing a single system to be used for multiple varieties of fruit. Small obstructions can also be picked up along with the fruit without risking the integrity of suction system's grip. To ensure that the fruit is not bruised during the gripping process, the interface between the suction system and the fruit is padded by a suction cup.

One refinement to the typical configuration is a slippery suction cup. Suction cups are often used as the last point of contact between a system and an object to be handled. The team has not seen applications that include a low-friction contact surface in fruit handling. Adding a low friction surface to the suction cup allows for the fruit to enjoy additional freedom of movement without compromising gripping suction. In practice, this means that the fruit will be allowed to self-align as the arm pulls out of the tree so that the stem is in line with the arm. In addition, the ability of the fruit to pivot within the cup prevents the torque on the stem caused by contact with the hoop from forcing the fruit out of the suction cup.

The prototype suction cup is a two part silicone composite. The main body of the cup is made of RTV silicone of Shore hardness 60. The rigidity of this portion keeps the fruit in one place, in line with the body of the end effector, once it is obtained so that it can be effectively manipulated by the hoop. The lip of the cup is made of a soft silicone of Shore hardness 30. As this portion of the cup actually comes into contact with the fruit, it is soft to prevent bruising damage and to provide compliance that allows for irregularly shaped fruit or obstructions. Silicone is the material of choice because it is durable and resistant to oil, grease, and ultraviolet light. The slippery feature of the suction cup is provided by PTFE tape applied to the lip of the cup. This effectively creates a low-friction surface on which fruit can slide.

The geometry of the suction cup starts out with a smaller diameter of approximately one inch near the end effector and flares out into a larger diameter of approximately one and three-quarters of an inch where the fruit will be held. This larger diameter is necessary for airflow that is sufficient to hold on to fruit effectively. The lip of the cup is relatively thick to provide sufficient padding and compliance.

Several urethane foams have been explored as padding material. Foam is a promising material because the airflow from the suction system is able to move through the pores of the foam which effectively increases its total area, and thus its gripping power on the fruit. It is important to ensure that a skin covers the exterior sides of the suction cup to prevent air flow out the sides of the cup. Foam also provides excellent compliance which reduces the bruising of fruit on contact or if obstructions are obtained in addition to fruit. The major concern with foam is its susceptibility to the dirty environment of orchards and groves which would likely necessitate frequent replacement.

Different suction cup geometries could also be used. A thin lipped design, such as those of suction cups found in orange packing houses, could allow for similar gains in compliance to prevent fruit bruising. Different designs could also be explored if it is found that more compliance is needed in the suction cup itself, that is, if movement of the fruit on the axis of the end effector is helpful as the fruit is obtained. For example, a single bellow design that collapses down when the fruit is obtained could provide this compliance.