**FINAL PROJECT REPORT**

**Project Title:** Evaluation of vacuum as a picking mechanism


**PI**: Curt Salisbury, Ph.D.
**Organization**: SRI International
**Telephone**: 650.859.5050
**Email**: curt.salisbury@sri.com
**Address**: 333 Ravenswood Ave
**Address 2**: EL194
**City/State/Zip**: Menlo Park, CA 94025

**Co-PI (2):** Rich Mahoney, Ph.D.
**Organization**: SRI International
**Telephone**: 650.859.6126
**Email**: rich.mahoney@sri.com
**Address**: 333 Ravenswood Ave
**Address 2**: EL196
**City/State/Zip**: Menlo Park, CA 94025


**Cooperators**: None

**Total Project Request:** **Year 1: $98,987 (ROM, assuming directed gift)**

**Percentage time per crop:** Apple: 50% Pear: 30% Cherry: 10% Stone Fruit: 10%

**Other funding sources**

**Agency Name:** SRI International
**Amt. awarded:** $100,000
**Notes**: Internal Research and Development funds to support this effort

**WTFRC Collaborative expenses:** None

**Budget 1**
**Organization Name: SRI International** **Contract Administrator: Mitesh Patel**
**Telephone: 650 859 2709** **Email address: mitesh.patel@sri.com**

| Item | 2014 |
|---|---|
| Salaries | $74,698.00 |
| Benefits | |
| Wages | |
| Benefits | |
| Equipment | $19,500 |
| Supplies | |
| Travel | $4,789.00 |
| Miscellaneous | |
| Plot Fees | |
| **Total** | **$98,987.00** |

**SRI will use a subcontract mechanism to avoid overhead charges*

## RECAP OF ORIGINAL OBJECTIVES

The objectives of this research were to:

1. Develop a vacuum-based end effector for picking fruit
2. Experimentally validate the effectiveness of the vacuum-based end effector

Careful study of the picking process from a robotics perspective suggests to us that a vacuum-based end effector would be the most successful at enabling the 2-pick per second performance requirement without damaging or dislodging the target fruit, adjacent fruit, or the tree. The vacuum-based end effector could avoid the pathologies of a grasping end effector. This is built around a powerful vacuum system (~30 hp) wherein the suction flow pulls the nearest apple to the suction nozzle, separates the apple from the tree, and then passes the apple through the nozzle to a subsequent conveyor (see Figure 4 below). This concept has the critically important advantages of: 1) enabling the picking of apples by contacting only the front surface of the apple and 2) realizing successful picks even with position errors of the end effector.

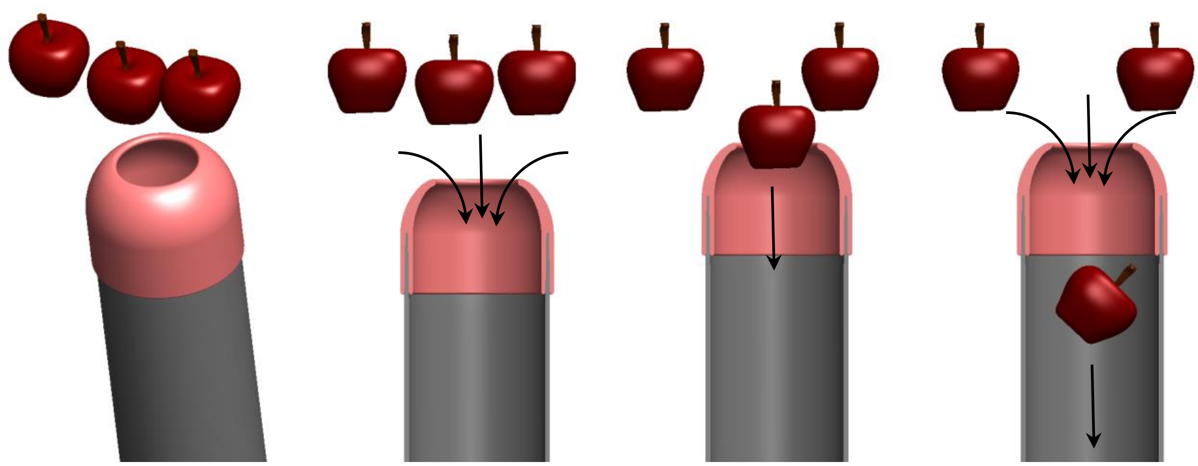

**Figure 1 Vacuum-based end effector - method of operation**

SRI International proposed to build and test this end effector concept. We evaluated the ability of the concept to separate an apple from a tree, and got a sense for both the tolerable positioning error and distance to apple when the apple separates from the tree as a function of vacuum power. We will also evaluated the location along the stem at which apple separates from the tree – characterizing the percentage of apples that have stem pulls, separations at the abscission, and separations closer to the tree.

## SIGNIFICANT FINDINGS

The significant findings from this work were:

- High-flow vacuum can apply forces at a distance to apples
- High-flow vacuum can remove apples from a tree with 100% success (given a properly sized nozzle)
- High-flow vacuum can remove apples without disturbing or damaging adjacent apples

- High-flow vacuum was shown to do a reasonable job of separating the stem at the abscission – but needs further development to improve the likelihood of stem separation at the abscission.

## RESULTS & DISCUSSION

SRI International conducted an evaluation of the general concept of a vacuum end effector in 2014. Our first evaluation was to observe the vacuum force applied to an apple as a function of proximity of the apple to the vacuum nozzle. The experiment was conducted with a 60 hp vacuum, a 4 inch vacuum nozzle, a plastic apple with a 3” diameter, and a force sensor mounted to a linear guide. The linear guide was adjusted and the force observed (See Figure below). We noted that the force on an apple exceeded 4 lbs before the apple crossed the front plane of the nozzle. We further noted that the maximum pull force on the apple was approximately 35 lbs – high enough to guarantee the removal of an apple from a tree.

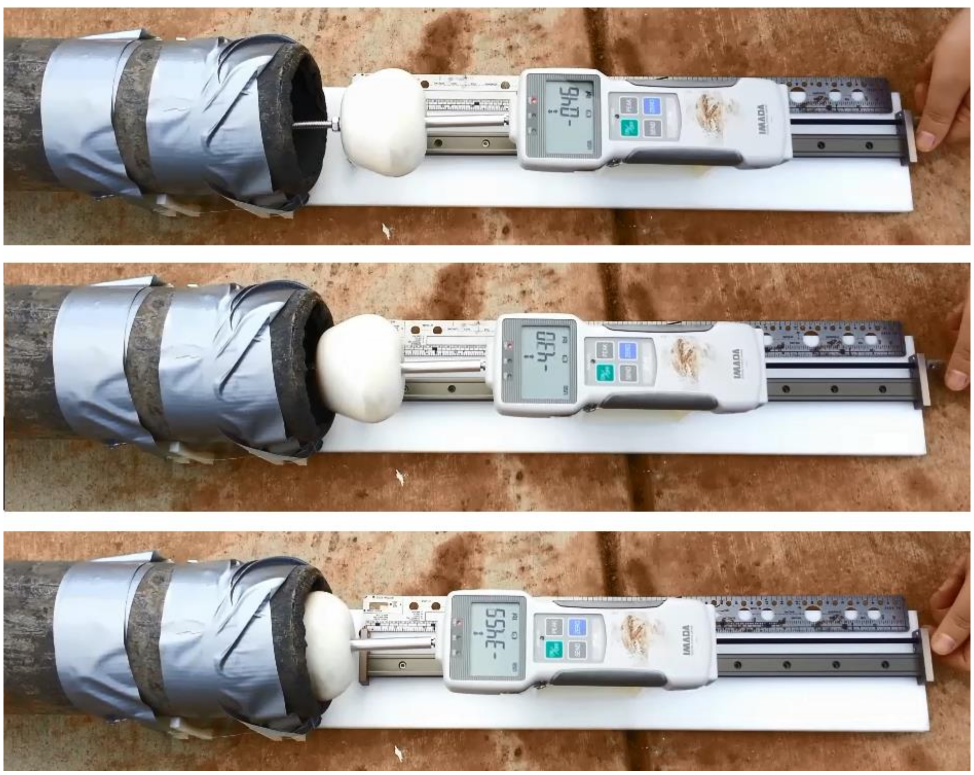


**Figure 2 Vacuum pull force test on a 3" apple**

Our second experiment entailed determining how many spur pulls and stem pulls a simple nozzle design would cause. We created an elastic webbing a few inches from the end of the nozzle to catch the apples after they separated from the tree (See figure below). We then removed 120 apples from 5 different varieties of trees with vacuum and observed the number of stem pulls and spur pulls induced by the removal method. The results showed 7% spur pulls and 38% stem poles. Only 2% of the total picked apples had stem pulls that resulted in flesh tears.

**Figure 3 Vacuum tube showing elastic webbing in black and the apple captured by the webbing**

**Table 1 Stem separation results from vacuum removal**

| variety | nozzle type | Picked | spur pull | stem pull | |
|---|---|---|---|---|---|
| **Gala** | taper | 20 | 3 | 11 | - |
| **Honeycrisp** | none | 21 | 1 | - | - |
| **Granny Smith** | taper | 22 | 1 | 20 | - |
| **Fuji** | taper | 20 | - | 3 | 1* |
| **Jazz** | taper | 19 | - | 6 | - |
| **Jazz** | none | 18 | 3 | 5 | 1* |
| | | **120** | **8** | **45** | **2*** |

*flesh tears

We consider these results to be encouraging, especially if it can be shown that stem pulls which do not result in flesh tears do not result in culls. We anticipate, however, that with some straightforward modifications to the nozzle design, we can significantly reduce the number of spur pulls and stem pulls.

The final experiment of the 2014 funded effort was to determine whether or not we can separate apples from the tree at a rate of 2 per second with this end-effector concept and separate an apple next to another without damaging or dislodging it. We found that we could indeed separate apples from the trees at a rate of 2 per second. We also found that we could pick apples from a cluster of apples without damaging or disturbing adjacent apples. The figure below shows a progression of picking an apple from a tree with that is touching another apple (to the right).

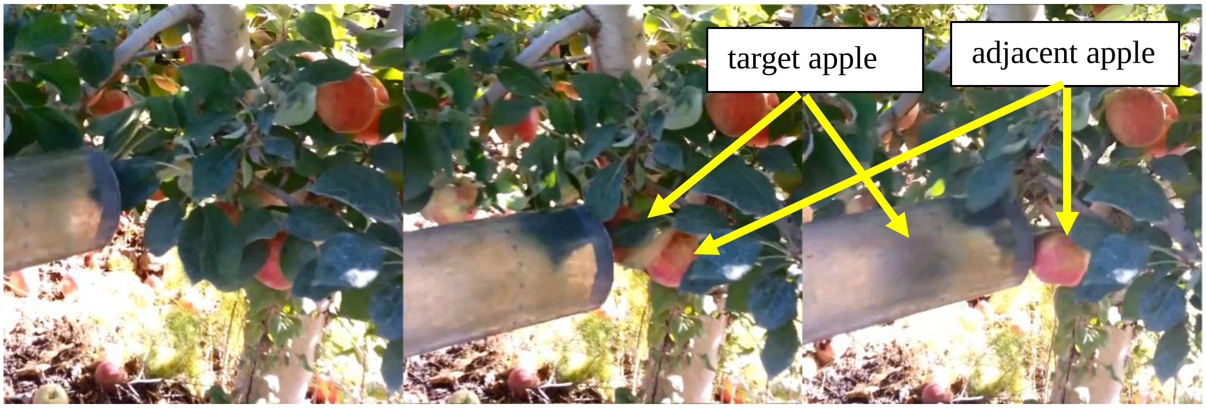


**Figure 4 Apple removal without disturbing adjacent apple**

Based on these results, we are confident that this concept is viable for an end effector for vacuum picking.

## Significance to the Industry and Potential Economic Benefit

Gross sales of apples[1], pears[2] and cherries[3] in Washington state approach $2B annually. Labor costs are approximately $500M, or 30% of gross sales and 60% of the variable costs. Picking alone costs Washington growers approximately $200M annually, or 8% of gross sales and 16% of the variable costs. While picking costs are a relatively small percentage of the total costs of a crop, they put the full revenue value of the crop at risk – a problem exacerbated by an unstable labor supply. Both the cost and risk of labor could be addressed by an automated picking system. Historically, automated systems have been unable to compete with the selectivity, yield (in terms of picker-caused mechanical damage), and *1.5¢ per pick cost of labor*. Recent developments, however, in both cultural practices and automation technologies might finally enable an automation solution to competitively pick orchard fruit.

The effective cost per pick of an automated system is a function of the machine purchase cost, machine operating cost, and the number of fruits the machine can pick over its useable lifetime. In order to reduce the cost per pick of the system, the designer needs to focus on reducing the machine purchase, reducing the machine operating cost, increasing the life of the machine, and increasing the number of fruits the machine can pick over that lifetime.

Given the assumptions shown in table 1, a machine which costs $522,000 (less operating costs) will have a payback period of 3 years if each robot arm can pick 2 fruits per second. If, however, the machine can only do 1 fruit per second, the payback period will be 6 years – too long for a business to successfully raise investment capital. The work done to date suggests that picking at a rate of 2 picks per second per arm is feasible, but needs one more round of development.

---

[1] http://cru.cahe.wsu.edu/CEPublications/FS005E/FS005E.pdf
[2] http://cru.cahe.wsu.edu/CEPublications/FS031E/FS031E.pdf
[3] http://www.tfrec.wsu.edu/pdfs/P569.pdf

**Table 2 Picking machine economics and performance requirements**

| | |
|---|---|
| | **APPLES PRODUCED PER FARM** |
| 160 | acres per farm (example farm) |
| 50 | bins of apples produced per acre per year |
| 80,000 | apples per acre |
| 12,800,000 | apples per farm |
| | **COST OF PICKING - PER APPLE** |
| $0.0144 | cost of human labor to pick a single apple ($) |
| $184,000 | cost of human labor to pick all apples per farm |
| | **MACHINE COST** |
| **$552,000** | **3 year payback period** |
| | **HARVEST MACHINE PICKING PRODUCTIVITY** |
| 11 | days to pick a single farm |
| 1,152,000 | apples picked per day by 1 machine |
| 16 | hours worked in a day per machine |
| 10 | number of robot arms per machine |
| **2** | **apples picked per second by 1 robot arm** |

# EXECUTIVE SUMMARY

## SIGNIFICANT FINDINGS

Careful study of the picking process from a robotics perspective suggests to us that a vacuum-based end effector would be the most successful at enabling the 2-pick per second performance requirement without damaging or dislodging the target fruit, adjacent fruit, or the tree. SRI International conducted an evaluation of the general concept of a vacuum end effector in 2014.

The significant findings from this work were:

- High-flow vacuum can apply forces at a distance to apples
- High-flow vacuum can remove apples from a tree with 100% success (given a properly sized nozzle)
- High-flow vacuum can remove apples without disturbing or damaging adjacent apples
- High-flow vacuum was shown to do a reasonable job of separating the stem at the abscission – but needs further development to improve the likelihood of stem separation at the abscission.

Based on these results, we are confident that this concept is viable for an end effector for vacuum picking. The tasks that remain are the focus of the proposed work and will address refining the concept to meet industry specifications.

## FUTURE DIRECTIONS

The proposed research will build upon results obtained from research funded in 2014 by the WTFRC.

The proposed research will:

1. **Refine the nozzle design** to reduce stem pulls, spur pulls and mechanical damage to below 5%
2. **Develop a decelerator** which enables fruit to be decelerated in a continuous fashion from the high-speed vacuum flow rates to conveyance flow rates – ensuring minimum additional culling.
3. **Integrate the End-Effector on a Commercial Robot Arm** to mature the nozzle, decelerator, and vacuum tube design so they are tightly integrated to a commercial robot arm
4. **Demonstrate Integrated Manipulation Solution** in the field and show the ability to pick apples at a rate of 2 per second per arm with less than 5% system-induced culls. (Note that this will demonstrate the manipulation subsystem only and will not yet be integrated with the vision subsystem)

These results will constitute a significant milestone towards both public and private fund raising for commercialization of the solution.