FINAL PROJECT REPORT

Project Title: Phase 2 System Integration

Contract No.: 2016-001

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Cooperators: Grower in Australia

Total Project Request: **Year 1:** $250,000

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

Other funding sources

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

WTFRC Collaborative expenses: Funded directly by WTFRC

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

Item	**2015 - 2016**
Salaries	$117,692
Benefits	$10,192
Wages	NA
Benefits	NA
Equipment	$75,000
Supplies	NA
Travel	$25,230
Miscellaneous	$21,886
Plot Fees	NA
Total	**$250,000**

ORIGINAL OBJECTIVES

The original objectives of the 2015-2016 funded research were:

1) **Improve apple visibility**
   a) Prior field tests showed that a fixed camera location provided poor visual access to apples and resulted in many undetected apples
   b) We proposed to make both hardware and software improvements to enable the system to see 95% of all of the apples on the near side of the trellis wire
2) **Increase robot workspace**
   a) Prior prototypes prevented the robot from accessing its entire workspace
   b) We proposed to make hardware changes to enable the robot to regain its 50 inch x 50 inch x 20 inch workspace.
3) **Demonstrate continuous picking while the vehicle is moving down the row**
   a) Prior field trials required the picking system to be stationary during both perception and picking
   b) We proposed both hardware and software changes to enable the system to move down the row while continuously picking 90% of all the apples on the near side of the trellis wire.

SIGNIFICANT FINDINGS

The significant findings from our 2015-2016 activities were:

1) **Improve apple visibility**
   a) We moved the optical sensor to the end-effector.
   b) We found that this sensor placement enabled detection of 91% of the accessible apples in a prepared canopy.
2) **Increase robot workspace**
   a) We made hardware changes to enable the robot workspace to grow to a 51 inch diagonal and 20 inch depth.
3) **Demonstrate continuous picking while the vehicle is moving down the row**
   a) We developed software to enable the system to pick apples which continuously moving down the row.
   b) The system was shown to have a pick rate that nearly matched the detection rate.

DETAILED REPORT

This report describes the results of the most recent phase of our multi-phase development path towards a commercial robotic harvester.

Improve apple visibility

Objective
Prior field tests showed that a fixed camera location provided poor visual access to apples and resulted in many undetected apples. The objective of this task was to make both hardware and software improvements to enable the system to see 95% of all of the apples on the near side of the trellis wire.

Materials
We modified the vision system to facilitate placement of the optical hardware on the end-effector. Modifications included partitioning the hardware into components that needed to be at the end-effector and components that could reside elsewhere on the system. The mass of the resulting hardware that needed to be places at the end-effector was adequately below the load capacity of the robot. An image of the placement is shown in Figure 1.

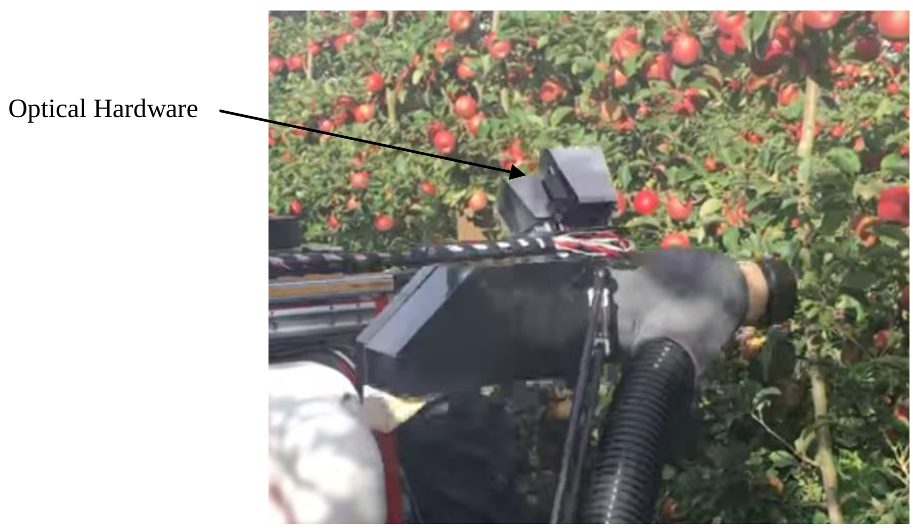


Figure 1 End-Effect with Optical Hardware Attached

We conducted a detection study in which we determined what percentage of the apples were detected by the vision system. We prepared the canopy for this study by thinning to singles and pruning tree growth to approximately 10 inches beyond the trellis wires. We also thinned apples that were physically inaccessible to our current robot. Apples were considered accessible if they were largely contained in the green volume illustrated in Figure 2. Otherwise they were considered inaccessible. In the illustration, Apples 1, 2 and 4 are considered accessible and apple 3 is considered inaccessible.

Procedure
The robot would begin by scanning the canopy directly in front of the initial robot position. Once a set of apples were identified, the robot moved the end-effector to a single apple and stopped. The experimenter would then remove the apple directly in front of the end-effector. The robot would then move the end-effector to the next detected apple and the process would repeat until the end-effector had been moved to all of the detected apples. Image collection and apple detection continued throughout each end-effector motion. The picking system would then move down the row a few

inches and the process would repeat. The experimenter would then go back and count missed apples and compare that to the number of detected apples.

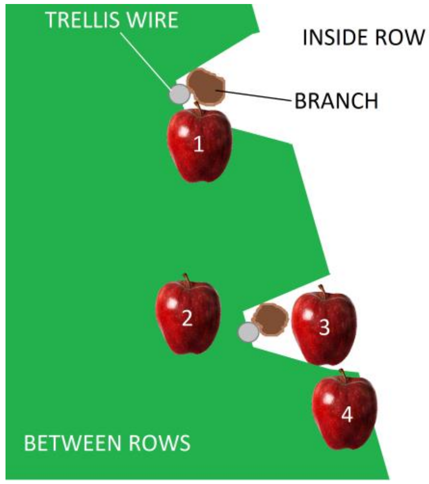


Figure 2 Accessible (green) and inaccessible (white) regions of the canopy

Results

341 apples were detected and 31 apples were missed, suggesting the vision system detected 91.7% of the apples in the prepared canopy. The 372 apples were distributed across 3 wires, starting from the bottom-most wire at an elevation of 30", the second wire at 46" and the third wire at 62". The detection rates varied substantially across wires (see Table 1). The vision system detected 79%, 94% and 97% of apples on wires 1, 2 and 3, respectively.

Table 1 Apple software detection results

	Total (apples)	**Missed (apples)**	**Detected (apples)**	**detected**
Wire 1	85	18	67	78.8%
Wire 2	179	10	169	94.4%
Wire 3	108	3	105	97.2%
Total	**372**	**31**	**341**	**91.7%**

Discussion

The difference in detection rates across wires could be attributed to both leaf vigor and the viewing angle of the optical hardware. Branches at the bottom of the tree tend to produce substantially more foliage than branches at the middle or top of the tree. As a result, visual access will be worse for apples on lower branches. Also, because the end-effector elevation was constrained to be nearly the same as the elevation of the bottom-most wire, the optical hardware was unable to see apples on that wire from a bottom-looking-up perspective. It is anticipated if the end-effector were to scan for apples from a lower elevation than the bottom wire that the detection rate would increase substantially for that wire.

Increase robot workspace

Objective

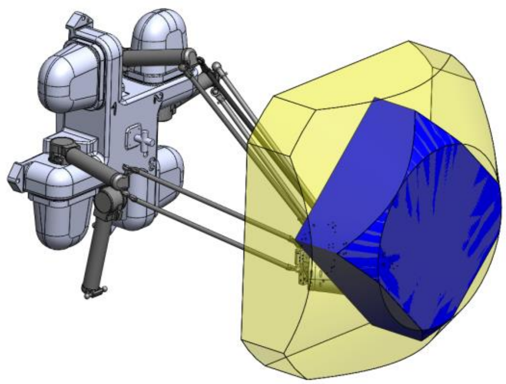
Prior prototypes prevented the robot from accessing its entire workspace. The objective of this task was to make hardware changes to enable the robot to regain its 50 inch x 50 inch x 20 inch workspace.

Method

A number of changes were made to increase the workspace of the robot. First we rebuilt the mounting structure for the robot base so the robot could be mounted 45 degrees about the Z-Axis from where it was mounted previously. Second, we removed the lower arm assembly of the robot. Because we are only using 3 of the robot's 4 degrees of freedom, removal of one of the arms could be achieved without compromising robot performance. Third, we moved the connection point between the robot arms and the end-effector to a position that is further back on the end-effector. Lastly, we reduced the size of the geometry that remained behind the connection point with the robot arms.

Results

The new workspace with a 51” diagonal and 20” depth is shown in Figure 3 in translucent yellow, and is compared to the useable workspace from fall 2015, shown in opaque blue. The adjustment in workspace enabled the robot to pick apples between 24 inches and 57 inches above the ground and is shown in Figure 3 below.



a)

b) c)

Figure 3 Improved robot workspace: a) new workspace (trasparent yellow) compared to old workspace (opaque blue), b) elevation and depth range of new workspace, c) elevation extremes shown in the field

Demonstrate continuous picking while the vehicle is moving down the row

Objective
While prior prototypes have conducted autonomous picking from fixed locations in the orchard, the commercial harvester will pick apples while continuously down the row. The objective of the task was to develop and integrate the technology necessary to enable picking while continuously moving down the row, and demonstrate this behavior in the field.

Materials
The principal software modifications required to enable continuous picking were to account for the motion of the system when moving the robot to a perceived apple. There is a time delay between when an apple is detected and when the robot will move the end-effector to the perceived apple. This delay can be the result of detecting an apple several seconds before the apple is scheduled to be picked, or it can be the result of the time it takes to move to the apple since it was last detected. During this delay, the system will have moved down the row some distance. The developed software generated a motion correction based upon the system velocity down the row and the time delay between image capture, apple detection, end-effector deployment, and pick event.

We used a Deutz Fahr Agroplus tractor which had a minimum forward speed of 0.05 mph (0.8 inches per second) when put in its lowest gear and with an engine speed of 1200 rpm (see Figure 4 below). With the PTO gearbox in its 1000:1 state and an engine speed of 1200 rpm, the PTO was still able to provide the required 540 rpm. The speed was varied by the tractor driver based upon the apple crop load in order to maintain the desired average pick rate of approximately 1 pick per second.

Figure 4 Photograph of the picking system attached to the tractor

We again prepared the canopy for this study by thinning to singles and pruning tree growth to approximately 10 inches beyond the trellis wires. We also thinned apples that were physically inaccessible to our current robot.

Procedure
The system was turned on and autonomous picking was enabled. The robot would then move the end-effector through an oscillating scanning routine. Once an apple was detected, the robot would immediately move the end-effector to the apple's location to pick it. Tests were conducted with the system moving a speeds ranging from 0.05 mph to 0.3 mph. Test runs consisted of the system continuously picking on the order of 100. Performance results were noted.

Results
The sequence of images in Figure 5 capture the system moving down the row continuously while picking. In our experiment, we were able to continuously pick. It was exceptionally rare for us to

detect an apple within the accessible region of the canopy and not be able to successfully remove it from the tree. We left on the order of a dozen detected accessible apples for every bin of picked apples, or approximately 0.6%. As a result, pick rates nearly matched the detection rates presented above. Exceptions to this would arise when we the system speed outran the ability of the robot to pick apples from the tree.

Figure 5 Image sequence of picking while continuously moving down the row

Discussion

These results suggest that our solution for enabling the system to pick continuously while moving down the row are sufficient for meet the anticipated performance requirements for the commercial harvester.

Quality Study

Objective
Every set of field trials is accompanied by an evaluation of the quality of apples coming through the end-effector. This enables us to make sure we are maintaining the apple quality requirements for the commercial harvester while adding system features. It also enables us to evaluate the effect of end-effector improvements on apple quality. As in prior evaluations, we gathered data on the amount of bruising observed in apples that passed through our system.

Procedure
We picked 200 apples using our vision-guided end-effector, let them sit in ambient-temperature storage for 18 hours, and then had them evaluated them for bruising by Karen Lewis, Washington State University Extension Regional Tree Fruit Specialist.

Results
The results are shown in Table 2 below.

Table 2 Quality Study Results

		Spring 2016	Fall 2015	
	VARIETY	PINK LADY	FUJI	
	SAMPLE SIZE	200	180	APPLES
BRUISING	ROBOT-APPLE	4.5	0	PERCENT
	TREE-APPLE	6	6	PERCENT
	PUNCTURE/CUT	0	12	PERCENT
	TOTAL CULL	**10.5**	**14**	**PERCENT**

Photos of the bruises on the bruised apples are shown in Figure 6 below**.**

Figure 6 Photo of the 9 robot-apple bruises (left) and the 12 tree-apple bruises (right)

We classified bruises into 2 categories: robot-apple bruises and tree-apple bruises. Robot-apple bruises (found on 4.5% of the test sample) are bruises caused by impacts between the apple and some part of the robot. Tree-apple bruises (found on 6% of the test sample) are bruises cause by significant contact between the tree and the apple.

Discussion

We determined that 4.5% of the bruising was robot-apple bruising. This was a surprise to us because we had not seen any bruising of this kind in our final configuration in Washington in 2015. Further investigation revealed that changes we made to the vacuum distribution system significantly reduced flow restrictions and consequently increase vacuum power to the end-effector. We also determined that all of the 6% tree-apple bruising was caused by the apple sliding along a branch as it is pulled into the end-effector.

We note that our overall results were better in Spring 2016 than in Fall 2015. We also note that the Spring 2015 evaluation was more conservative because it evaluated bruising on a more bruise-prone variety (Pink Lady vs Fuji) and picking for the bruise evaluation was done with computer vision rather than manual teaching. The testing was less conservative, however, in that we pruned the growth back to approximately 10 inches from the trellis wire. Lastly, we expect to substantially reduce the robot-apple bruising now that we understand the effect increased vacuum flow had on bruising.

CONCLUSIONS AND FUTURE WORK

This phase of work enabled us to make substantial progress toward our end goal of bringing a commercial robotic harvester to market. We found that placing the optical sensor on the end-effector enabled good visual access to and subsequent detection of physically accessible apples. Our hardware changes which increased the robot workspace enabled us to test a workspace similar to the workspace envisioned for the final version of the robot implementation. We were also able to successfully pick accessible apples while moving continuously down the row. Lastly, we found that our bruise rates have been reduced from prior prototypes and have a clear direction for how to improve those rates further. The next phase of development is focused on integrated the complete flow path of the apple - from the tree through the end effector and into the bin.

EXECUTIVE SUMMARY

This report describes the results of the most recent phase of our multi-phase development path towards a commercial robotic harvester.

Improve apple visibility

We moved the optical sensor from a fixed position on the base of the robot to the end-effector of the robot. We found that this enabled us to detect 91.7% of the apples in a prepared canopy. We also found that the detection rates varied substantially across wires (see Table 1).

Table 3 Apple software detection results

	Total (apples)	Missed (apples)	Detected (apples)	detected
Wire 1	85	18	67	78.8%
Wire 2	179	10	169	94.4%
Wire 3	108	3	105	97.2%
Total	**372**	**31**	**341**	**91.7%**

The difference in detection rates across wires could be attributed to both leaf vigor and the viewing angle of the optical hardware. It is anticipated if the end-effector were to scan for apples from a lower elevation than the bottom wire that the detection rate would increase substantially for that wire.

Increase robot workspace

We made a number of hardware changes which enabled us to increase the workspace substantially – to a 51" diagonal and 20" depth. The adjustment in workspace enabled the robot to pick apples between 24 inches and 57 inches above the ground, though removal of the 4th robot arm restricted motion below 30 inches.

Demonstrate continuous picking while the vehicle is moving down the row

We also made software modifications required to enable continuous picking while the system moved down the row. We found that our pick rates nearly matched detection rates. Based on these results, we anticipate that our solution for enabling the system to pick continuously while moving down the row was sufficient for meet the anticipated performance requirements for the commercial harvester.

Quality Study

We also conducted another bruise quality study. The results are shown in Table 2 below.

Table 4 Quality Study Results

		Spring 2016	Fall 2015	
	VARIETY	PINK LADY	FUJI	
	SAMPLE SIZE	200	180	APPLES
BRUISING	ROBOT-APPLE	4.5	0	PERCENT
	TREE-APPLE	6	6	PERCENT
	PUNCTURE/CUT	0	12	PERCENT
	TOTAL CULL	**10.5**	**14**	**PERCENT**