Project Title: Automated Apple Harvester

Report Type: Final Project Report

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Cooperators: N/A

Project Duration: 3 Year

Total Project Request for Year 1 Funding: $180,000
Total Project Request for Year 2 Funding: $140,000
Total Project Request for Year 3 Funding: $140,000

Original Objectives and Significant Findings

Below are the goals and objectives as described in the 2023 Continuing Report and 2024 Project Proposal.

1. Modify current harvesters based on prior year's learnings and build more harvesters for a total fleet size of at least 10 harvesters. As a note, currently we do all assembly at our facility in Davis, CA. When we start ramping up production, we will need a manufacturing partner for mass production. It is possible that we will leverage our investors, Kubota or Yamaha for assistance with that.
2. Have pilot contracts to harvest on multiple ranches.
3. Improve vision system to be able to pick night and day.
4. Start planning expansion into different orchard structures (such as V trellis and wider/narrower rows).
5. Fully automated driving, which enables one worker to operate up to five machines.
6. Add an automated stem cutter to the machine in order to further reduce labor cost. (Prior to 2024, stems will need to be cut manually.)

Below is a summary of the actual performance against each goal:

1. We chose <u>not</u> to ramp production to 10 harvesters, and instead opted to build 2 machines. This made for easier testing and was also a reflection of the state of the industry; apple growers are not in a position to support scaled testing operations nor does advanced.farm have the resources at this phase.
2. We harvested 8 different varieties across 7 different growers' ranches. As noted later, we picked over 450,000 apples.
3. We upgraded our vision system to an off-the-shelf camera from Stereolabs and regularly picked at night and during the day this season.
4. We focused only on vertical-wall trellised orchards with 9-12 foot row spacing. But, we did pursue a broad review of over 40 ranches to understand product requirements for various growing structures and strategies (including V Trellis).
5. Because we operated only a single machine, we did not prioritize driving an entire fleet autonomously. However, we did achieve autonomous in-row navigation by using the tree line to stay centered along the row without operator intervention.
6. Because of the large number of apples we picked, we clipped stems by hand. However, we did prototype various mechanisms for automated stem clipping and run tests at a smaller scale to inform future development.

Significant Findings over the course of the project are listed below.

Note: please also refer to prior year continuing reports to see key lessons learned from previous seasons of development.

- Horticultural strategy makes a meaningful impact on the success of robotic harvesting. Any effort to improve fruit visibility and reduce obstacles on the way to an apple (i.e. leaves and branches) can result in appreciable improvement to robot performance. Between the 2023 and 2024 seasons, we paid special attention to this and even followed a published procedure (below) to ensure preparedness of our orchard testing partners.

At orchards where growers followed these procedures or a similar practice, we saw "thoroughness" (i.e. % available apples picked) of 30%, versus 10% at a typical, "unprepared" site. At the best-prepared sites, we saw 50% thoroughness.

PRUNING GUIDELINES TO FACILITATE ROBOTIC APPLE HARVEST

Date: Dec. 9, 2023

By: Hermann G Thoennissen, HTG International, LLC

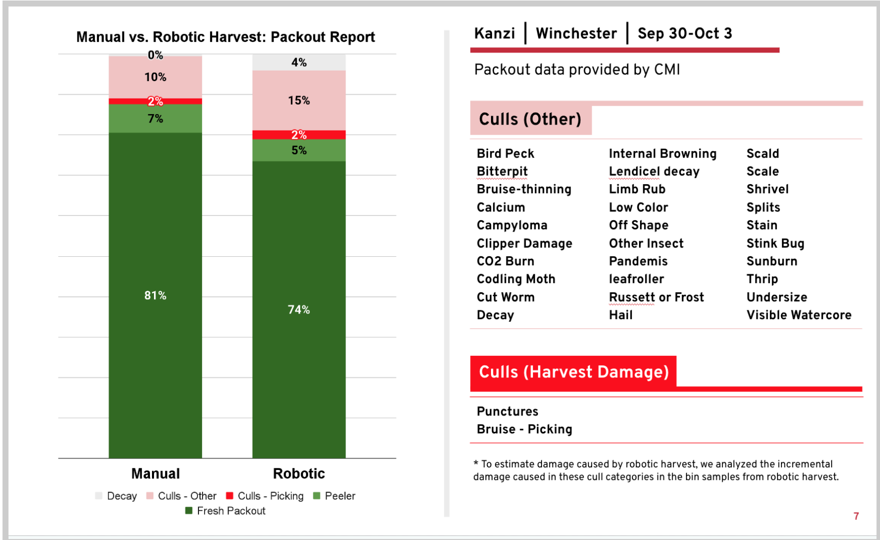
The following guidelines were used when preparing a 10x3 Gala planting for mechanical harvest.
In January of 2023 we decided to allocate a portion of a nine-year-old Gala on M9 rootstock block for experimenting with mechanical harvest. The decision was made to transform the canopy as quick as possible. The block was of medium to low vigor, certainly not vigorous. Few suckers exceeded 24 inches in length. The trellis is a single plain with 5 wires. Target tree height is about 11 feet.
The block has drip-, undertree- and overtree irrigation.
One of the goals is to eventually drive the harvester down every other row only and pick the entire tree canopy from one side, thus reducing travel distance and turnaround time by half.
This is easier said than done. It requires a significant change of traditional mindset.
We selected a small group of experienced pruners and explained to them what the ultimate goal is, why we wanted to prune in this highly unusual and novel way. This became a good discussion with significant input from these experienced employees.

- Limit canopy width to about 16 to 20 inches at pruning, no exceptions.
- Try to not leave thick branches pointing straight into the drive row.
- Prune with replacement of branches in mind.
- Prune with replacement of spurs along the wires in mind.
- No branch tying in the future. The pruning shear is the only tree training tool.
- Do not allow for pendant wood over ten inches. Goal is to bring it back to 4 inches once a flower bud has developed within the 4-inch space.
- Reduce spurs to one or two end points. Do not leave old gnarly spurs with multiple ends.
- Work towards designing the fruit position to be one that is hanging down. This will take several years and forward-thinking on the behalf of the pruner. Experience is needed.
- Communicate with supervisor and pruners.
- All involved must agree and pursue the same vison and goal.
- A very high level of uniformity is key.
- Be prepared to do summer pruning, esp. on vigorous trees.
- Summer-prune/remove suckers at length of 8-10 inches prior to lignification.
- Direct growth/energy into spurs.
- Keep in mind this is a multi-year process.
- One observation made, now after the foliage has dropped: Dormant pruning will be minimal to none on some trees.
- Incorporate management of fireblight when planning/timing your pruning approach.
- Create light windows between trellis wires for even coloring of fruit.
- ? Can we achieve enough coloration to pick only onetime? We kept this goal in mind when pruning.

We also found that thoughtful pruning can also result in higher equipment reliability. Stray branches can get stuck in conveyors and in the drive system, and can also result in torn grippers.

Finally, we are still working to understand the right tradeoffs between costs incurred during orchard preparation and performance during harvest. For example, reducing doubles and clusters with more aggressive thinning can reduce the number of dropped apples during harvest. However, lower yield may not be acceptable. Some of these tradeoffs will also be handled with technological improvements (i.e. can robots pick doubles?) - but, taking a systems-level view and meeting in the middle where possible is important to accelerating the introduction of robotic harvesting at scale.

- Fruit damage is (obviously) multi-faceted but that has very practical implications on overall system design. For example, this year we demonstrated that our robotic harvester can achieve comparable results to a human picker with respect to damage caused from the act of picking until an apple is placed into a bin. However, we had not completely accounted for rejecting the obvious culls caused by environment (i.e. sunburn) and pests or disease (i.e. bitter pit). We now must tackle the scope to reject this fruit before the bin, which spans beyond the initial scope of the project but is a major impediment to broad adoption. Example packout report from the Kanzi variety is below.



- We have discovered various techniques about how to identify, pick, drop and convey an apple successfully and consistently across different varieties. These techniques are proprietary and are outside the scope of this summary. But, achieving results consistently over the season gives us confidence that many of the fundamentals have been de-risked and will broadly apply even if we were to change various parts of the harvester or even the robotic arm design.

Results and Discussion

This season, we harvested eight varieties across ranches operated by seven different growers. The table and image below outline our performance at each ranch. The machine consistently harvested around one bin per hour, and regularly picked for several hours each day. As noted above, thoroughness ranged from 20-45%. At peak performance, our harvester picked 24 bins across 24 hours of operations. As noted in a previous section, the range in performance and reliability was partially due to the range of conditions we faced. However, some of the variation was certainly due to inconsistency in our own technical performance, and because we tested new features that sometimes resulted in worse "headline" statistics.

advanced.farm 2024 Season Snapshot

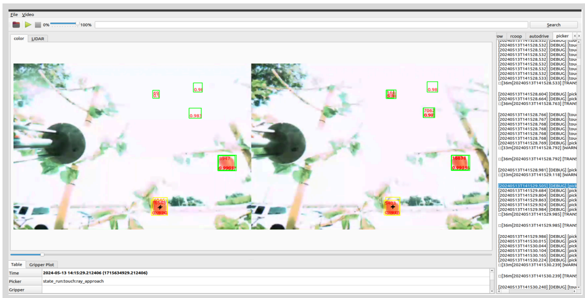
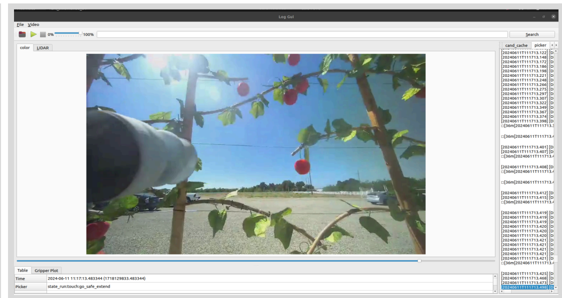
Linked slide

Grower Partner	NWFM	International Farming	Columbia Fruit Packers	Columbia Reach Chiawana Orchards	Taggares Fruit Company	Columbia Fruit Packers	allan bros	Taggares Fruit Company	Price
Variety	Wildfire Gala	Gala	Gala	Honeycrisp	Cosmic Crisp	Kanzi	Envy	Fuji	Pink Lady
Region	Mattawa	Sagemoor	Quincy	Cowiche	Pasco	Quincy	Pasco	Pasco	Yakima
Harvest Date *(estimate)*	7/29-8/1	8/17-8/23	8/26-9/13	9/16-9/20	9/23-9/24	9/30-10/5	10/7-10/11	10/14-10/17	10/28-11/1
Area Harvested (acres)	0.8	1.6	4.7	1.8	4 rows[1]	1.25	1.5	6 rows[1]	3
Harvest Strategy (# Passes)	1 pass	2+ passes	2+ passes	2+ passes	2+ passes	2+ passes	2+ passes	2+ passes	2+ passes
Bins Sent to Packhouse (#)	6	20	36	36	6	25	32	N/A	15
Pick Rate (apples/hr) - Avg Hr	980	1,900	1,060	2,310	2,090	2,330	2,560	1,420	1,230
Pick Rate (apples/hr) - Best Hr	1,770	3,770	2,990	4,070	2,910	3,650	3,900	2,360	2,430
Thoroughness (% fruit picked)	20%	30%	20%	45%	N/A	25%	30%	N/A	30%
Damage from Robots (%)	12%	12%	TBD	20%[2]	N/A	0%	TBD	N/A	TBD

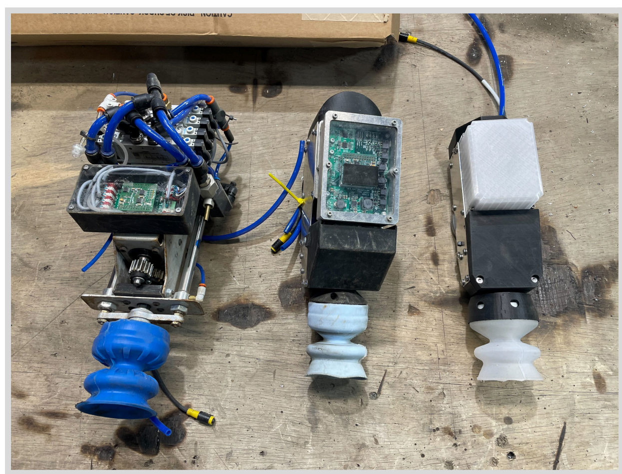
1. This ranch was a last-minute addition to the agenda in an effort to see a new variety and fill in a gap within our harvest schedule. We did not see substantial picking time to acquire meaningful data nor are the orchard conditions representative of our typical performance.
2. This is the total harvest-related damage from the robotic harvest, not just the amount incremental damage over the human harvest packout which would presumably be lower.

We moved to a new stereo camera this year, the Zed mini platform produced by Stereolabs. This camera provides better calibration, is more robust for the outdoors, and seamlessly integrates with the NVIDIA compute platform. Before this year, we had been using a stereo camera that we designed, manufactured, calibrated and maintained on our own. This created issues on the ranch, many of which were resolved with the platform change. See below a picture of the camera's view. In this picture, boxes of various colors correspond to a ripeness estimate based on color.

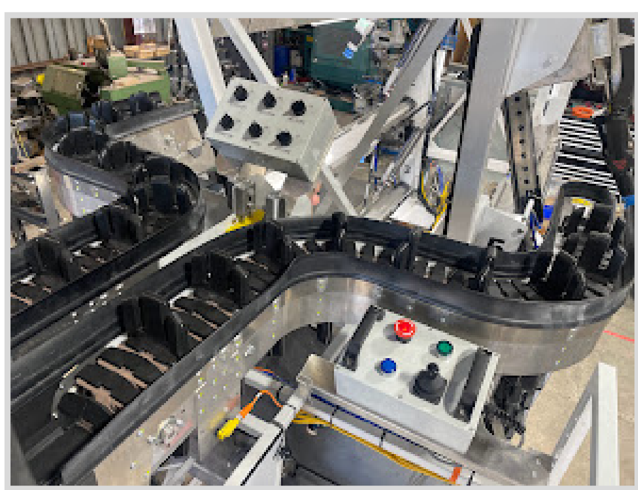
Consistent with this year's goal to pick better during day and night, the camera also had better dynamic range to handle a variety of lighting conditions. See below the view from our old camera (left) and the Stereolabs camera (right), side by side.

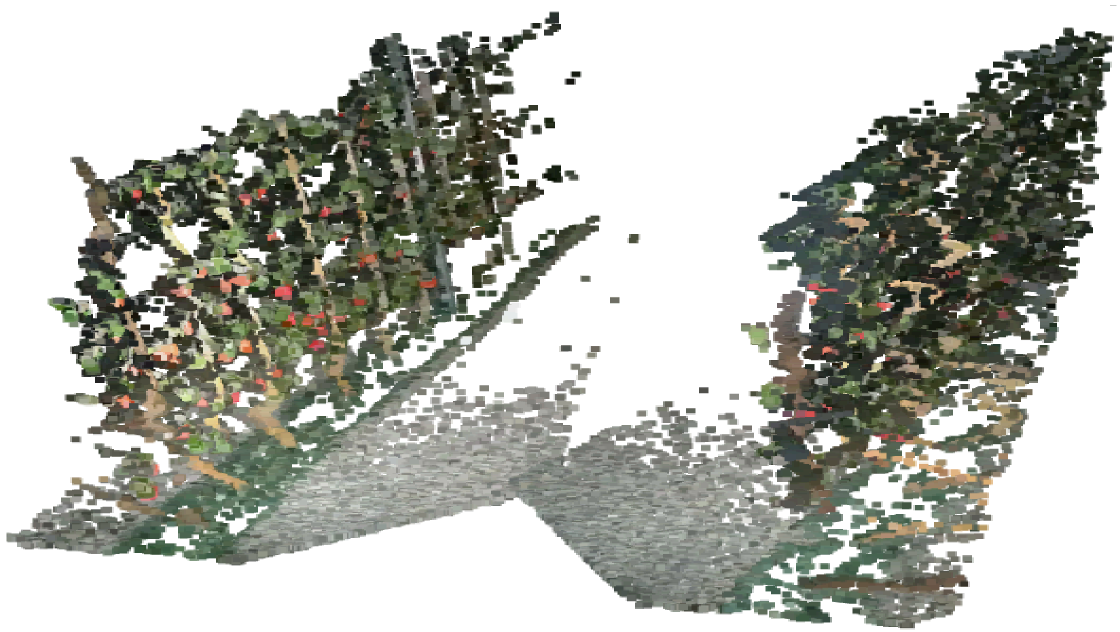
In 2024, we made a number of improvements to the system overall. For example, we reduced the mass of the gripper, which is now just 30% of the weight of the original prototype we deployed in 2022. The suction cup is also made from a more durable material, reducing tears.



We also focused on making the fruit conveyance softer, with gentler transitions. As noted above, this resulted in parity with humans with respect to the quality of bins.



With front-facing cameras (in lieu of LIDAR), we moved to a new approach to navigating through orchard rows using the tree line to stay centered. The image below represents a point cloud acquired by our front-facing camera.



Finally, as we move forward with this project, we have developed a number of standard operating procedures and infrastructure to collect data from the orchard. This is not a trivial development, as it is always challenging to find ground-truth data in a dynamic environment. The next challenge will be to continue to learn and make progress while also giving more operational control to our grower partners. We will continue to rely on the WTFRC for support as we move into this next phase of our company.

Executive Summary

Project Title: Automated Apple Harvester

Key words: automation, apples, robot, robotics, harvest

Abstract:

Washington apple growers face pressures from labor supply and cost, especially during harvest. This pressure will likely continue to worsen, as wages are expected to double (again) in the next decade.

This project explores a new "robot-first" reality in which robots lead during harvest, picking 30% or more of ripe fruit as they pass, with a smaller human picker crew following behind. To make robotic harvest reliably cost competitive, several technological discoveries and advances are necessary. For example, robotic arms need to be affordable, reliable and flexible. Grippers need to be designed to handle fruit gently while also causing minimal damage to the tree. Once picked, apples need to be placed gently into a standard industry bin. All of this needs to be done to a near-human standard for color picking, and without disruption to typical harvest operations. Over the course of three seasons from 2022-2024, Advanced Farm Technologies developed prototype robotic apple harvesters that achieved many of these goals. These efforts have made robotic apple harvest within reach, and have also significantly advanced the overall state of the art in robotics and farm equipment.