FINAL PROJECT REPORT

Project Title: Refinement/integration of vacuum-based end effector for fruit picking

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Cooperators: N/A

Total Project Request: **Year 1: $300,000 (ROM)**

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

Other funding sources

Agency Name: SRI International
Amt. awarded: $425,000
Notes: Internal Research and Development funds to support this effort

WTFRC Collaborative expenses: $15,000

Budget 1
Organization Name: SRI/Abundant **Contract Administrator: Dan Steere**
Telephone: 650 868 8467 **Email address: dan@abundantrobotics.com**

Item	**2015**
Salaries	$160,000
Benefits	
Wages	
Benefits	
Equipment	$120,000
Supplies	
Travel	$20,000
Miscellaneous	
Plot Fees	
Total	**$300,000**

ORIGINAL OBJECTIVES

The original objectives of the 2015 funded research were:

- **Refined the nozzle design**
    a. The first proposed refinement to the nozzle design was aimed at reducing stem pulls and spur pulls.
    b. The second refinement to the nozzle design focused on minimizing damage caused to the body of the apple by the nozzle.
- **Developed an ultra-compact decelerator**
    a. Because the flow rates needed to apply a pull force on an apple from a distance are high, the speed of the apple once it enters the nozzle is exceptionally high. We proposed to develop a mechanism to decelerate the apples without bruising them.
- **Integrated the End-Effector on a Commercial Robot Arm**
    a. We proposed to integrate our end-effector with a commercial robot arm to ensure that our end-effector design is compatible with a robot arm and to facilitate a demonstration of the manipulation subsystem.
- **Demonstrated Integrated Manipulation Solution**
    a. We proposed to take the integrated test platform into the fields during 2015 harvest to evaluate its performance and demonstrate the system to the commission and growers.

SIGNIFICANT FINDINGS

The significant findings from our 2015 activities were:

- **Refined the nozzle design**
    a. We commissioned a careful study of the effect of pulled stems on apple storage life.
    b. We moved the urethane-polycarbonate interface to a location that would not cut the apples.
- **Developed an ultra-compact decelerator**
    a. We identified memory foam as a material with preferred viscoelastic properties for decelerating apples without bruising them.
- **Integrated the End-Effector on a Commercial Robot Arm**
    a. We integrated our end-effector with a commercial robot arm and a 3D stereo sensor developed by Carnegie Melon University and showed that our end-effector design is compatible with a robot arm.
- **Demonstrated Integrated Manipulation Solution**
    a. We tested autonomous picking in 7 different orchards in 2015, demonstrated the system to growers and the commission, and gathered data on a subset of the autonomously picked apples.

RESULTS AND DISCUSSION

Refine the nozzle design

<u>Stems</u>

The first proposed refinement to the nozzle design was aimed at reducing stem pulls and spur pulls. Early in the performance phase, we discovered that a couple of small experiments had been conducted to determine the effect of stem pulls on apple decay in storage. The results suggested that there might be little to no difference in decay between apples with an intact stem and apples with pulled stems. Rather than invest resources in minimizing the machine-induced stem pulls, we instead took the preliminary step of commissioning a formal experiment across multiple varieties to determine the effect of pulled stems on fruit decay in storage.

A postharvest study is currently underway to evaluate the quality of stored apples that were harvested without stems. In the fall of 2015, five bins of Granny Smith, Jazz, and Pink Lady, and six bins of Fuji (three of first pick and three of second pick) were harvested with an approximate ratio of 50:50 stem-on to stem-off. Photos of the test groups are shown in Figure 1 below. The test bins were placed on trailers with 'normal' fruit, bound for storage facilities. Test bins were placed randomly on a trailer and multiple trailers were used for each variety. Test bins were drenched using Scholar fungicide. Drench cycle number was recorded. Currently, the apples are in CA storage and will be evaluated alongside 'normal' harvested bins of fruit. Each bin will be evaluated for stem bowl rot or other defects attributed to a stemless condition. Evaluation is expected to start in March after approximately six months of storage.

Figure 1 Photos of Fuji apples included in our experiment to determine the effect of pulled stems on the decay of apples in storage. Note apples with stems and apples without stems in the image on the right

<u>Damage reduction</u>

The second refinement to the nozzle design focused on minimizing damage caused to the body of the apple by the nozzle. The nozzle used during the 2014 field trials was a urethane extension on a polycarbonate tube. The transition between the urethane and the polycarbonate was abrupt and caused some cuts and indentations to the apple. We moved this transition to be just beneath the urethane orifice. This put the sharp edge transition in a place that the apple could not contact.

Develop an ultra-compact decelerator

We determined that the least expensive, most reliable, and most compact decelerator would be a monolithic piece of viscoelastic foam. The viscous property decelerates the apple without causing the apple to bounce back at a high rate of speed, and the elastic element enables the material to restore its shape before the next impact. It was important to find a material with the right balance between these two properties. We found that Memory foam had the right balance of viscous and elastic properties. Originally developed by NASA for improved seat cushions, this material does an excellent job of distributing contact forces across the surface of the apple, and quickly decelerating the apples without bruising them. Initial experiments were conducted by dropping apples from a 19 ft height.

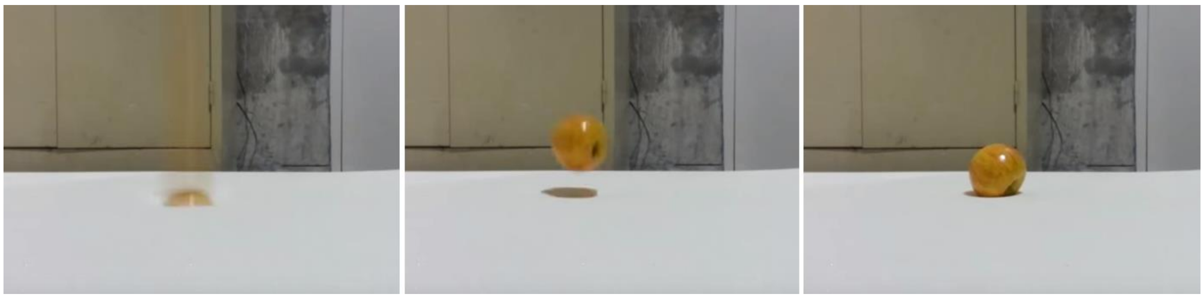

Figure 2 Drop testing of apples onto Memory foam. Left: Impact. Center: Rebound. Right: Resting Position.

Gravity accelerated the apples to a speed of 35 feet per second (approximately 24 miles per hour) upon impact and no bruising was observed across different apple varieties and sizes. Despite the drop height of 19 ft, the apples did not rebound more than approximately 3 inches (see Figure 2 above), but the memory foam would recover to near its original geometry within under a second. This is the optimum tradeoff between viscous and elastic behaviors. We then integrated the memory foam into our nozzle design and showed with lab testing that apples could be pulled into the vacuum nozzle, exit through check-valve doors and decelerate by colliding with the memory foam, all without bruising.

Integrate the End-Effector on a Commercial Robot Arm

We proposed to integrate our end-effector with a commercial robot arm to ensure that our end-effector design is compatible with a robot arm and to facilitate a demonstration of the manipulation subsystem. The integrated system is shown in Figure 3 below. The end-effector was mounted to the commercially available pick-and-place robot which was in turn mounted to the structure of a utility trailer. Also attached to the trailer structure was the vision system developed by Carnegie Melon University. We subcontracted a part of our grant funds to Carnegie Melon University to integrate their existing sensor with our picking platform in an effort to demonstrate fully autonomous apple picking.

Other significant hardware shown in the photo is the vacuum system, driven by the PTO of the tractor pulling the system. When an apple is not passing through the end-effector, the vacuum system draws 15 hp: 3 hp across the silencer, 6 horsepower across the pump, and 6 hp across the hoses and nozzle. The event of separating and apple from the tree and passing it through the end-effector has a duration of approximately 100 ms. At a picking rate of 1 per second, the average additional horsepower draw is approximately 2 hp.

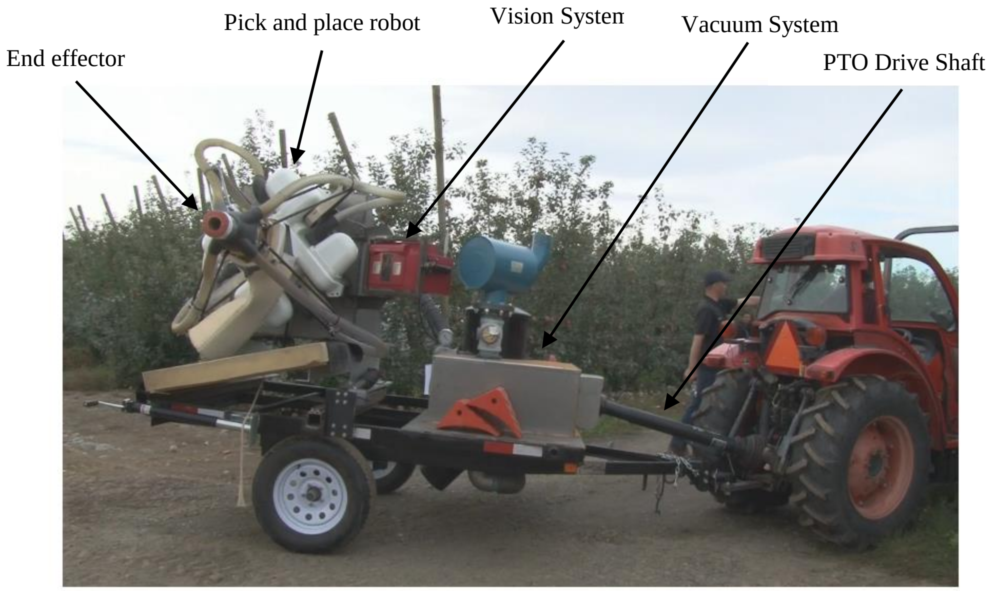

Figure 3 Photo of the demonstration and evaluation system

Demonstrate and Evaluate the Integrated Manipulation Solution

We brought the demonstration platform to Washington State for some initial testing September 8-11. Based upon those results, we returned the platform to SRI for some repairs and modifications. After the updates, the platform was sent again to Washington State for additional testing October 5-9. Our September testing was conducted at Yakima Valley Orchards' Glead ranch, Chiawana Orchards' Glead ranch and Doornink's Selah Ranch. Our October testing was conducted at Matson's Fruit Orchard in Wapato, McDougall and Sons' Gambler Ranch, Yakima Valley Orchards' Airport ranch and Flemming Farms in Quincy. We tested in multiple locations to enable us to evaluate our performance with a variety of different horticultural (pruning, training, etc) approaches. We also attempted to test in northern and southern geographies to enable as many growers to observe our evaluation and demonstration as possible. A map with the test locations is shown in Figure 4 below.

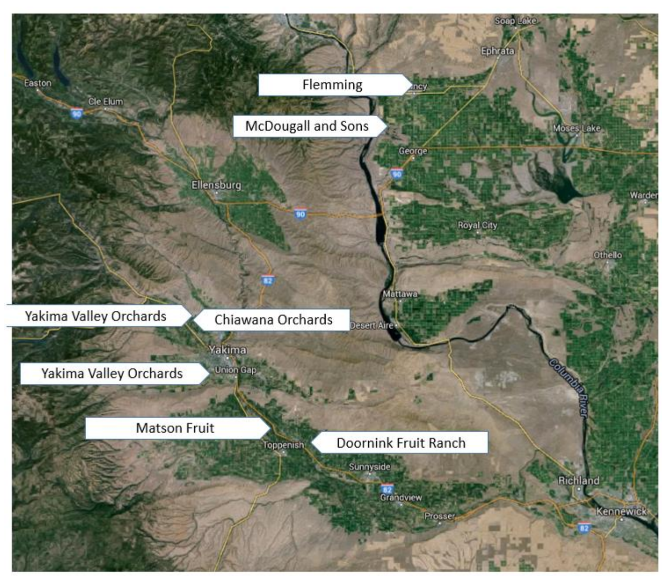

Figure 4 Map of Eastern Washington showing the 7 test locations

Our testing procedure was to park the system in an orchard row and press a key on the keyboard to initiate an autonomous picking sequence. Once initiated, the sensor would capture a photo of the trellis, recognize apples from leaves, determine the 3D coordinates of the recognized apples and then send those coordinates to the robot. The robot would then deploy the end effector to those coordinates and in the ideal case, the end effector would successfully pick the apples. A set of frames from one of our autonomous picking runs is shown in Figure 5 below. The image in the center shows the photo captured with the 3D sensor and includes circles drawn to indicate where the vision algorithm identified apples. The frames show the end effector moved to each of those locations. The system successfully picked all seven of the apples shown in the image in the center. This was one of hundreds of picking sequences we did throughout our field testing. We picked thousands of apples.

Figure 5 Frames of video capturing the pick events. The sensor output is shown in the center and the pick sequence is clockwise from the top left frame

As a part of this activity, the Washington Tree Fruit Research Commission collected 180 of the apples which we picked. The variety was Fuji. The results are shown in the table below.

SAMPLE SIZE		180	APPLES
BRUISING	DOWNGRADE	4	PERCENT
	CULL	2	PERCENT
PUNCTURE/CUT		12	PERCENT
TOTAL CULL		14	PERCENT

22% of the apples were found to have stem pulls, and none of the apples had spur pulls. The photos below show an example of the bruises and cuts in the experiment that were considered culls. An interesting finding was that the likely cause of nearly all of these culls was the apple rubbing across a branch during the picking event. If the canopy had long flexible branches, the branch would be sucked into the end-effector before the apple, and as the apple was subsequently sucked into the end effector it would slide along the branch causing either a bruise or a cut.

Figure 6 Left: Bruised Apple, Right: Cut Apple

CONCLUSIONS

Based upon our development and testing activities in 2015, we were able to demonstrate a vision system and end-effector solution that are capable of recognizing, localizing, and picking apples without bruising the apples. We demonstrated the ability of these systems to work together to support a picking rate of faster than 1 pick per second. We identified cuts as the principal cause of culls, and have a working hypothesis of the cause of these cuts. Specifically, it appears that the presence of long flexible branches near apples cause the end-effector to be prone to cutting the apples. We understand from growers that this issue can be reasonably addressed by pruning the long flexible branches from the tree.

EXECUTIVE SUMMARY

Refine the nozzle design

We took the preliminary step of commissioning a formal experiment across multiple varieties to determine the effect of pulled stems on fruit decay in storage. Currently, the apples are in CA storage and will be evaluated alongside ‘normal’ harvested bins of fruit. Each bin will be evaluated, beginning in March, for stem bowl rot or other defects attributed to a stemless condition. The second refinement to the nozzle design focused on minimizing damage caused to the body of the apple by the nozzle. The transition between the urethane and the polycarbonate was moved to be just beneath the urethane orifice. This put the sharp edge transition in a place that the apple could not contact.

Develop an ultra-compact decelerator

We determined that the least expensive, most reliable, and most compact decelerator would be a monolithic piece of viscoelastic foam. The viscous property decelerates the apple without causing the apple to bounce back at a high rate of speed, and the elastic element enables the material to restore its shape before the next impact We found that Memory foam had the right balance of viscous and elastic properties. We then integrated the memory foam into our nozzle design and showed with lab testing that apples could be pulled into the vacuum nozzle, exit through check-valve doors and decelerate by colliding with the memory foam, all without bruising.

Integrate the End-Effector on a Commercial Robot Arm

We integrated our end-effector with a commercial robot arm to ensure that our end-effector design is compatible with a robot arm and to facilitate a demonstration of the manipulation subsystem. We conducted some initial lab test to tune the integrated test platform.

Demonstrate and Evaluate the Integrated Manipulation Solution

We brought the demonstration platform to Washington State for demonstration and evaluation September 8-11 and October 5-9. The system successfully autonomously picked thousands of apples. As a part of this activity, the Washington Tree Fruit Research Commission collected 180 of the apples which we picked. The variety was Fuji. The results are shown in the table below.

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In conclusion, our development and testing activities in 2015 demonstrated a vision system and end-effector solution that are capable of recognizing, localizing, and picking apples without bruising the apples. We demonstrated the ability of these systems to work together to support a picking rate of faster than 1 pick per second. We identified cuts as the principal cause of culls, and have a working hypothesis of the cause of these cuts. Specifically, it appears that the presence of long flexible branches near apples cause the end-effector to be prone to cutting the apples. We understand from growers that this issue can be reasonably addressed by pruning the long flexible branches from the tree.