FINAL PROJECT REPORT

Project Title: Design and Development of apple harvesting techniques

PI: Manoj Karkee
Organization: WSU CPAAS, Prosser
Telephone: 509-786-9208
Email: manoj.karkee@wsu.edu
Address: 24106 N. Bunn Rd
City/State/Zip: Prosser, WA 99350

Co-PI (2): Qin Zhang
Organization: WSU CPAAS, Prosser
Telephone: 509-786-9360
Email: qinzhang@wsu.edu
Address: 24106 N. Bunn Rd
City/State/Zip: Prosser, WA 99350

Co-PI(3): Karen Lewis
Organization: WSU Extension and CPAAS
Telephone: 509-760-2263
Email: kmlewis@wsu.edu
Address: 24106 N. Bunn Rd
City/State/Zip: Prosser, WA 99350

Co-PI (4): Mark De Kleine
Organization: WSU CPAAS, Prosser
Telephone: 509-786-9257
Email: m.dekleine@wsu.edu
Address: 24106 N. Bunn Rd.
City/State/Zip: Prosser, WA 99350

Cooperators: None

Other funding sources: None

Total Project Request: **Year 1:** 53,395

Budget History:

Item	2012
Salaries[1]	$30,534
Benefits[1]	$1,997
Wages[2]	$6,240
Benefits	$624
Equipment	
Supplies[3]	$10,000
Travel[4]	$4,000
Plot Fees	
Miscellaneous	
Total	$53,395

Footnotes:

[1] Salary and benefit for a graduate student
[2] Wages and benefits for hourly help to fabricate sensor platform and collect field data
[3] Cost to purchase materials and build sensor platforms
[4]Travel cost for field data collection and testing

Objectives

Our long term goal was to improve the sustainability and productivity of tree fruit production through reduced labor use and associated costs. Originally the project was proposed for three years with the following specific objectives:

1. Design and develop two prototypes for semi-automated apple harvesting techniques.
2. Characterize the efficiencies of harvesting in two variations of fruiting wall architectures.

The project was funded for only the first year to demonstrate the feasibility of the concept. The scope for the first year for this project involved prototype development and preliminary evaluation in lab and field environments.

Significant Findings

- Two Prototype fruit removal end effectors were developed: Rotational (RAH) and Linear Actuators (LA), and a provisional patent has been filed with WSU (10/2013).
- The RAH and LA prototype mechanisms can remove apples from a limb while retaining fresh-market quality.
- For RAH, the speed of rotation is not a significant factor in resulting fruit removal condition; variety was a significant factor; same direction of rotation achieved the best result.
- Horizontally trained limbs, that are short and stiff, and short spurs are suitable for the rotational harvesting technique.
- Removal rate for RAH was estimated at 2,400 apples per hour; similar to human labor on a mobile platform.
- Removal rate for LA were estimated at 20,000 apples per hour.

Results and Discussion

RAH End-Effector: Results indicate that the rotational apple harvester (RAH) end-effector developed in this project can successfully remove apples from a limb. In this research, the removed fruit was initially classified into three fruit removal conditions (FRC): stem-intact, stempull, and spurpull (figure 1). The fresh-market total (FMT) was defined as the sum of stem-intact and spurpull conditions, while considering that spurpull should be minimized to retain fruiting wood for the next year. Initially, the FMT assumed only the FRC and did not regard other quality issues including bruising downgrades, cuts, and punctures. Damage data relating to bruising was measured in 2013 and will be addressed in further research. Likewise, data relevant to CA fruit storage for some fruit harvested in the fall of 2013 is currently underway. The results will yield supplemental data for these harvesting results and provide further quantifiable data and insight into acceptable fruit removal condition.

Figure 1. Fruit removal condition (L-R): stem-intact; stempull; spurpull.

Ten total varieties of apples were tested using the RAH removal technique: five in 2012 (Jazz, Pacific Rose, Golden Delicious, Granny Smith, Jonagold) plus five in 2013 (Gala, Fuji, Red Delicious, WA-17, Honeycrisp). Four varieties were duplicated in testing, either in location or year (Gala, Granny Smith, Golden Delicious, and Fuji). A total of 14 tests were conducted for the varieties listed. Table 1

shows the results based on FRC percentage for the varieties tested in 2012 and 2013. Seven out of the fourteen tests resulted in a FMT of 84% or better. The highest percent of apples classified as FMT was for 'Honeycrisp' at 98%. The damage rate associated with 'Honeycrisp' was 32%. All apples that were removed from a limb were allowed to fall to the orchard floor. Damage due to fruit falling through the canopy was not isolated during the first year of testing. It is suggested that a trellising system can improve the "catchability" of RAH removed apples and subsequently lead to a decrease in the damage rate. Research and development regarding localized catching and transport is still needed to move the RAH and LA techniques into complete semi-autonomous harvesting systems.

Variety has a significant effect on the FRC. Two tests with Granny Smith ranked 12th and 14th, out of 14 total tests, as least likely to have a successful FMT. Some consistency is noticeable in table 1, as can be seen with Fuji and Golden Delicious varieties. Two tests with Fuji were conducted in the same year at different orchards, yet ranked 5 and 6 for FMT. Two tests with Golden Delicious were conducted at the same location during two different years and ranked 7 and 8 for FMT. The lack of dispersion for FMT in these varieties make them more suitable, and predictable, for using the RAH technique. However, certain varieties including Granny Smith and Red Delicious were not as suitable for this removal method in both removal condition and horticultural growing characteristics (short stiff limbs).

Table 1 FRC percentage using RAH removal technique for 2012 and 2013.

Year	Variety	***% FMT***	% Stem-intact	% Spurpull	% Stempull
2013	Honeycrisp*	***98***	94	4	2
2013	WA-17 *	***97***	88	9	3
2013	Gala (#1)**	***94***	87	7	6
2012	Pacific Rose**	***92***	86	6	8
2013	Fuji (#1)*	***89***	84	5	11
2013	Fuji (#2)**	***84***	71	13	16
2013	Golden Delicious (#1)**	***84***	58	26	16
2012	Golden Delicious (#2)**	***82***	80	2	18
2012	Jazz*	***80***	70	10	20
2013	Gala (#2)**	***79***	67	12	21
2013	Red Delicious**	***77***	67	10	23
2013	Granny Smith**	***61***	46	15	39
2012	Jonagold**	***60***	58	2	40
2013	Granny Smith**	***36***	36	0	64

* Commercial Orchard

** Research Orchard

Formally trained growing systems achieved a higher removal rate (no. of apples harvested per unit time) than random growing branches. These open systems allowed the user to easily identify an apple and apply the RAH. Three out of the ten varieties tested were grown in formally trained fruiting walls (Gala, Jazz, Pacific Rose) and two of them were in the top five of the FMT ranking. It was observed that fruit was removed better, with less user manipulation, when grown on short branches with a relatively low apple density per spur. Longer, unconstrained, branches are not preferred for use with the RAH technique; so to improve the harvesting results, the length of the branch should be minimized when horticulture permits. Apples growing in clusters were not treated any differently

than single apples and the results showed that the RAH was effective in removing fruit in clusters as well.

The removal rates using the RAH method were similar to a human working on a mobile orchard platform (assumed to be 45 apples/min). The removal rates projected, approximately 2,200–2,400 apples per hour for RAH and 20,000 apples per hour for LA, were almost exclusively calculated on removal rates measured in fruiting wall architectures with no formal training. It is hypothesized that these removal rates will be improved with a formally trained horizontal limb system. Likewise, the horizontal limb system could facilitate the expansion of the RAH technique into a multiple wheel system that allows the user to increase removal rates to an economically justifiable level. The RAH system was not considered to be a selective harvesting method although the multiple wheel system will have the potential to individually activate a section when triggered by a color scheme or human input. The RAH can be used as a type of semi-automated technique with further improvement to aid in labor handling and ergonomics. More research and development is needed to further this type of system.

The materials used for the prototype are all off-the-shelf components. Two 18V electric drill motors (18 ft-lb torque) are suitable for removing an apple from a limb. A soft rubber, TPE type or 30-55 Type A rubber, is sufficient for non-abrasive contact with an apple and provides adequate surface friction during fruit removal. Further work is needed to autonomously control the applied pressure to the surface of the fruit. Year 3 of the initial proposal was to incorporate this mechanism for pressure application.

LA End-Effector: The materials used for the LA prototype include an 18V hand-held linear actuator with a hook that grasped a limb. Preliminary tests conducted in a formally trained horizontal limb system with WA-17 variety showed that actuation can be isolated to a branch with no residual effects, or fruit removed, on upper or lower branches. The precise application of actuation combined with the projected removal rates and FMT rates provide a valuable component for the economic analysis using semi-autonomous fruit removal techniques. Similar to RAH, variety has a significant effect on FRC. However, for Fuji apples tested using LA, FMT averaged 80%. For WA-17, the LA FMT decreased 14% compared to RAH FMT, from 97% to 84%. On the other hand, the removal rate for LA increased by 1,200% from 1,800 apples per hour to 22,000 apples per hour, compared to RAH. Furthermore, a dual motor actuator has been developed to specifically isolate movements to the stem-spur junction by applying rhythmic-patterned actuation. This type of system has the potential to further increase the FMT removal percentages. This research is currently ongoing and expected to continue during Fall 2014 and beyond.

It should be noted that no correlations were made between: a) fruit removal condition and starch-iodine maturity level or b) fruit removal condition and fruit pressure number in either of two prototype evaluations. It is also noted that further research is needed in horizontal limb trellised orchards to incorporate the RAH and LA techniques into a full scale bulk harvesting system.

Executive Summary

This report provides an insight and evaluation of two fresh-market fruit removal techniques developed and tested in apples; a first step in achieving a semi-automatic or fully automatic fruit harvester. Two hand-held devices were compared: a mechanism that rotates fruit vertically and a patterned actuating device. Methods of analysis include fruit removal condition, location, variety, and removal rates, as well as mechanism parameters. Results of data analyzed show that fresh-market quality fruit can be removed from a branch without sustaining significant damage for either technique. Variety is a significant factor on fruit removal condition for each technique. Removal rates for linear actuation were 1,200% higher than rotational. Damage rates ranged 10-50%. Suggestions discussed are:

- that horizontal limb training will improve removal rates and lower damage percentage within the canopy;
- that variety be considered when choosing a technique;
- that actuation removal rates need more economic consideration especially with a modified canopy structure.

The report also discusses the limitations for scaling up these techniques. Some limitations include: horticulture growing characteristics and access to fruit within the canopy. This report also suggests future research and continued development in: rhythmic-pattern actuation, to isolate movement to stem-spur junction; and catching mechanism strategy.